Flightcrew Response to Aircraft System Failures, Malfunctions, and Systems Not Functioning as Expected

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14. ABSTRACT

The primary goal of this research was to analyze operational data to study flightcrew response to system failures, malfunctions, and systems not functioning as expected. Data from normal flight operations show that pilots are exposed to such situations regularly. We reviewed 20 records from the Aviation Safety Reporting System (ASRS) public database and five public accident reports (Qantas 72, US Airways 1549, Qantas 32, Lion Air 610, and Ethiopian Airlines 302). Data from the accident reports are presented at three levels of detail. First, a short summary of basic facts introduces the reader to the malfunctions and pilot responses that occurred. Second, a bulleted summary focuses on the flightcrew perspective, what they experienced, and how they responded to the malfunction and overall situation. Finally, detailed quotes from the accident reports that support the summaries are provided in an appendix. We highlight key observations from both the ASRS analysis and the review of accidents. In addition to the data analysis, this report has a review of associated literature covering research on aircraft system problems, alerts and checklists, pilot training, and pilot response. The literature review illustrates the broad scope, variety, and depth of research connected to pilot response.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

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List of Abbreviations

Acronym	Definition
AC	Advisory Circular
ACARS	Airborne Communication Addressing and Reporting System
ACN	Accession Number
AD	Airworthiness Directive
ADIRU	Air Data Inertial Reference Unit
ADR	Air Data Reference
AFM	Aircraft Flight Manual
AFS	FAA Flight Standards Service
ALPA	Air Line Pilots Association
ALT	Altitude, Altimeter
AND	Aircraft Nose Down
ANU	Aircraft Nose Up
AOA	Angle Of Attack
AOPA	Aircraft Owners and Pilots Association
AP or **A/P**	Autopilot
APU	Auxiliary Power Unit
AQP	Advanced Qualification Program
ARC	Ames Research Center
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATP	Airline Transport Pilot
ATPL	Air Transport Pilot License
ATSB	Australian Transport Safety Bureau
AVS	FAA Aviation Safety organization
BEA	French Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile
CA	Captain
CAS	Crew Alerting System
CASA	Civil Aviation Safety Agency
CASR	Civil Aviation Safety Regulation

Acronym	Definition
CAST	Commercial Aviation Safety Team
CBT	Computer Based Training
CG	Center of Gravity
CPL	Commercial Pilot License
CVR	Cockpit Voice Recorder
CRM	Crew Resource Management
DFDR	Digital Flight Data Recorder
DOT	Department of Transportation
EAIB	Ethiopian Aircraft Accident Investigation Bureau
EASA	European Aviation Safety Agency
ECAA	Ethiopian Civil Aviation Authority
ECAB	Engineering Cab (Flight Simulator)
ECAM	Electrical Centralized Aircraft Monitor
EFIS	Electronic Flight Instrument System
EGPWS	Enhanced Ground Proximity Warning System
ELAC	Elevator and Aileron Computer
EICAS	Engine Indicating and Crew Alerting System
EOW	Extended Over-Water
ETH	Ethiopian
ETOP	Extended Overwater Operations
ESL	English as a second language
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCC	Flight Control Computer
FCOM	Flight Crew Operating Manual
FCPC	Flight Control Primary Computer
FCTM	Flight Crew Training Manual
FD	Flight Director
FDR	Flight Data Recorder
FHA	Functional Hazard Analysis
FltDAWG	Flight Deck Automation Working Group

Acronym	Definition
FMGES	Flight Management Guidance and Envelope System
FO or **F/O**	First Officer
FOM	Flight Operations Manual
FPM	Feet per minute
FSB	Flight Standardization Board
FSIM	Flight Standards Information Management System
FWC	Flight Warning Computer
FWS	Failure Warning System
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
IAA	Intra-agency Agreement
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
IR	Inertial Reference
KLGA or **LGA**	LaGuardia Airport
KNKT	Komite Nasional Keselamatan Transportasi
LH	Left-hand
LNI	Lion Air
LPA	Landing Performance Application
LPSOV	Loss of the Fuel Isolation Valves
MA	Master Flight Director Indicator
MCAS	Maneuvering Characteristics Augmentation System
MDS	MAX Display System
MEL	Minimum Equipment List
MOM	Multi Operator Message
MPL	Multi-crew Pilot License
N/A	Not available
NASA	National Aeronautics and Space Administration
NG	Next Generation
NLR	National Aerospace Laboratory
NNC	Non-Normal Checklist

Acronym	Definition
NTSB	National Transportation Safety Board
OEB	Operations Engineering Bulletins
OEM	Original Equipment Manufacturer
OIG	Office of the Inspector General
OIS	Onboard Information System
OIT	Onboard Information Terminal
OMB	Operations Manual Bulletin
PARC	Performance-based operations Aviation Rulemaking Committee
PDF	Portable Document Format
PF	Pilot Flying
PFD	Primary Flight Display
PH	Pilot Handbook
PIC	Pilot in Command
PLI	Pitch Limit Indicator
PM	Pilot Monitoring
PTU	Power Transfer Unit
PTSD	Post-Traumatic Stress Disorder
QF	Qantas
QRC	Quick Reference Checklist
QRH	Quick Reference Handbook
RA	Resolution Advisory
RAAF	Royal Australian Air Force
RH	Right-hand
SAFO	Safety Alerts for Operators
SIC	Second-in-Command
SO	Second Officer
SPD	Speed
STS	Speed Trim System
TCAS	Traffic Alert and Collision Avoidance System
TE	Terminal East
TEB	Teterboro Airport

Acronym	Definition
TEM	Threat and Error Management
TOGA	Takeoff/Go-Around
UERF	Uncontained Engine Rotor Failure
US	United States
UTC	Universal Time Coordinated
VHF	Very High Frequency

Preface

This document was prepared for the FAA NextGen Human Factors Division (ANG-C1), the Aviation Safety (AVS) organization, and the Flight Standards Service Air Transportation Division, Training and Simulation Group (AFS-280). This research is funded by ANG-C1 under intra-agency agreement (IAA) FM07C122, "Analysis of Flight Crew Response to Aircraft System Failures, Malfunctions, and Systems Not Functioning as Expected" under tasks VN582, VN697, WN582, WP931, WP926, and AAP931. This document satisfies the IAA deliverable "Final Technical Report (Version 1) in 508-Compliant PDF, updated based on FAA feedback."

The Volpe Center thanks the FAA program manager, Dr. Chuck Perala, and the technical sponsors, Dr. Kathy Abbott (AVS) and Joshua Jackson (AFS-280). We thank Randy Mumaw (San Jose State University) and Beth Lyall-Wilson (MITRE) for their informal feedback on our efforts. Janeen Kochan contributed to the early stages of this research. Kim Cardosi, Tracy Lennertz, and Sara Yahoodik also helped us to identify related literature.

Executive Summary

The primary goal of this research was to analyze operational data to study flightcrew response to system failures, malfunctions, and systems not functioning as expected. Data from normal flight operations show that pilots are exposed to such situations regularly.

We reviewed 20 records from the Aviation Safety Reporting System (ASRS) public database and five public accident reports (Qantas 72, US Airways 1549, Qantas 32, Lion Air 610, and Ethiopian Airlines 302). These accidents were selected by the Federal Aviation Administration (FAA) technical sponsors of this study as pertinent examples. We used a descriptive approach for analyzing these sources of operational data, viewing pilot response as a sequence of actions and decisions, in line with early research done for the Air Force Office of Scientific Research. In addition to the data analysis, this report has a review of associated literature covering research on aircraft system problems, alerts and checklists, pilot training, and pilot response. The literature review illustrates the broad scope, variety, and depth of research connected to pilot response.

With just our small sample of ASRS records, we confirmed some previous findings reported in the literature. This sample helped us to understand the difficulties that pilots face in operations, including problem recognition, diagnosis, and management. For example, we found several cases where checklists and standard operating procedures were applied and effective. One new observation is that it is challenging for pilots to decide when to stop troubleshooting the malfunction and begin planning to divert. Data from the ASRS records did not allow us to draw inferences about pilot training, the effectiveness of alert format and priority, or about how different alerts were related to each other.

The review of accident reports was iterative and labor intensive. The reports are long and detailed, but they varied in their completeness and readability. Even accident reports, rich sources of accident data, have their limitations. Each accident was unique, and each report was unique as well. Some of the malfunctions in the events were complex; they varied in how difficult they were to diagnose. Some of the accidents had many alerts and malfunctions; if the counts were not reported in the report, they are difficult to calculate retroactively. Because of the qualitative method we employed, analyzing crew response as a sequence of actions and decisions, we did not quantify the pilot response. Also, our insights and observations were extrapolated from the data in the accident reports; they go beyond what is directly stated and are therefore somewhat speculative.

Data from the accident reports are presented at three levels of detail. First, a short summary of basic facts introduces the reader to the malfunctions and pilot responses that occurred. Second, a bulleted summary focuses on the flightcrew perspective, what they experienced, and how they responded to the malfunction and overall situation. Finally, detailed quotes from the accident reports that support the summaries are provided; these quotes provide the most detailed insights about the situation.

Two general observations were clear from our analysis of the accident reports. First, pilot experience impacts effective management of the situation. Pilot experience may be hard to quantify or judge objectively, but in these reports, the judgments and decisions made by experienced crews were well reasoned, well timed, and effective. The second observation is that time pressure, and related higher levels of workload, are factors in crew response. More time pressure and workload prior to the malfunction may impact pilot response negatively. Additional observations were related to (1) flightcrew decisions about whether to operate the aircraft manually, (2) the potential impact of the flightcrews' English language skills on their interpretation of the situation, (3) the captain's technique in crosschecking right and left side flight deck displays, which was sometimes helpful, and (4) the roles and tasks that the different flightcrew members assumed during the event.

1. Introduction

This research for the Federal Aviation Administration (FAA) examines air carrier flightcrew response to system failures, malfunctions, and systems not functioning as expected. The goal is to provide scientific and technical information, related to this subject, that the FAA could use to improve and integrate existing human factors guidance on air carrier pilot training and qualification for transport category aircraft systems and avionics equipment. Such guidance may include FAA recommendations to industry standards organizations, such as SAE International and updates to Advisory Circulars (ACs).

We focus on analyzing operational data related to flightcrew response to system malfunctions, partial system failures, and systems not performing as expected. These systems could include, for example, aircraft components such as engine, electrical, hydraulic systems, and flight control systems, including the autopilot. Automated systems are integrated with these aircraft components, so they are within the scope of this research insofar as they touch upon the systems necessary for controlled flight.

Operational data from accidents and incidents demonstrate that pilots experience challenges when responding to system malfunctions, partial failures, and systems not performing as expected. Moreover, these challenges occur regularly; malfunctions were identified as a threat to flight path management in 20% of normal flight operations[1] (Performance-based operations Aviation Rulemaking Committee [PARC]/Commercial Aviation Safety Team [CAST] Flight Deck Automation Working Group [FltDAWG], 2013; Lyall-Wilson et al., 2017). The PARC/CAST FltDAWG report also notes that malfunctions were identified as a threat in over 50% of the major incidents the working group reviewed and were a factor in 15% of the accident cases studied (p. 34).[2]

The PARC/CAST FltDAWG report (2013) focused on the task of flight path management, but the current project focus is different. This project addresses a variety of problems that pilots may encounter related to aircraft systems that malfunction or fail to operate as expected. The PARC/CAST FltDAWG report considers the effect of system malfunctions on flight path management. That report motivates the current project in that it points out the need for developing guidance for pilots on strategies and procedures for managing malfunctions—in particular, for situations that currently have no specific flight deck procedure or for which the current procedures or checklists do not completely apply.[3] The intent of this recommendation is to support pilots when existing procedures for handling a malfunction do not properly address the situation or are inadequate. As noted later in the PARC/CAST FltDAWG report[4], the highly integrated nature of newer avionics systems makes it more difficult for manufacturers to test for all potential failures or combinations of failures to subsequently identify all the detailed procedures pilots might need.

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[1] This rate is based on data from Line Operations Safety Audit (LOSA) flights.

[2] The PARC/CAST FltDAWG study reviewed 734 ASRS reports (submitted from 2001 to 2007) and 26 world-wide accidents (for which final reports were available by 2009), as well as data from Aviation Safety Action Program (ASAP) reports, LOSA flights, and interviews with operators, manufacturers, and a training organization. The study was later updated with data from more recent accidents and incidents (from 2006 to 2016) and updated LOSA data (Lyall-Wilson et al., 2017).

[3] See PARC/CAST FltDAWG report (2013). Finding 3 is discussed in Section 3.2.3, Managing Malfunctions (p. 34). Recommendation 7 (p. 7) is related to Finding 3.

[4] Recommendation 5, p. 111.

For our analysis of operational data, we reviewed reports from the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) database and five accidents that were selected by the FAA as pertinent examples of flightcrew response to system malfunctions, partial system failures, and systems not performing as expected. In addition to analyzing operational data, we originally planned to discuss these issues with industry operators and an original equipment manufacturer (OEM). Our plan for the industry discussions is documented in Appendix A. However, we were unable to hold these meetings and no industry data were gathered. Instead, we completed a more ambitious review of research literature and related documents to supplement our analysis of the operational safety data.

Section 2 presents an overview of related research, including past analyses of accidents and incidents related to flightcrew response to malfunctions. Section 3 presents our analysis of operational data. Section 3.1 describes our review of ASRS reports and Section 3.2 describes our analysis of accident data. Further information about the accidents is in Appendix B. The report conclusions are in Section 4 and Section 6 has a list of references.

2. Background

This section begins with a guide to the research space associated with pilot response to malfunctions (Section 2.1). Next, Section 2.2 presents findings from research studies where pilot response to malfunctions was either analyzed or collected for real or simulated flight operations. Section 2.3 briefly discusses FAA guidance related to response time.

2.1 Overview of the Research Space

We identified many studies related to the topic of pilot response to aircraft system problems such as malfunctions, partial failures, and systems not performing as expected. Figure 1 is a representation of the research space. It shows the **aircraft system problem(s)** at the top, to indicate that this is the catalyst for the situation. The problem may generate one or more **alerts**, as shown by the downward arrow on the right side of the figure. The problem may also affect the **pilot response**, as indicated by the downward arrow on the left side of the figure. **Pilot training** is in the center of the diagram because it is connected to the malfunction(s), alerts, and pilot response. Aircraft system problems are addressed in Section 2.1.1, alerts are covered in Section 0, and pilot training is covered in Section 2.1.2.2. Research on pilot response is addressed in more depth, in Section 2.2.

2.1.1 Aircraft System Problem(s)

Within each box in Figure 1 are examples of the research issues studied for that topic. For example, Hopf-Weichel, et al. (1979) documents six research tasks leading to recommendations for training of military pilots on making emergency decisions related to malfunctions; one of the tasks examined the *nature of malfunctions*. They had pilots use a card-sorting task to rank the safety and time criticality associated with various system failures in different phases flight. For example, a total engine failure is almost always ranked high on safety and time criticality, but there is more time to react when flying high and fast than during other flight phases (p. 6-16). Mumaw, Feary, Fucke et al. (2018) point out that studies about malfunctions often focus on specific system components (e.g., propulsion or autopilot). This was true of the malfunctions studied by Hopf-Weichel et al., which were related to engine malfunctions, stall, electrical failures, fuel malfunctions, and instrument failures, etc. Malfunctions can be the result of a single system failure, or multiple failures, which may or may not be related. One failure might increase the probability of other failures and alerts.

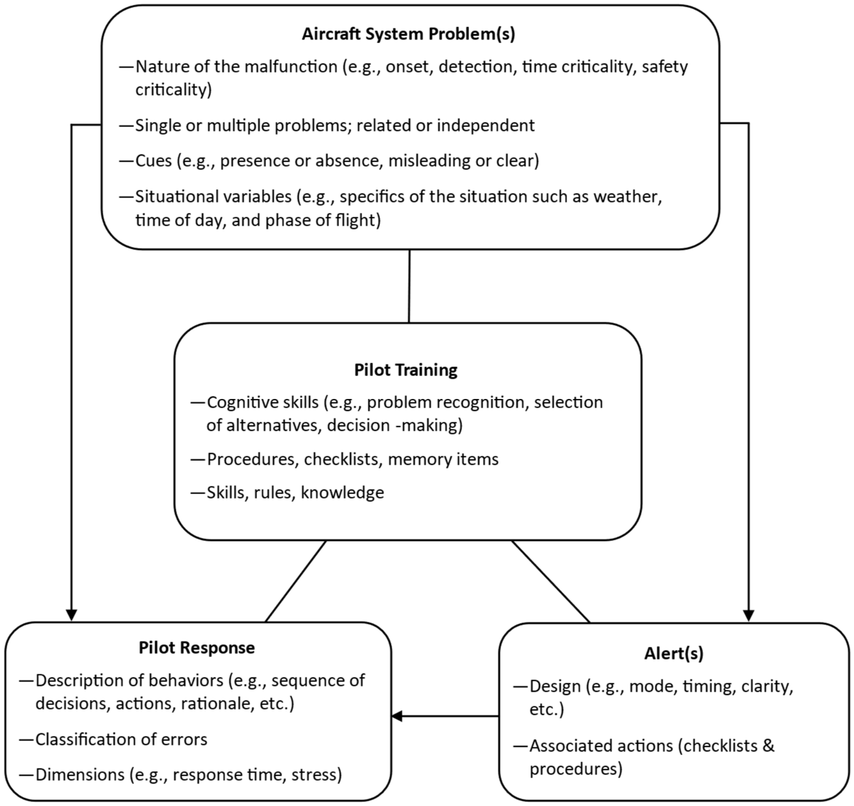

Figure 1. Research areas connected to pilot response to aircraft system malfunctions.

Various studies (e.g., Hopf-Weichel et al.,1979; Lucaccini et al., 1980; Berman et al., 2017) examine cues for malfunctions. Cues may be visual, aural, tactile/kinesthetic, or olfactory (e.g., engine vibration, engine surge, or explosion noise). Situational variables (e.g., weather, time of day, and phase of flight) are also important to how a pilot should handle a malfunction.

Lyall-Wilson and McKnight (2019) documents an extended analysis of the data from Lyall-Wilson et al. (2017) to understand the relationships between factors that co-occurred in accidents. Lyall-Wilson and McKnight document a strong association between "failure assessment was difficult" and "threats related to aircraft malfunctions." They also identified a significant association between "threats related to aircraft malfunctions" and "failure modes were unanticipated by designers."

Regarding sensor-related malfunctions, the PARC/CAST FltDAWG (2013) report says:

> …flight deck systems are often dependent upon input from various sensors including pitot/static, angle of attack, and others. Failure of these sensors or incorrect outputs can cause unexpected and unpredictable cascading indications in the flight deck which may lead to incorrect response by the pilot. (PARC/CAST FltDAWG, 2013, p. 34).

The angle of attack (AOA) sensor failed on two of the five accidents we analyzed.

2.1.2 Alerts

This section is divided into two parts. First, Section 2.1.2.1 discusses the design of alerting systems briefly. Then, Section 2.1.2.2 presents more detail about memory items and checklists associated with alerts.

2.1.2.1 Alert Design

There are many research studies on the *nature and design of alerts* and related checklists/procedures (e.g., Berman et al., 2017; Boorman, 2001; Boucek et al., 1981; Burian, 2004; Hanson et al., 1982; Mumaw, 2017; Mumaw, Feary, and Fucke, 2018; Mumaw, Feary, Fucke et al., 2018; Mumaw et al., 2019; Singer & Dekker, 2000). For a review of early alert-design literature, see Boucek et al. (1981). Feldman et al. (2017) is an annotated bibliography of literature on the design of flight deck procedures, including procedures for handling emergencies. FAA AC 25-1322-1, titled Flightcrew Alerting, describes guidance on alerting system design.[5]

These alert and checklist studies focus on the perspective of system design. They evaluate how the design of the alerting system or design of a checklist could have been improved to produce a more effective response by the pilot. Mumaw (2017) writes that the purpose of an alert is to elicit an appropriate operator response to a hazard. Specifically, alerts help the operator to *orient* to a change, *understand* the nature of the change, then *identify, prioritize, and execute* appropriate actions. Singer and Dekker (2000) consider how pilots handle dynamic fault management. All of the systems they tested presented failures in a list of messages, but different warning systems could provide different contributions to ease the cognitive demands of handling dynamic faults. Flight deck displays such as the primary flight display (PFD) and alerting systems such as the engine indicating and crew alerting system (EICAS) on Boeing aircraft, and the electronic centralized aircraft monitor (ECAM) on Airbus aircraft can help pilots sort, prioritize, and guide pilots on what actions to execute, or show which systems are still operational, or a combination of these functions.

Data from Mumaw et al. (2019), however, shows that newer aircraft do not always have alerting systems that are more effective than older aircraft. Figure 2a of this report (p. 18) shows failure to orient as it relates to year of manufacture marked by hazard and Figure 2b (p. 19) shows failure to orient related to year of manufacture by airplane model.

2.1.2.2 Memory Items and Checklists Associated with Alerts

One topic of interest related to alerts and checklists is memory items. Holder & McKenzie (2004) first identified the issue of poor performance on memory items that pilots were required to recall prior to accessing a non-normal checklist. Au (2005) studied pilot recall of memory items in response to different malfunctions. His participants included 16 Boeing 737 pilots from major airlines who were told that the purpose of the study was to design new alerting systems (so that they did not review memory items in preparation for the study). He observed that pilots had trouble identifying the cause of the failure and selecting the correct procedure when they were not expecting to be tested on memory items. Pilots committed errors in recalling memory items even though the task was only done in a low-stress

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[5] Like all AC material, this AC is not, in itself, mandatory, and does not constitute a regulation. It describes an acceptable means, but not the only means, for showing compliance with the requirements for transport category airplanes.

environment; the pilots were sitting in front of a poster of the flight deck, not in a simulator. Finally, Burian (2014) counted memory items on the checklists of 11 operators. Table 6 of this Burian report (p. 29) shows that the total number of memory items across checklists ranged from 1 to 87. Several operators had 20 to 30 memory items across checklists. For example, for the Boeing 737NG, one carrier had 10 memory items for the runaway stabilizer checklist alone.

There are two key points from the literature about memory items; the first is related to learning the memory items and the other about the maximum number of memory items. First, Hopf-Weichel et al. (1979) describes military training on memory items, which is called “BOLDFACE” training. BOLDFACE training emphasizes responses that are necessary when discrete and specifiable malfunctions occur, i.e., when the malfunction and its cues can be predicted and accurately described. It consists of memory items must be actively rehearsed and tested. For military pilots, all memory items were *reviewed* at least three times each month and they were *tested* on all memory items at least once per month. Pilots who did not accurately recall memory items on tests could have their flight privileges suspended. Maltby (2013) also makes the point that memory items need to be retained in long-term memory, which requires repeated effort. Au (2005), however, reports that air carrier line pilots do not study memory items except in preparation for a proficiency check, which is usually every 6 or 12 months.

The second important point for memory items is that, for airline operations, the number of memory items should be minimized. The United Kingdom (UK) Civil Aviation Authority (UK CAA, 2006) advises that there should be a maximum of six memory items, preferably four or fewer. Similar guidance is mentioned in FAA AC 120-71B (2017), which advises that memory items should be avoided whenever possible. If they are necessary, they should be clearly identified, limited to three items, and should not contain conditional steps.[6]

Between the 1979 Hopf-Weichel et al. study and the 2017 FAA AC 120-71B, many changes affecting the design of checklists and memory items were implemented in the flight deck. For example, typical airline operations changed from three flightcrew members (captain, first officer, and flight engineer) to two, eliminating the position of the flight engineer (Aerospace Industries Association [AIA] and European Association of Aerospace Industries [AECMA], 1998). The flight engineer responsibilities included monitoring engine parameters; this function was essentially assumed by flight deck systems (e.g., the full authority digital engine control [FADEC] on different aircraft, the EICAS on Boeing aircraft, or the ECAM on Airbus aircraft).

Electronic checklists (ECL) systems were implemented in the early 2000s, presenting checklists on flight deck displays with real-time feedback about what items have been completed to mitigate potential pilot errors. Boorman (2000) and Boorman (2001) describe the benefits of ECLs on Boeing aircraft. Airbus also integrates electronic checklists within their ECAM systems. This system can also present checklist memory items on flight deck displays. Myers (2016) has a good discussion of older literature on checklist design and is a nice complement to the Feldman et al. (2017) annotated bibliography; it focuses on ECLs. FAA guidance for the operational use of electronic checklists and modification of their data by air carriers is given in AC 120-64 (1996); this AC does not give design guidance for ECL systems.

Another development since the Hopf-Weichel et al. (1979) study was the introduction of the Quick Reference Checklist (QRC) (Hamman, 1997). The Hamman study compared pilot performance with a QRC versus use of memory items during simulated Line Operational Evaluations. Crews using the QRC achieved higher performance ratings for the evaluation, and crew ratings favored the QRC over the memory checklist. The QRC reduced crew errors (i.e., errors of omission, commission, and order). Crews

[6] FAA AC 120-71B was issued after the Burian (2014) study and other related (unpublished) studies.

took longer to complete the emergency checklists with the QRC, but with the improved accuracy of performance they received overall higher evaluation ratings from instructors. Holder & McKenzie (2004) present data (from surveys, structured interviews, and direct observations in flight simulators) that were used to update Boeing QRHs. Use of the Quick Reference Handbook (QRH), a compilation of QRCs, is now the norm for airline operations.

2.1.3 Pilot Training

The central box in Figure 1 encompasses pilot training, a very broad subject that we will mention only briefly. Several FAA guidance documents for pilot training are provided as references (in both Sections 6.1 and 6.2). One important reference is AC 120-51E (FAA, 2004) on crew resource management (CRM) training. CRM is foundational to many aspects of flying, especially as a crew. CRM can also help pilots to handle emergencies and stressful situations more effectively. Other relevant FAA guidance can be found in AC 121-42 (2020) on leadership and command training for pilots in command, which has a short section on decision making and critical thinking. FAA AC 60-22 (1991) is an older document about aeronautical decision making in general. It focuses on general aviation and does not address emergency situations that might occur in complex aircraft, though it does mention some basic stress management techniques.

The Advanced Qualification Program (AQP) program is used by most major air carriers in the United States. It was established in 1991 by the FAA through AC 120-54.[7] A good overview by Pettitt and Dunlap and related research papers can be found on the FAA AQP website. The AQP program uses simulator-based training scenarios, similar to the Situational Emergency Training (SET) military training program described by Hopf-Weichel et al. (1979). SET and AQP both use mission scenarios to present aircraft emergencies to pilots. Scenarios for both programs are often based on problems that have occurred in real operations. It is difficult to generate a large library of training scenarios. Hopf-Weichel et al. conclude that SET and BOLDFACE (memory item training) are complementary; both are useful, and they serve different purposes.

In addition to the recommendations for handling malfunctions, the PARC/CAST FltDAWG report (2013) points out issues related to managing automated systems for the purpose of flight path management and related policies. Section 3.2.4 discusses pilot reliance on automated systems, and in particular, the potential for degradation of manual flying skills and over-reliance on the automation. Over-reliance on automation could adversely affect a situation in that pilots may not be prepared to handle malfunctions or non-routine situations. The FAA recently released AC 120-123 (2022) on flight path management; this AC contains guidance on manual flight operations in addition to other topics.

Section 3.3.2 of the PARC/CAST FltDAWG report (2013) makes a distinction between design philosophy, which is established by the manufacturer of a system, and operational policy, which is established by the airline/operator to describe when and how a pilot should use systems. Guidance from manufacturers may thus differ from the guidance given by operators.

2.2 Operational Research on Pilot Response to Malfunctions

In this section, we take a closer look at previous studies of pilot response (see the lower left corner of Figure 1). The studies we examined all took an operational perspective, examining either real accident/incident data or gathering data (e.g., from simulated flight operations or interviews with airline

[7] This was updated in 2017 to AC 120-54A.

pilots about flight operations). Because of the detailed nature of the data and the (often) complex situations, researchers need significant expertise in flight operations to understand and/or classify pilot behavior from operational data. At least one of the researchers typically has flight experience in similar situations as those studied.[8]

Most of these studies assume some model of human performance or cognitive information processing underlies the pilot's behavior.[9] Differences between the studies' assumptions and methods are explored below in Section 2.2.1. Next, we consider studies where existing operational data were analyzed (Section 2.2.2). Section 2.2.3 considers studies evaluating pilot response to malfunctions where data were collected. Section 2.2.4 briefly considers limitations of these studies.

2.2.1 Assumptions and Methods

In broad terms, the studies of pilot response to malfunctions can take one of two approaches. In the first, researchers attempt to classify single pilot actions relative to a normative model that specifies a "correct" response.[10] In other words, there is a correct action that pilots need to be aware of, select, and execute. The researchers classify the pilot action as correct or incorrect (or "inappropriate" instead of "incorrect").[11] They make judgments about how to determine error classifications as needed; pilot response is essentially "graded." After categorizing pilot response, researchers tabulate the data. These studies often use large datasets, analyzing the data at a high level. Examples of these types of studies include Roelen and Wever (2005) and the AIA and AECMA (1998) study.

There are at least two limitations to the normative models that are applied to operational data with pilot response to malfunctions. First, normative models (e.g., Reason, 1990 or Rasmussen, 1982, which are both cited by AIA and AECMA, 1998) only apply to individual human performance, not to team performance. In air carrier operations, the flightcrew should be acting as a team, supplementing each other's knowledge and roles, at least ideally. This points to the value of CRM training, once again, as a key skill for air carrier pilots. The second limitation of normative human error models is that they do not consider situational variables such as stress, misleading cues, or incongruous/incomplete data. They assume the pilot is a rational actor who is not affected by uncertainty and confusion.

An alternative approach to studying pilot response to malfunctions is when researchers see the event as a sequence of actions and decisions. Hopf-Weichel et al. (1979) and a follow-on study by Lucaccini et al. (1980) are examples of this type. These studies view pilot actions through the lens of a decision-making process, as described in this quote:

> It is a truism among experienced flying personnel that there is usually more than enough time to deal with most emergencies and, further, that it is not the first mistake, or even the second, that

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[8] For this study, two of the three researchers had experience as private pilots, but they did not have experience flying airline operations.

[9] The PARC/CAST FltDAWG report (2013) used the threat and error management model to classify errors instead of a cognitive model.

[10] See Baron (2012) for an explanation of a normative model for judgement and decision making.

[11] The AIA and AECMA report from 1998 explains that "Inappropriate response includes incorrect response, lack of response, or unexpected or unanticipated response" (p. 10). Inappropriate response to an engine malfunction could be the result of an incorrect diagnosis or an incorrect action after a correct diagnosis (p. 14 of AIA and AECMA, 1998). Roelen and Wever (2005), however, use the term "inappropriate" response, which they define as a pilot response that does not comply with the aircraft manufacturer's recommended "correct" procedure.

> kills pilots, but the third. An aircraft emergency might be viewed, then, as a sequence of events and decisions, which, if not recognized and resolved at an earlier stage, culminate in a crisis. (Hopf-Weichel, et al., 1979, p. 1-3).

In these studies, pilots perceive information about the environment, use long-term and short-term memory to comprehend and analyze the data and choose a course of action, then they execute this action. These studies consider each of the different decisions and whether the pilot made the optimal choice at each point. They observe and describe pilot actions, rationale, and decisions in detail. They tend to use smaller, detailed datasets, sometimes just as case studies. They may be more theoretical, expanding a taxonomy, or developing models of human performance. They may use pilot interviews, simulator studies, or other data-collection methods to understand how pilots might handle such a situation in flight operations, rather than analyzing existing evidence from an accident or incident. In addition to Hopf-Weichel et al. (1979) and Lucaccini et al. (1980), studies by Au (2005), Beringer and Harris (1997), Burian (2004), Burian and Barshi (2003), and Sevillian et al. (2016) are examples of this approach.

A challenge with descriptive studies is that they rely upon a lot of data about pilots' actions and decision processes and internal deliberations that may or may not be visible through observed behavior. Another is that because these studies tend to describe pilot behavior in detail for specific situations, it can be difficult to compare results across cases.

The PARC/CAST FltDAWG study (2013) used a threat and error management model instead of a cognitive model of human performance. It did not directly address pilot response to aircraft system problem(s), but it does have some related findings. The study identifies different types of pilot errors that result from insufficient knowledge and skills for flight path management (Finding 11, p. 64), such as procedural errors, communications errors, manual-handling errors, and programming errors, which is a different way of classifying errors than being correct or incorrect. Finding 27 touches upon underlying factors in accidents and incidents (p. 103). This finding recognizes the importance of latent factors and recommends more specific descriptions of pilot error. Knowing the category of pilot error was not enough information to make recommendations for actions to take to address the concern. Studies that describe pilot response may be able to provide more information about latent factors than studies that classify pilot actions as correct or incorrect.

2.2.2 Data Analyses

First, we review studies where pilot responses in existing operational data were classified (Section 2.2.2.1). Next, we consider studies where existing operational data were analyzed to describe pilot response as a sequence of actions and decisions (Section 2.2.2.2).

2.2.2.1 Classifying Pilot Response

AIA and AECMA (1998) and Roelen and Wever (2005) classified pilot response to malfunctions. The AIA and AECMA study on propulsion malfunctions has a detailed explanation of how they classified pilot error and the cognitive models underlying their normative responses (see Appendix 14 – Human Factors). They begin by noting that, although the reliability of aircraft propulsion systems improved significantly over the past 20 years, the rate of occurrence per airplane departure for propulsion system malfunction with inappropriate crew response accidents has remained essentially constant; this suggests that the rate of inappropriate crew response to these situations has increased over time. Part of the explanation may relate to the fact that pilots at the time were no longer starting out as flight engineers, who became experts at handling engine issues. In other words, the experience of the pilot population was changing over time, affecting how they handled malfunctions.

Roelen and Wever (2005) examined 476 world-wide accidents that occurred from 1990 to 2000. The study focused on six types of failures: avionics/instruments, electrical systems, engine, flight controls, landing gear, and hydraulic systems. The aircraft in the study were built between the 1950s through the 1990’s (with fly-by-wire control systems). Roelen and Wever compare the pilot’s actions to those specified in the aircraft manufacturer manuals. They found that inappropriate responses were more prevalent in the older aircraft (25%) versus the latest aircraft (4%). This appears to be a statistically significant result, although it is not reported as such. However, the rest of their results do not account for the variation in aircraft date of manufacture, so it is not known how date of airplane manufacture affects the rest of the data they present. Also, in cases where the operator’s manuals specified different actions than the manufacturer manuals, they consider the manufacturer’s guidance to be the correct response. So, if the pilots followed the operator’s guidance when it contradicted the manufacturer’s guidance, the pilot response was marked as “incorrect.” This interpretation potentially oversimplifies the situation from the pilot’s perspective.

2.2.2.2 Describing Pilot Response

We describe two studies that analyzed existing operational data to study pilot response as a sequence of actions. They did not gather new data. One was a case study based on an accident report (Burian, 2004) and the other was an analysis of ASRS reports (Burian & Barshi, 2003). Both studies focused on the use of checklists.

Burian (2004) studied the design of checklists for response to an in-flight fire. The study examined data from an accident investigated by the NTSB, but checklist design was not listed as a causal factor in the accident. The crew had 18 minutes to prepare for an emergency landing and evacuation. They correctly called for and completed the memory items for the first checklist. However, they then took other steps from memory without consulting other checklists, for emergency descent and evacuation. One issue related to the selection of a branch of the checklist (for “descent not required”) without consulting the captain; this issue is related to CRM. As a result, the aircraft was not readied for depressurization, which delayed evacuation.

Burian and Barshi (2003) screened 250 ASRS reports (filed from Jan 1999 to July 2000) to understand circumstances associated with flightcrew response to abnormal and emergency events; 107 reports were pertinent to the study. They found complications related to checklist design and usage and crew related factors during emergencies (e.g., distraction, poor coordination). They determined that current training practices only prepare pilots for a small number of emergency situations that occurred. Pilots resolved emergency situations for which they had been trained well, but they often found themselves ill equipped and ill trained for actual situations. Almost 25% of the reports (25 of 107) described situations that were handled well.

2.2.3 Data Collections

We review several studies that gathered new data to analyze pilot response as a sequence of actions. Two of these studies (Au, 2005; Hopf-Weichel et al., 1979) were also mentioned earlier in Section 2.1.2.2.

Au (2005) used a low-fidelity environment to assess pilot recall of memory items on checklist without advance preparation and study. Qualified airline pilots were seated in front of a poster of the flight deck.

The experimenter described a normal flight situation, then interjected cues to suggest a particular failure. Subjects were asked to react as they normally would in flight, performing any necessary procedures. Participants could use the QRH. Each session was 30 minutes long, covering five scenarios with non-alerted abnormal procedures and memory items: aborted engine start, engine limit/surge/stall, rapid depressurization, runaway stabilizer trim, and a dual-engine failure. None of the five failure conditions had distinct indicator lights; pilots had to analyze the cues to determine the appropriate procedure. Results showed that pilots had difficulty identifying the cause of the failure and selecting the correct procedure. Common errors were to insert steps, leave out steps, do steps in the wrong order, or do the wrong checklist.

In addition to the findings described in Section 2.1.1 (about the time and safety-criticality of the malfunction), Hopf-Weichel et al. (1979) interviewed military pilots about decisions necessary when handling emergency situations. They used a sorting task to examine the types of decisions necessary for different kinds of malfunctions. They distinguished between *problem structuring* tasks, *alternative selection* tasks, and a *complete decision task*, which combines both types of tasks.

Based on these and other results, Hopf-Weichel et al. (1979) developed a taxonomy of emergency situations incorporating situational and task specific elements as cognitive attributes of a decision task performed under emergency conditions, as detailed below:

> **Situation 1** covers events for which the behavior and outcomes are predictable, which generally includes only single malfunctions. Their cues are well-defined, recognizable, and have high diagnosticity and reliability. There is a simple relationship between the cues and malfunction. As a result, little decision making is required after the malfunction is diagnosed. The pilot's task is to recognize the situation and match a template of actions to the situation. The pattern must be trained so that correct responses are immediate.
>
> **Situation 2** covers situations that are partially predictable. These are situations that can be foreseen, but for which decisions cannot be rigidly programmed in advance because the decisions are complex. If there is just one malfunction, but its cues are ambiguous, it falls into this category. Compound or sequential malfunctions may also fall into this category because it is not possible to train for all possible combinations. Pilots must be able to evaluate applicable procedures at the time of the emergency, rather than rely on prescribed responses. These situations require more active memory recall than simple recognition and matching done with Situation 1 emergencies.
>
> **Situation 3** covers unpredictable situations. These malfunctions may have complex and ambiguous cues because the malfunction cannot be foreseen. If the cues are recognizable, they may be misleading. No template of actions is available. The pilot must be able to integrate their knowledge across systems. Effective responses will be similar to create problem solving, where old solutions may need to be applied to problems that have never been encountered before.

Lucaccini et al. (1980) used this taxonomy and other findings from Hopf-Weichel et al. (1979) to develop paper and pencil training scenarios to help military pilots learn decision-making skills for emergencies.

In addition to the taxonomy of emergency situations, Hopf-Weichel et al. (1979) make an important distinction between decisions that are "anticipatory" and decisions that are "on-going," meaning that they are part of a decision sequence (which is the more common situation). Anticipatory decisions are rule-based actions with well-defined criteria for recognition that trigger a BOLDFACE (memory) set of actions (e.g., a decision to eject from the aircraft or reject a takeoff). These actions are scripted and must be completed immediately. If the actions are pre-planned, they can be completed very quickly.[12] Other examples of scripted responses include actions to take upon receiving alerts from the Ground Proximity Warning System (GPWS) and Resolution Advisories (RAs) from the Traffic Alert and Collision Avoidance System (TCAS). Although GPWS and TCAS RAs are not alerts for malfunctions, they do require pilots to take specific actions immediately. Anticipatory decisions are well suited for error classification because there is a clear correct response.

Sevillian et al. (2016) addresses an entirely different problem related to pilot response to malfunctions through pilot interviews of pilots for whom English is a second language (ESL); these pilots are described as ESL crew. This study focuses on ESL pilots' ability to use flight deck crew alerting systems (in general) in flight operations. The researchers interviewed 30 ESL pilots for major airlines for 1.5 hours each. Challenges for these pilots include the use of English in written technical information, information misinterpretation, and communication on the flight deck. These challenges are related to comprehension of system status messages, spoken and written English on the flight deck, and decision-making processes. Challenges related to alert displays and the use of written technical documentation (e.g., the Flight Crew Operating Manual [FCOM] and QRH) in both normal and non-normal conditions were identified.

Findings from interviews were related to responding to system malfunctions and failures. Table 2 of Sevillian et al. (2016) (p. 97-98) lists five thrusts of the results, which are summarized below.

- Acronyms and abbreviations are hard to understand. System issues can be misjudged if acronyms and abbreviations are not understood. Crew coordination is also impacted.
- Sentence structure in flightcrew manuals is confusing; verbose language confuses ESL crews. This can result in longer wait times to respond to system malfunctions and failures due to misunderstandings. This often leads to increased workload.
- Manuals are translated into the native language to accommodate ESL crews. This can lead to confusion and misinterpretation of system descriptions and nomenclature, which can lead to longer time to complete tasks.
- Multiple languages used on the flight deck may cause crew members to become confused with respect to system malfunctions and failures. Misunderstandings with ESL crewmember accents can lead to docile attitudes related to communication with other ESL crew members when making decisions.
- Spoken and written communication by ESL pilots who are not technically proficient with systems and malfunctions are confused and create confusion when solving technical problems. Use of mnemonics by one ESL pilot and then communication with another about system malfunctions and failures cause confusion regarding disposition of system malfunctions/failures.

Beringer and Harris (1997) also gathered data related to pilot response to malfunctions, specifically, for autopilot malfunctions. This study was done in a fixed based simulator of a Piper Malibu aircraft with general aviation pilots who had a minimum of 300 flight hours. Although the test population was not airline pilots, the general pattern of results is still of interest. This is one of the only studies we identified that collected data on response time, both for detecting the failure and acting to manage the situation. The tests involved four different autopilot failures including a "command-over" (rate = 6 deg/sec) roll,

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[12] See Leach, 2004 for a similar discussion of response time in survival situations. When the situation is new and different options must be generated and chosen, human response will be slower and may be ineffective in emergency situations.

soft roll (rate = 1 deg/sec), soft pitch (0.2 deg/sec), and runaway pitch trim up. The command-over roll was easiest to detect; 18 of 29 pilots did an "immediate" disconnect (where there were no other significant actions between failure and disconnect) and nine pilots chose to manually override the autopilot. The soft roll was third in difficulty to diagnose, but easiest to correct. The soft pitch was most difficult to diagnose, but third easiest to correct (almost a tie with second easiest).

The condition with the runaway pitch trim was different because there was only one way to correct it, by pulling the pitch-trim circuit breaker. An interim solution was the autopilot disconnect/trim interrupt switch. Only three pilots chose the optimal response of depressing and holding the autopilot disconnect then pulling circuit breaker; 21 of 25 pilots responded immediately, two manually overrode, two changed the autopilot mode. Beringer and Harris (1997) report two response times of interest, first the time to detect the malfunction and initiate *some* action. Second, they report the time between the initial action and pulling the circuit breaker. The time for initial action averaged 10.46 seconds across 25 pilots, with all but one response greater than 3 seconds. The time to pull the pitch-trim circuit breaker averaged 35.4 seconds (range 4.91 to 109.69).

2.2.4 Limitations

A common theme of the studies that examined safety data from actual accidents and incidents is that the richness of data varies, and this affects the analysis. These limitations are mentioned in an extensive study to classify pilot errors in response to propulsion malfunctions (AIA and AECMA, 1998) and in a study by Hanson et al. (1982). Hanson et al. studied events from an early implementation of the NASA ASRS database, which had less data than the current system. The aircraft accidents they studied often also appeared to not have flight data recorders, or even flight deck voice recorders. The AIA and AECMA study mentions that inferences often had to be made to classify pilot errors.

Hopf-Weichel et al. (1979) and Lucaccini et al. (1980) were the only studies we found that focused on training pilots for response to malfunctions. However, since the focus was on military aircraft, which are often single-pilot operations, CRM issues were not discussed in either study.

2.3 Response Time in Flight Operations

FAA guidance on response time is likely distributed across multiple documents. However, much of the guidance may be written from an equipment-design perspective and this project is focused on pilot training and operational impacts. Here we focus on the guidance in FAA AC 25-7D (2018), which is a lengthy (481 pages) flight-test evaluation guide for certification of transport category airplanes (as opposed to for evaluating operating requirements). A search of key words related to pilot response time identified pilot response to the management of engine failures, either during takeoff or inflight. The response time guidance is conveyed in terms of seconds (i.e., how many seconds it should take pilots to identify the problem and then to execute the required actions). For example, for a rejected takeoff, three actions are required: brakes, throttles, and spoilers. Each of the actions should take just a few seconds (see Section 4.3.6 of AC 25-7D on accelerate-stop time delays, starting on p. 4-22).

Even the recognition of failure modes and malfunctions is expected to be detected and handled within a few seconds:

> A three-second delay added to the measured time increment between pilot recognition of an automatic pilot malfunction and pilot corrective action has been considered acceptable for climb, cruise, and descent phases of flight. A one-second delay is considered appropriate for flight phases where the crew is expected to be closely monitoring FGS [flight guidance system]

control inputs, such as during approach, and for FGS use during takeoff from shortly after liftoff through flap retraction. (Section 33.7.10.1.4, AC 25-7D, p. 33-21)

As noted above (Section 2.2.3), Hopf-Weichel et al. (1979) classify these types of decisions as "anticipatory" because, once specific criteria are met, there are defined actions to be taken by the pilot. Other examples of such situations include pilot response to an alert from the TCAS or to an alert from the GPWS, although these are not alerts for malfunctions.

Interestingly, while the immediate response to GWPS and TCAS warnings is specified, the full response may vary based upon pilot technique. For example, a Flight Safety Foundation (1986) study found that while pilots responded to the GWPS alert within approximately 5 seconds, their rotation rates and pitch attitudes were too shallow and slow for survival in many terrain encounters. This points to the value of examining the decision sequence and not just the initial response when developing a remedy. Beringer and Harris (1997), discussed in Section 2.2.3, also illuminate the value of studying the full pilot response, and not just initial actions in response to clear cues.

FAA (2011), an introduction to TCAS, describes pilot training on TCAS RAs. Once again, pilot response time is expected to be on the order of a few seconds, but in this case, the full pilot response is articulated more clearly:

> *Note: In modeling aircraft response to RAs, the expectation is the pilot will begin the initial 0.25 g acceleration maneuver within five seconds to an achieved rate of 1500 fpm [feet per minute]. Pilot response with 0.35 g acceleration to an achieved rate of 2500 fpm is expected within 2.5 seconds for subsequent RAs.* (FAA, 2011, p. 29)

3. Analysis of Operational Data

This section outlines our analysis methods and findings from our two sources of operational data, ASRS reports and accident reports. The purpose of this analysis is to understand the reported role of factors related to the following topics during events involving system malfunctions, partial system failures, and systems not performing as expected.

The FAA is particularly interested in the following topics:

- Flightcrew training, knowledge, experience, and proficiency
- Format, purpose, priority, and frequency of individual, multiple, and cascading flight deck alerts
- Flightcrew procedures, checklists, and memory items associated with response priority and presentation of individual, multiple, and cascading flight deck alerts
- Flightcrew management of time, workload, tasks, procedures, checklists, and memory items
- Predictability, reliability, and intended function of systems

This work is focused on airline operations, which are typically operated with two pilots working together. As such, crew coordination is an important aspect of pilot response.

We take the Hopf-Weichel et al. (1979) view of an emergency as a sequence of decisions, rather than trying to classify single responses as correct or incorrect. The sequence of responses may not be clearly correct or incorrect, but they should move the situation towards a safe resolution. Berman et al. (2017) has a similar definition of pilot response:

> The activity accomplished due to the presentation of an alert or cue as to the existence or potential existence of a situation or condition. Pilot responses may include such things as actions, decisions, consideration of situation/cues/alerts, prioritization of response activities, or search for additional information, among others. (Berman et al., 2017, p. ix)

We also consider all aspects of pilot response, including its timeline relative to alerts and cues, detection/awareness, diagnosis and assessment, decisions, actions, communications, workload, task and resource management, coordination and communication, and even the emotional response. Responses involve decisions and actions under uncertainty. Operational factors such as time pressure and stress also affect pilot response.

Each source of data is covered in its own section as follows. Section 3.1 covers ASRS Reports and Section 3.2 covers Accident Data.

3.1 ASRS Reports

The purpose of the ASRS analysis was to understand how pilots respond to malfunctions in actual operations. ASRS data can provide pilot perspectives on the types of system malfunctions they experienced, how well checklists worked, and the strategies pilots used to diagnose and recover from malfunctions.

The ASRS Program combines multiple *reports* of the same event (i.e., submissions by different witnesses) into a single record; each record is identified by an accession number (ACN). We reviewed and analyzed 20 *records* from the ASRS database. Each record thus corresponds to a single *event* and each event may have one or more *reports*.

3.1.1 Selection of Reports for Analysis

We started by searching the ASRS database for records that met the following criteria, where the bolded italic text is the title of an ASRS search field.[13]

- ***Date of incident*** was between April 2021 and July 2022
- Aircraft was operating under ***Federal Aviation Regulation (FAR) Parts*** 121 (regularly scheduled air carrier) or 135 (on-demand charter or air taxi services)[14]
- ***Reporter organization*** was Air Carrier (i.e., there was a report submitted by a pilot)
- ***Event type/anomaly*** was classified as having an Aircraft Equipment Problem

In combination with the above criteria, we searched the reporter *narratives* and event *synopsis* for terms related to alerting and checklists/procedures. We identified search terms based on past ASRS studies on related topics (Bliss, 2003; Burian & Barshi, 2003; Kochan, Breiter, & Jentsch, 2004; Mitman et al., 1994; Mosier et al., 2012; Rehmann, 1995) and iterated on the terms with test searches. The final search used the following terms and their derivatives:

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[13] Note that the ASRS Program uses "incident" and "event" interchangeably.

[14] This field refers to Title 14 CFR Part 121, "Operating Requirements: Domestic, Flag, and Supplemental Operations" and Part 135, "Operating Requirements: Commuter and on Demand Operations and Rules Governing Persons on Board Such Aircraft."

- Alerting terms: alarm, alert, warning, caution, advisory, annunciation, flag, message or msg, Electrical Centralized Aircraft Monitor or ECAM, Engine Indicating and Crew Alerting System or EICAS, Crew Alerting System or CAS
- Procedures/checklists terms: land as soon as possible, turn back, divert, emergency procedure, abnormal procedure, non-normal procedure, stall, sterile cockpit, Quick Reference Handbook or QRH, emergency checklist, abnormal checklist, non-normal checklist

The search returned 456 records. We eliminated 128 records because they had narratives that were not sufficiently detailed (200 words or fewer). We reviewed the remaining records (over 300) in a random order until we found 20 records that were suitable for further analysis. To be selected for analysis, the record must have had an event with a system malfunction that had (or could lead to) a direct impact on the flightcrew's ability to maintain control of the aircraft.

3.1.2 Limitations of ASRS Data

ASRS narratives are self-reported and subjective. Pilots write them from memory, which can be flawed, especially considering that the events may have been stressful. In hindsight, pilots may also recall the events and their decision-making processes differently than what actually happened. They might misinterpret situations based on their own experiences or biases, or they might leave out important details. Many of the records (i.e., events) have only a report from one single individual, so the situation cannot be corroborated. The frequency of events in the ASRS dataset does not necessarily represent the frequency of those events in general flight operations. We also do not know the timeline (i.e., what happened and when) from the narrative. The narrative may describe key points in the event (e.g., the activation of an alert), but not how long each step took (e.g., how long before the alert was resolved). The reports can also be difficult to interpret.

3.1.3 Analysis Method

We developed a rubric to summarize each of the 20 ASRS records. Table 1 shows an example of a fully coded record, with a list of the data we gathered, plus a field to note any potential questions or recommendations for industry for future consideration. Note that we generated our own summary of the event ("Volpe Event Summary") but also recorded the Synopsis generated by the ASRS Program ("ASRS Synopsis"). Information about the system malfunction, partial failure, or system not functioning as expected contained several sub-elements:

- **Equipment Component**. This field identifies the system, or system component, that had a problem.
- **Urgency/Criticality** of the malfunction, partial failure, or system not functioning as expected (e.g., how much attention pilots had to pay to it)
- **Time Course/Progression** of the malfunction over the course of the event
- **Onset/Detection** of the malfunction (e.g., how the malfunction developed and appeared to the flightcrew, and how it was detected)
- **Diagnosis** of the situation by the flightcrew (e.g., what steps the flightcrew took to understand the nature of the problem)
- **Resolution** of the malfunction by the flightcrew

Three researchers reviewed each record. One researcher coded the record using the rubric, and the others reviewed it for completeness and accuracy.

Table 1. Example of a fully coded ASRS report

	1780300 (January 2021)
Volpe Event Summary	Intermittent and cascading failures of multiple systems, starting with flight director (FD). No solution in QRH or from Maintenance and Dispatch, so crew returned to departure airport for overweight landing. (Part 121)
ASRS Synopsis	B737 flightcrew reported multiple systems indicating failures, resulting in the decision to execute a return to departure airport and a precautionary landing.
Potential Recommendation or Question for Industry	What are pilots trained to do when aircraft behavior/state does not match alerts? What are the procedures when the QRH does not address a problem?
Outcome	Precautionary (overweight) landing at departure airport.
Malfunction, Failure, or Unexpected System Behavior	**Equipment Component:** System monitor: indication and warning (malfunctioning)
	Urgency/Criticality: Started as intermittent malfunction of captain's (CA's) FD. Progressed to multiple alerts/failures: auto throttle and stab trim (stabilizer out-of-trim), fuel pump low pressure, and intermittent malfunction of both FDs.
	Time Course/Progression: Multiple, cascading failures/alerts. Started after takeoff with intermittent disappearance/reappearance of pitch and roll command bars on CA's FD. Issues with autopilot advancing one engine then auto throttle disconnecting, followed by left fuel pump light and flickering STAB TRIM light, then Master Flight Director Indicator (MA) lights alternating between both FDs.
	Onset/Detection: CA noticed intermittent FD malfunction. There were no associated alerts at first.
	Diagnosis: There were no changes in pitch or airspeed associated with the STAB TRIM light. Fuel pressure low light appeared even though there were 22,000 lbs. of fuel. Crew realized they had multiple failures not covered in QRH. "There was no clear solution to our situation."
	Resolution: None. Returned to departure airport for precautionary landing
Flightcrew Response	**Procedures, Checklists, Memory Items:** Consulted QRH. Malfunctions not covered in QRH.
	Communication: Requested level off from Air Traffic Control (ATC). Called Dispatch and Maintenance. Maintenance agreed there was no clear solution.
	Workload/Task Management: Requested to level off while they assessed the situation and consulted QRH. Later requested priority handling. Had to use chart to calculate landing distance because the computer would not calculate it for the overweight landing. CA decided to land heavy instead of burning off extra fuel, which would take 2.5 hours.
	Other: Before deciding to divert, the crew discussed the threats involved: automation issues, night landing in mountainous terrain, long duty day.
Flightcrew Training	N/A
Notes	N/A

3.1.4 Description of Dataset

Sixteen of the 20 ASRS records described events in aircraft operating under Title 14 CFR Part 121 and four described events in aircraft operating under Title 14 CFR Part 135. There were eight events in Boeing aircraft; four in Airbus aircraft; two each in Bombardier and Dassault aircraft; one each in Cessna, Embraer, and McDonnell Douglas aircraft; and one in an unspecified commercial fixed-wing aircraft.

The dataset contained five events with engine malfunctions; four with flight control system malfunctions; three with electrical system malfunctions; and two each with fuel system, hydraulic system, avionics/instrument, and sensor system malfunctions.

3.1.5 Example of Summarized ASRS Reports

Each subsection below summarizes one of nine (of the 20) ASRS records from our dataset, as examples. This subset of ASRS records illustrates the range of pilot responses that we observed. For each record, we provide an event **Summary** (a brief narrative of what occurred) followed by brief descriptions of five event and response characteristics that map to the coding rubric. The five characteristics are explained below:

Detection: Describes the onset of the malfunction (e.g., clear and sudden, gradual, intermittent) and whether it impacted the flightcrew's ability to detect the malfunction. The way that the malfunction began often affected the flightcrew's assessment of whether it was real or spurious.

Diagnosis: Describes any challenges the flightcrew experienced when attempting to diagnose the problem.

Alerts: Describes how alerts appeared to the flightcrew in terms of format (e.g., aural, visual, or tactile mode) and onset (e.g., whether multiple alerts appeared simultaneously, intermittently, or if they were staggered). The ASRS reports did not always describe the alerts in detail (e.g., if a visual alert was accompanied by an aural alert) and were not sufficient to determine if staggered alerts were related (e.g., if one alert caused the next). Note that data for this field does not include cues such as smells or vibrations that may have made flightcrews aware of the problem.

Checklists actions: Describes whether (and what) checklists were used to address the problem, and whether flightcrews had any issues using checklists.

Resolution/outcome: Describes whether and how the flightcrew resolved the problem.

3.1.5.1 ACN 1833765

Summary: Immediately after turning on the anti-ice system, the flightcrew detected a clear and sudden loss of multiple instruments and flight control panel functions, accompanied by multiple red flags on the primary flight display. Realizing they had lost a lot of functions, the flightcrew hand-flew the aircraft while consulting Maintenance and the QRH. They troubleshooted with the QRH "for some time" but could not find an explanation or solution to the multiple failures and decided to divert.

Detection: Clear and sudden onset/detection

Diagnosis: Difficult to diagnose via checklists

Alerts: Multiple (visual) flags, simultaneous onset

Checklist actions: Followed QRH. Checklist insufficient

Resolution/outcome: Unable to resolve in flight, diverted

3.1.5.2 ACN 1876387

Summary: The flightcrew detected high engine vibrations during climb and saw that engine temperature was slightly high but within the normal range. The flightcrew continued to climb while consulting the QRH and leveled off early to troubleshoot, at which time the engine vibrations increased and the flightcrew could not reduce it by altering thrust. The flightcrew shut down the engine as directed by the QRH and diverted. The flightcrew was aware before the flight that there was a similar issue on the previous flight.

Detection: Gradual onset, detected potential for problem early based on vibration cue

Diagnosis: No issues, quick assessment of malfunction due to awareness of problem on previous flight

Alerts: None

Checklist actions: Followed QRH. No issues

Resolution/outcome: Shut down engine and diverted

3.1.5.3 ACN 1857441

Summary: The flightcrew detected a fuel imbalance during a fuel quality check (directed by the cruise checklist) before receiving any alerts. Fuel flow and burns appeared equal, so the flightcrew thought it was an inaccurate fuel reading and started checking circuit breakers and inverters to verify it. Fuel levels dropped gradually and the Low-pressure Warning lights eventually appeared. The flightcrew followed the Abnormal Checklist for each warning, except that they did not open the cross-feeds to prevent fuel loss. The crew shut the engine down shortly after and the flightcrew immediately landed at their destination.

Detection: Gradual onset, detected before alerts

Diagnosis: Investigated possibly erroneous indications

Alerts: Warning lights, simultaneous onset

Checklist actions: Followed abnormal checklists. Made exception to checklist.

Resolution/outcome: Unable to resolve in flight, immediate landing at destination.

3.1.5.4 ACN 1780300

Summary: The captain experienced an intermittent FD malfunction but there were no associated flags. The flightcrew began to assess the situation with the First Officer's FD. The First Officer's auto throttle unexpectedly advanced. While attempting to stabilize thrust, the flightcrew received a Fuel Pressure Low light and a flickering STAB TRIM (stabilizer out of trim) light, despite having adequate fuel and no changes in pitch or airspeed associated with the STAB TRIM light. The Master Flight Director Indicator (MA) lights alternated between both FDs. The flightcrew leveled off to evaluate but found "no clear solution" in the QRH and returned to their departure airport.

Detection: Clear and sudden onset/detection

Diagnosis: Malfunction with no associated alerts (at first). Indications did not match alerts.

Alerts: Multiple lights, intermittent, staggered onset

Checklist actions: Followed QRH, checklist insufficient

Resolution/outcome: Unable to resolve in flight, returned to departure airport

3.1.5.5 ACN 1824392

Summary: The flightcrew received a Master Caution light and Hydraulic System light. They turned off the pump as directed by the QRH and noted conflicting indications with normal hydraulic pressure but zero fluid. The flightcrew anticipated a total system loss even though the system did not yet meet QRH criteria for a total loss. They continued to their destination but on descent, they noticed a loss of pressure and received Low Pressure lights and ran the QRH for system loss.

Detection: Clear and sudden onset/detection, but problem got worse

Diagnosis: Conflicting indications, but anticipated total system loss

Alerts: Multiple lights, simultaneous onset

Checklist actions: Followed QRH with no issues

Resolution/outcome: Unable to resolve in flight, landed at destination with loss of hydraulic system

3.1.5.6 ACN 1789251

Summary: The flightcrew noticed a rising oil temperature reading during climb. They found no guidance in the checklist. They adjusted engine power to troubleshoot and looked for indications to confirm the temperature reading but could not verify it. The flightcrew anticipated that the issue might develop into something more serious, such as an engine fire or failure, so they decided to shut down the engine and divert.

Detection: Gradual onset, flightcrew monitored the situation

Diagnosis: Investigated possibly erroneous indications

Alerts: None

Checklists: Followed unspecified checklist. Checklist insufficient

Resolution/outcome: Unable to resolve in flight, shut down engine and diverted

3.1.5.7 ACN 1867341

Event Summary: The flightcrew experienced an Elevator and Aileron Computer (ELAC) pitch trim fault before takeoff and returned to the gate. They consulted the Minimum Equipment List (MEL) checklist but disagreed on how to interpret it, and their decision ultimately led them to continue the flight. They were unaware that the aircraft was not safe for flight. The flight was normal until final approach, when the First Officer/Pilot Flying's control switch failed to disconnect the autopilot. The flightcrew immediately diagnosed the problem as being related to their MEL decision. With no time to troubleshoot, they switched roles and used the captain's (functioning) controls and landed at their destination.

Detection: Clear and sudden onset/detection of the autopilot issue

Diagnosis: Precipitated by previous issue related to interpretation of the MEL

Alerts: None during the flight (the ELAC pitch trim fault occurred on the ground before takeoff)

Checklists: Confusion over interpretation of MEL checklist

Resolution/Outcome: Used captain's controls as a quick workaround and landed at destination

3.1.5.8 ACN 1886900

Summary: During cruise, the flightcrew experienced an ELAC1 pitch trim fault and autopilot disconnect. There were no actions to perform in the ECAM and the flightcrew reengaged the autopilot. While analyzing the issue, the flightcrew experienced an ELAC2 fault and the autopilot disconnected again. Their "display" (not identified in the report narrative) directed them to use manual trim but their trim wheel was frozen so they hand-flew the aircraft. Hand-flying required frequent adjustments, so the flightcrew opted to divert. The pitch trim became usable again on descent. Prior to the flight, the flightcrew was aware that the previous flight experienced an ELAC1 fault that resolved on descent.

Detection: Clear and sudden onset/detection

Diagnosis: No issues, quick assessment of malfunction due to awareness of problem on previous flight

Alerts: Single, format unspecified

Checklist actions: Consulted ECAM. No ECAM actions associated with the first fault

Resolution/outcome: Unable to resolve in flight, hand-flew in alternate law and diverted

3.1.5.9 ACN 1882203

Summary: Just after reaching cruise altitude, the flightcrew heard a sound they described as associated with an electrical failure that was followed by the loss of multiple displays and the appearance of multiple lights and ECAM actions. The flightcrew began completing the ECAM actions in the order they were listed. They reset the generator according to the ECAM, which restored some systems but not others. Some faults went away on their own. The flightcrew consulted the QRH for items they recalled seeing in the ECAM, because some had gone away or fixed themselves. They also consulted the Flight Manual for reset procedures. The generator failed again, but it was not associated with the same losses as before. The flightcrew conducted a few more restarts but we could not determine whether they could clear every ECAM action. The flightcrew diverted to an airport that was 50 miles away, rather than the closest airport, to allow adequate time to prepare for landing. They did not request priority handling because they did not see anything in the QRH or ECAM that suggested urgency.

Detection: Clear and sudden onset/detection

Diagnosis: No issues, appeared able to diagnose with checklists

Alerts: Multiple lights and ECAM messages, simultaneous onset

Checklist actions: Consulted ECAM, QRH, and Flight Manual. Some ECAM messages went away on their own

Resolution/outcome: Unable to resolve in flight, diverted

3.1.6 Summary of Findings from ASRS Reports

This section describes our high-level observations of flightcrew responses to system malfunctions across the 20 ASRS records. These observations are organized by event and response characteristics, but some of these are connected or overlapping.

Detection. In most of the reports we reviewed, the system malfunction had a clear and sudden onset, usually indicated by an alert or apparent loss of instruments or functions. Sometimes flightcrews detected issues before any alerts appeared, either via their instruments or from audible or tactile cues. Other malfunctions developed gradually or appeared intermittently, and it took time for the flightcrews to determine whether they needed to be actively addressed or merely monitored.

Diagnosis. Flightcrews experienced challenges diagnosing the malfunction in about half of the events. Some flightcrews had difficulty verifying malfunctions because there were no associated alerts at first. Some received alerts but could not verify them. Some flightcrews questioned whether their instruments were erroneous and spent time troubleshooting but could not confirm whether the malfunction was real. Some flightcrews experienced conflicting indications which made it difficult to diagnose the problem.

In a few events, the flightcrews may have been quick to diagnose a particular issue based on their awareness of a similar malfunction on a previous flight.

Alerts. The records describe a mix of situations with single alerts/malfunctions and multiple alerts/malfunctions. Multiple alerts either appeared simultaneously or they appeared at different times throughout the course of the event. It was not possible to determine whether multiple alerts were related to or independent of each other. Alerts were formatted as lights, messages, and aural indications. The reports did not mention any tactile alerts specifically, but some alerts were accompanied by external sensory cues such as engine noise or vibrations. Since the ASRS narratives often did not describe the alerts in detail, we could not determine whether the format of alerts had an impact on flightcrew response.

In most events, the alert directed the flightcrew to the nature of the problem and the flightcrew consulted the appropriate checklist(s). Sometimes the flightcrew perceived the malfunction before the aircraft systems notified them, which gave them additional time to start diagnosing and troubleshooting. We do not know how many other events/malfunctions could have been detected earlier but were missed.

Checklist actions. Most of the time, flightcrews followed the procedures as prescribed in their checklists. There were a few events in which the flightcrews made exceptions to checklist procedures based on their judgment. There were also a few events in which the checklist information was insufficient for the scope of the problem. For example, there were two events containing multiple failures that the crew could not resolve with the QRH. There was one event in which the flightcrew disagreed on the interpretation of an MEL checklist and followed the wrong interpretation, which may have triggered the system malfunction.

Resolution and outcome. In nearly all the events, the flightcrew was unable to resolve the malfunction in flight. Most resorted to diverting or returning to their destination airport as a precaution. In two events, the malfunction resolved itself when entering a different phase of flight. In another event, the flightcrew's actions (based on the checklists) resolved some malfunctions but not others.

Impacts of training. Just three of the 20 records mentioned flightcrew training. In the first mention, a pilot credited "great training" for the flightcrew's ability to control the aircraft despite being startled and stressed by the event. In the second record, a pilot credited their recent training for the flightcrew's "simple and effective" response. In the third record, a pilot stated that the flightcrew completed the memory items and QRH procedures per company training.

3.1.7 Key Observations from ASRS Reports

This section summarizes our key observations from the ASRS analysis. These focus on what we learned (or could not learn) about pilot response to system malfunctions from the 20 ASRS records we analyzed.

1. Determining whether a malfunction has actually occurred can be challenging.

Pilots spent time and effort troubleshooting potential malfunctions when it was unclear if the malfunction was real, still present, or nearing a critical state requiring action. For example, some pilots had difficulty determining whether an indication signified a real malfunction or an indication error because they could not find data to verify it. In other examples, the malfunction/alerts appeared intermittently or went away on their own, which made it difficult to determine if the malfunction was still present or if it was real in the first place. Moreover, one malfunction might lead to another malfunction or multiple malfunctions may appear at once, making it even more difficult to isolate the problem. Finally, there were some events in which the malfunction developed gradually, i.e., showed indications of a potential malfunction at first, but took time to reach a critical state. In these cases, the flightcrew monitored the situation to determine whether a malfunction had occurred and needed to be addressed.

2. Diagnosing malfunctions can be difficult, especially when there are conflicting indications or intermittent malfunctions.

Pilots had difficulty identifying the nature of the malfunction in about half of the ASRS dataset. Some pilots experienced intermittent malfunctions. Not only was it difficult to determine whether intermittent malfunctions were real, but the erratic nature of the indications made it difficult to assess the situation and determine what might have caused it. In other examples, pilots experienced conflicting indications or malfunctions that had no associated alerts, and it was difficult to decide which data to trust.

3. Checklists and SOPs worked well in several reports.

The majority of the ASRS reports in the dataset described events in which the flightcrew identified and complied with the appropriate checklist and SOPs. In a few examples, pilots made exceptions to the checklist based on their judgment of the situation. The checklists were insufficient in just a few situations, as described next. Given our small sample size of 20 ASRS reports, this observation is not incompatible with results from Burian and Barshi (2003), who analyzed a larger sample of ASRS reports. They found that checklists worked well for 25% of the 107 ASRS reports in their dataset.

4. Checklists may be insufficient for diagnosing and resolving multiple malfunctions.

It can be difficult to find and prioritize the correct checklists when multiple malfunctions occur at the same time. Moreover, the situation may be complicated or novel in that there is no checklist that addresses it. In these cases, pilots cannot rely on checklists and SOPs to resolve the situation.

5. Deciding when to stop troubleshooting and begin planning to divert can be challenging.

Nearly all the reports in our dataset described an event in which the flightcrew diverted or returned to the departure airport. Often, pilots spent time troubleshooting the situation before making the decision to divert. As discussed earlier, it can take time and effort to determine whether a problem exists, why it exists, and whether/how to respond. It is not clear how long pilots should troubleshoot a malfunction before deciding to divert.

6. The dataset was not sufficient for the following goals:

a) We could not draw any conclusions about pilot training.

Only a few reports mentioned training, and those only mentioned when pilot training was helpful for the situation at a high level; they did not provide specific details about training (e.g., what about it was effective). This is likely to be a limitation of the ASRS narratives, rather than a limitation related to the small size of our dataset.

b) We could not draw any conclusions about the effectiveness of alert format and priority.

Most of the ASRS reports in our dataset did not provide sufficient detail on alert priority schemes or format (e.g., color, aural or visual or tactile, etc.). This is likely to be a limitation of the ASRS narratives, rather than a limitation related to the small size of our dataset.

c) We could not discern how alerts were related to one another.

We cannot determine whether alerts described in the event were "cascading" or independent of one another.

3.2 Accident Data

We reviewed five accidents, selected by the FAA, to understand pilot response to aircraft systems that have failed, malfunctioned, or not operated as expected during scheduled air carrier flight operations. The accidents we reviewed were Qantas (QF) 72, US Airways 1549, Qantas 32, Lion Air (LNI) 610, and Ethiopian Airlines (ETH) 302. The accidents are relevant to this project because they each had multiple alerts and involved the use of checklists and procedures. Each of these accidents is described briefly in Section 3.2.1 to introduce the reader to the types of failures and pilot responses that occurred in the dataset. Our method for reviewing the accident data is described in Section 3.2.2. Key observations from this analysis are presented in Section 3.2.3. Detailed data from reviews of the accident investigations are in Appendix B.

3.2.1 Basic Accident Facts

The summaries below provide the basic facts of the accidents, as an introduction to the types of malfunctions and pilot responses that occurred.

Qantas 72 (7 October 2008, Airbus A330). Two minutes after an unexpected automatic disconnect of the autopilot during cruise, the flightcrew experienced the first of two sudden descents. The descents were due to erroneous data spikes in AOA combined with a logic failure in the software for the flight control computer. The malfunction generated several spurious alerts and some real alerts, with frequent associated aural and visual indicators that were distracting. Some alerts had associated ECAM messages that scrolled with each new caution being placed at the top of the list. Some faults kept recurring. The crew could not effectively interact with the ECAM to action and/or clear the messages. The crew was highly experienced in general but had no specific training for this rare event. Although the captain could not diagnose the problem during the event, he successfully executed a work-around to the problem by using the first officer's and standby displays to manage the flight. The captain flew the aircraft manually and diverted to land as soon as operationally practicable, flying cautiously in case there were other upsets.

There were no fatalities and 12 serious injuries due to the vertical accelerations because many of the occupants were not wearing seat belts. The Australian Transport Safety Bureau (ATSB) declared this an accident due to the extent of injuries.

US Airways 1549 (15 January 2009, Airbus A320). The flightcrew experienced an unexpected loss of thrust in both engines triggered by impacts with multiple birds at low altitude (approximately 2800 ft above the ground). The problem was unique because of the low altitude, but the diagnosis of a dual-engine failure was clear. After considering different landing options, the captain decided that a water landing was the safest course of action. The crew experienced multiple aural alerts and visual indications as they prepared to ditch the aircraft. They were overloaded with visual cues (e.g., from alerts, instruments, and the visual scene out the window as they searched for a landing location). The flightcrew decided to follow the Dual Engine Failure checklist but did not have time to finish it because it was designed for a dual engine failure at higher altitudes and had many steps. There was no flightcrew training or checklist for a dual-engine failure at low altitude. The flightcrew had trained for ditching at low altitude, but with one working engine.

The aircraft was flying the runway heading after taking off from Runway 4 at LaGuardia airport until the bird strike occurred. From takeoff to "landing" in the Hudson River, the event took just under four minutes. The crew prepared the cabin for an expedited evacuation during the ditching.

There were no fatalities and 5 serious injuries.

Qantas 32 (4 November 2010, Airbus A380). The flightcrew experienced a sudden engine fire/failure in one of four engines, 6 minutes after takeoff during climb. The initial malfunction caused multiple other failures, affecting many different systems. The diagnosis of an engine failure and fuel leak were easily identified by the crew due to the noise of the malfunction and the clearly visible fuel leak reported by passengers and confirmed by the crew. The crew identified additional system failures with the help of the ECAM. The flightcrew received many ECAM warnings and cautions. Each warning was annunciated by an audio alert, a visual alert, a local light and/or the automatic display of the applicable system page. The flightcrew actioned ECAM messages for 50 minutes while holding near the airport. New ECAM messages appeared even as the flightcrew was handling previous ECAM messages. The flightcrew tried to understand and verify every ECAM message. Eventually they began to doubt the ECAM instructions.

The flight landed 1 hour and 50 minutes after the failure. Several alerts that had been inhibited by the ECAM when the aircraft was in flight appeared when the aircraft slowed down during landing. The crew was not able to shut down one of the three working engines after landing, so the evacuation was delayed by 50 minutes while the aircraft remained on the landing runway. There were no injuries to the crew or passengers.

Lion Air 610 (29 October 2018, Boeing B737 MAX). A defective AOA sensor initiated the event. The left stick shaker (a tactile stall warning) activated as the nose gear lifted off the runway. Within a few seconds, multiple warnings triggered for a variety of conditions. The warnings included both aural and visual indications. The Maneuvering Characteristics Augmentation System (MCAS) activated after the flaps were retracted, functioning as it was designed to work, but based on the incorrect AOA value.

The crew was unable to diagnose the AOA sensor malfunction with the information they had. The captain called for the Airspeed Unreliable checklist, but the first officer could not remember the memory items and had difficulty locating the checklist. The crew was consumed with attempting to complete the unreliable airspeed checklist while managing backpressure and trim inputs to counter the multiple MCAS activations. They were unable to manage the multiple alerts. They began, but did not complete, the checklist before the crash. The flightcrew had received training on recognizing non-normal events and applying non-normal checklists but did not manage the non-normal situation effectively. Both pilots had negative remarks on their training records. However, they had received no training about MCAS, specifically, and had no procedures in place to mitigate erroneous AOA data.

The flight lasted approximately 11 minutes. All on board were fatally injured.

Ethiopian Airlines 302 (10 March 2019, Boeing 737 MAX). Shortly after takeoff, the left AOA sensor failed, resulting in multiple erroneous indications on the left (captain's) side. The stick shaker on the left (captain's) side was the first warning to occur and it lasted throughout the short flight. The Master Caution and Anti-Ice warnings also activated initially. Several other warnings and confusing indications appeared at various points in time (e.g., GPWS alerts, overspeed clacker, Indicated Airspeed [IAS] Disagree, pitch flight director bars disappearing). The MCAS activated four times. The crew was unable to diagnose the AOA sensor malfunction with the information they had.

The flightcrew attempted to control the pitch by exerting backpressure on the control column, but the forces required were too great to manage. They attempted to engage the autopilot four times. There were several actions the crew should have taken, in accordance with their training, that they did not do. There are gaps in understanding the crew response, which was not fully examined by the investigation board.

The flight lasted about five minutes. All on board were fatally injured.

3.2.2 Method for Reviewing Accident Data

Here we describe the steps we took to analyze the five accidents mentioned above. The steps involved selecting topics of interest (Section 3.2.2.1), extracting the relevant quotes and data from the reports and other reference materials (Section 3.2.2.2), then documenting the data (Section 3.2.2.3). Finally, we describe some of the differences between the data available for the different accidents, and how we addressed the challenges posed by these variations (Section 3.2.2.4).

3.2.2.1 Selecting Topics of Interest

We started with the list of topics identified by the FAA described in Section 2.3. The initial list focused on flightcrew response to a system problem. It included elements such as flightcrew knowledge, proficiency, and training, alerts (format, purpose and priority), use of checklists and procedures, task and workload management, and system predictability and reliability.

The topics of interest were refined and clarified over the course of the project. Our final list is shown in Table 2. For example, the final list calls for a description of aircraft systems and alerts, general flight training separated from flight training relevant to the event, and official safety recommendations. We considered data from the onset of the event to completion, which included passenger evacuation for the Qantas 32 and US Airways 1549 accidents.

Table 2. General organization and content of the data gathered for each accident.

Source(s)	*Includes citation of the accident report, which has the date and location of the event, plus aircraft type. Also includes the date the report was released.* *Any other sources are also listed.*
Overview of Event Flightcrew on Board (for some events) Similarity of Event to Other Known Cases and Resolution Initial and Subsequent Malfunction(s) Official Statements Related to Cause Official Findings related to Training/Procedures/Operations	 *Pilot roles and other general situation of the flightcrew* *What was the malfunction? How did the crew become aware of the malfunction (alert, aircraft handling, or unaware)? What was the trigger for the situation?* *Official recommendations from the investigation.*
Description of Aircraft Systems and Alerts	*Type of aircraft, alerting system, etc. Design of alert (format, frequency). Distinguish between aural and visual information if possible.*
Flightcrew – General Experience	*Pilot qualifications and flight hours*
Flightcrew – Training Related to Event	*Describes training the flightcrew did (or did not) receive that applied to the event*
Flight Deck Alerts During the Event	*What alert(s) occurred? (Purpose, priority, and frequency of individual and multiple flight deck alerts.)*
Flightcrew Responses to Alerts General Procedures Checklists	*How did the flightcrew respond to the alerts? This covers checklists, memory items (including response priority and presentation of individual and multiple alerts). Include implications for design of emergency/abnormal checklist design. Highlights any examples of crew resilient behavior.* *Sometimes joined with "checklist" section below. There is not always a clear distinction between procedures and checklists in the event description.*
Flightcrew Task Management Communications Timeline Operations CRM	*How did the flightcrew manage tasks in the situation?* • *Timeline of events, workload, tasks, procedures, checklists, and memory items.* • *Critical communications and decisions made by crew* *This covers communications with Air Traffic, Dispatch, cabin crew and others outside the flight deck.* *Key points within the event timeline.* *Flightcrew decisions, as applicable to the event.* *As applicable. This includes communication within the flightcrew.*
Predictability, reliability, and intended function of systems	*Further description of the system and malfunction.*
Official Safety Recommendations	

3.2.2.2 Extracting Data

Extracting relevant data was a labor-intensive process that involved multiple, iterative reviews of the accident reports and other data sources. We took a "bottom-up" approach to the analysis; our findings were dictated only by the data available in published reports. The reviewers began by reading and digesting the full story in the accident report for comprehension and understanding. We did not start with any hypotheses about what to expect.

Next, we reviewed the reports for preliminary data extraction; we summarized the text from the report in notes. In later reviews, we copied specific quotes from the report and recorded their locations, rather than summarizing the content in our own words. Often quotes on similar topics were scattered throughout the document. Sometimes the quotes were similar and overlapping; we made judgement calls about what was new information. Each time the list of topics was altered in any way, we reviewed the report again and extracted more quotes.

Two reviewers examined each accident report; each one studied the full report. They coordinated efforts at multiple points. One reviewer read the supplementary data sources. We used a keyword search of the accident report in later rounds to ensure that we had done a thorough review. We used the electronic (PDF) accident-report file to track our progress and to coordinate between reviewers.

3.2.2.3 Documenting Extracted Data

One challenge we faced was to accurately capture the lengthy detailed accident report quotes and highlights in a short format for audiences who may need this material for different purposes. Our decision was to describe the accidents in three formats. The first, a short summary for unfamiliar readers was presented above in Section 3.2.1, Basic Accident Facts.

The other two, more detailed, versions are in Appendix B. This appendix has both a bulleted summary (approximately four pages for each accident) and the full quotes (approximately 20 to 30 pages for each accident). The bulleted summary focuses on the flightcrew perspective. It answers key questions about what the flightcrew experienced and how they responded to the malfunction and to the overall situation.

The full quotes cover all the topics in Table 2. The quote-gathering process was iterative during the writing stage. If we determined that additional quotes were needed to support our summary versions, we went back to the reports and added those.

Paraphrasing the quotes from the accident reports is challenging and can easily alter the accuracy and intended meaning of the original text. We paraphrase quotes only in the bulleted summaries, which are intended to increase general familiarity with the accident. We recommend reviewing the full quotes for any other purpose.

3.2.2.4 Variation across Accident Reports

Different accident reports had information about different topics. For example, memory items were not an issue for the Qantas 72 and Qantas 32 accidents. Also, there was no pilot training specific to the upsets in the Qantas 72 accident. As a result, there is some variability in the data recorded, based on the specific event and what was relevant.

Although the accident reports are more comprehensive than ASRS reports, they may still be missing information that would have been useful for understanding how pilots handled malfunctions. Because each accident and its report are unique, different information may be missing in different reports. We explore some of these limitations, as applicable to the different reports, in Appendix B.

In addition, the data available for each accident varied in readability. The US Airways 1549 National Transportation Safety Board (NTSB) report and ATSB reports for Qantas 72 and Qantas 32 were clearly written and organized. In all these events, the actions and decisions of the crew were clearly documented and explained. The Lion Air 610 and Ethiopian 302 accidents were more difficult to process, both because of the complexity of the accidents and because of the clarity of the text in the report. For Qantas 32 and Qantas 72, one reviewer read the supplementary books by the captains and matched their content with that of the accident investigation. These books were easier to read than the accident reports but still comprehensive. No significant mismatches were found; the books were highly consistent with the investigation reports, and in some cases, potentially offered new insights about flightcrew response and decision rationales.

Some accidents were easier to understand than others, and as a result were easier to process. The US Airways report was the least time consuming because the system malfunction was relatively simple to understand, and the report was clearly written. The Qantas 72 report was also relatively straightforward, although the system malfunction was more complicated because it involved both hardware and software. The Qantas 32 accident had many stages and was complicated by the long duration and stages of the event, and a very large number of ECAM actions.

The two Boeing 737 MAX accidents were more complex, both in terms of the nature of the malfunction, and the clarity of the accident reports. The Lion Air 610 report, for example, had information about the history of flights on the accident aircraft. Although a previous flight (Lion Air 43) warranted its own official investigation[15], it was only documented within the report on Lion Air 610. The Ethiopian 302 report was the most complicated report to process for at least two reasons. First, the final report was not released until relatively recently, and there were significant changes to the analysis in the final version relative to the interim report. For example, the interim report did not have the transcript of the cockpit voice recorder (CVR). Second, the NTSB and French Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) disagreed with some of the conclusions in the final report, so we had to review and reconcile multiple versions and explanations of the flightcrew response.

3.2.3 Key Observations from Accidents

This section describes our high-level observations of flightcrew responses to system malfunctions across the five accident reports. The insights here were extrapolated from the data in the accident reports and are somewhat speculative as a result. With such a small data sample, there is not sufficient data to make conclusive findings across accidents. And, even though the accident reports are comprehensive, they sometimes do not have the specific information needed for this analysis of pilot response.

Each of the main points is numbered. The text includes links to supporting quotes for traceability. The supporting quotes below can be accessed with a Ctrl + Click on the links. To return to this section after visiting the linked quote in Appendix B, use the keyboard shortcut Alt (Option) + left arrow when the file is opened with Adobe Acrobat.

[15] According to the International Civil Aviation Organization (ICAO) Annex 13, CASR part 830 and OM-part A, the flight [Lion Air 43] is classified as a serious incident which required investigation by the Komite Nasional Keselamatan Transportasi (KNKT) in accordance with the Aviation Law Number 1 of 2009 and Government Decree Number 62 of 2013 (KNKT, 2019, p. 211). See quote here (p. B.63).

1. Malfunctions can be easier or harder to diagnose.

The accidents varied in terms of how difficult it was for the crew to diagnose the malfunction based on the information and training they had. The engine failures in Qantas 32 and US Airways 1549 were easy to diagnose, with clear cues (see quotes here on p. B.30 for US Airways; here on p. B.63 and here on p. B.60 for Qantas 32).

The crews were not able to diagnose the cause of the malfunctions for Lion Air 610, Ethiopian 302, and Qantas 72. The Qantas 72 captain, however, was able to manage the problem by using the first officer's and standby flight instruments (see quote here, p. B.16) without understanding why it occurred.

This observation from the accident reports is similar to the ASRS key observation (Section 3.1.7) that diagnosing malfunctions can be difficult, especially when there are conflicting indications or intermittent malfunctions.

2. When there are multiple malfunctions or alerts, it is difficult to separate them from each other.

The accidents contained multiple malfunctions and alerts, and it was difficult to separate them. In Qantas 32 one problem (an engine failure) caused several others (see quote here, p. B.51). There was a physical failure within the engine that physically cut the electrical connections for the other systems.

With the Lion Air 610 and Ethiopian Airlines 302 accidents, a failure of one AOA sensor led to other alerts and problems (see quotes here and here, p. B.77 and p. B.106). With the AOA sensor failures, there was a more complicated relationship between failures. The MCAS logic worked as designed, but it was based on bad data. The bad data generated numerous alerts within a short period of time.

The accident reports do not report a count of alerts for a variety of reasons. For example, in Qantas 32, the event went on for a long time, beyond the recording capacity of the flight deck voice recorder (see quote here, p. B.63) so the beginning of the ECAM message sequence was reconstructed based on crew recollection. In addition, in this same accident, the alerts were often recurring; they reappeared even after the crew handled them and sometimes the alerts turned on and off before the crew could action them (see quote here, p. B.58). Also in Qantas 32, lower priority alerts were suppressed, by phase of flight, by design (see quote here, p. B.59). In Qantas 72, many of the alerts were spurious (see quote here, p. B.14). Finally, some alerts are not recorded in the flight data recorder so they cannot be counted accurately. For example, the ALT DISAGREE and IAS DISAGREE were not recorded in the Ethiopian 302 accident (see quote here, p. B.119).

If the alerts are not separated from each other within the accident report, it is very difficult to calculate how many there were retroactively. Given that some accidents have *many* alerts (e.g., Qantas 32 and Qantas 72), it is not clear how a specific count of alerts/malfunctions would be determined. At some point, the system behavior is not fully describable.

3. Flightcrew decisions about whether to operate the aircraft manually varied.

In some cases, the captains made the decisions to operate the aircraft manually after the onset of the malfunction. The Qantas 72 and Qantas 32 pilots flew manually, immediately after onset of the system failure/malfunction, and for an extended period of time; see quotes here, p. B.23 and here, p. B.60. Even the captain of Lion Air 43, the flight before the Lion Air 610 accident flight, chose to fly manually after the stall warning activated (see supporting quotes here on p. B.77 and here on p. B.77).

In contrast, the Ethiopian 302 flightcrew tried repeatedly to engage autopilot. The Ethiopian Aircraft Accident Investigation Bureau (EAIB) speculates that they did this because they misinterpreted the emergency Airworthiness Directive (AD); the crew might have thought that MCAS would not activate if the autopilot was engaged. However, the NTSB says the AD clearly stated that the stabilizer trim needed to be cutout, regardless of the autopilot status, and the crew did not follow the AD guidance (see quote here, p. B.130).

The US Airways 1549 flightcrew flew the entire event manually, from takeoff through the ditching; the report does not mention any use of autopilot. Similarly, there were no recorded autopilot engagements in Lion Air 610 (see quote here, p. B.92).

Some of the situations in these accidents might have been addressed by the guidance newly available to operators in the United States in the FAA AC 120-123 on Flightpath Management, which was released in 2022. This FAA AC discusses maintaining proficiency on manual flight operations as well as factors to consider when deciding whether to fly manually.

4. **Some captains found that crosschecking right and left side flight deck displays was helpful for understanding the situation.**

In two cases, Lion Air 43 and Qantas 72, the captains noticed a discrepancy between their display and the first officer's display (supporting quotes here, p. B.76 and here, p. B.16.). In Ethiopian 302 and Lion Air 610, however, neither pilot appeared to notice discrepancies between the right and left side displays. If they had, that might have helped them to understand and manage the situation more effectively.

5. **The roles and experience of flightcrew on board affected how the flightcrew managed the malfunction.**

In long-haul flight, it is common to have a third pilot (a second officer) on board, to allow one pilot to be on break at a time. This was the situation for Qantas 72 and for Qantas 32. Qantas 32 actually had two additional pilots, a check captain (who was evaluating the captain's performance) and a supervising check captain (who was evaluating the performance of the check captain). Although not necessary for flight safety, having more than two pilots on board has some advantages. (See supporting quote here on p. B.53.)

In US Airways 1549, the captain took control of the aircraft and announced that to the other crew member after the malfunction occurred. In all the other accidents, the captain was the pilot flying from the beginning of the problem. In Lion Air 610, however, the captain repeatedly asked the first officer to take over the manual flight, apparently to get relief from the high backpressure he was exerting. However, the captain did not use good communication and the first officer was unprepared to manage the excessive backpressure when he finally accepted control (see quote here, p. B.93). In addition, in Lion Air 610, the captain asked the first officer to manage both the checklists and ATC communications, which was not in accordance with standard operating procedure (see quote here, p. B.89).

6. **Time pressure, and related higher levels of workload, are factors in crew response.**

The accidents varied in terms of how much time pressure and workload was imposed on the flightcrew, both prior to and during the malfunction. The Qantas 72 event, for example, occurred in cruise phase while the aircraft was in steady flight, with no bad weather or turbulence in the area (see quote here, p. B.7). Thus, the flightcrew was in a relatively low workload state when the malfunction occurred.

The Qantas 32 problem began during a steady initial climb (maintaining 250 kts) after a normal takeoff, 6 minutes into the flight (see quote here, p. B.64). There was no weather in the area (see quote here, p. B.50). Their workload would have been lower than immediately after takeoff. The flightcrew was able to maintain altitude as they tried to make sense of the situation.

The US Airways 1549, Lion Air 610, and Ethiopian 302 accidents all happened shortly after takeoff, at low altitudes and prior to being established in a climb, when they would have been occupied with normal departure-related tasks. All three events needed quick decisions and actions. The Lion Air and Ethiopian flightcrews were not able to manage the situation under time pressure. It is not clear whether they would have been able to manage without time pressure either, but the time pressure likely degraded the crew response.

7. Pilot experience impacts the effective management of the situation.

In the accidents where there were no fatalities, the captains (in particular) and flightcrew (in general) were experienced. That experience manifested in specific actions and decisions that were taken proactively, and in task prioritization in general (see Table 3 below). For example, the flightcrews of US Airways 1549 and Qantas 32 demonstrated a good understanding of aircraft systems. This is an area of knowledge that is sometimes insufficient, as identified in Finding 3 from the PARC/CAST report (2013), which is about managing malfunctions.

In the accidents where no one survived, the captains (in particular) and flightcrew (in general) were less experienced. The lack of experience manifested in specific actions and decisions as shown in

Table 4.

8. English language skills may be confounded with overall accident outcomes and pilot experience.

Based on the findings of Sevillian et al. (2016) we wondered what effects English language proficiency of the pilots may have had on the accident outcomes. With Ethiopian 302, for example, the NTSB believed that the FAA AD was clear in describing the procedure to cutout the stabilizer trim, but the EAIB did not believe the language was clear. Possibly, the Ethiopian investigators (for whom, we suspect, English was also a second language) had a similar problem interpreting the English construction of the AD as the pilots did.

The flightcrews of Ethiopian 302 and Lion Air 610 came from countries where languages other than English were used routinely. Although the flightcrew of Ethiopian 302 was trained to International Civil Aviation Organization (ICAO) standards on English (see quote here, p. B.114), they were communicating with each other in a mix of English and their native language (see quote here, p. B.130). This may imply that they were more comfortable speaking their native language. The flightcrew of Lion Air 610 were of different nationalities; the captain was from India (see p. B.83) and the first officer was from Indonesia (see p. B.84). They appeared to be communicating in English, but the accident report does not specify whether English was their first language.

The two hull loss accidents (Lion Air 610 and Ethiopian 302) both had crews who may have spoken English as a second language. These crews had, in general, fewer hours of flight experience than the flightcrews for the other accidents we studied. Flightcrews for the other three accidents were likely native English speakers from Australia and America, although this is not called out specifically in the accident reports. So, the flightcrews with the better accident outcomes were also likely the ones with the best English language proficiency. The native English-speaking pilots also tended to have higher levels of flight experience, which also may have been a factor in the accident outcomes. So, flight experience and English proficiency were confounded. It is difficult to determine whether English proficiency affected the accident outcome, but it might have been a factor. There may also have also been cultural factors involved, other than the pilots' native language.

Table 3. Examples of how flightcrew experience impacted pilot response for Qantas 72, US Airways 1549, and Qantas 32.

Accident	*Examples of Flightcrew Experience on Pilot Response*
Qantas 72	The captain began to fly the aircraft manually flight after the autopilot disconnected automatically, which was approximately two minutes before the first upset. He flew the aircraft manually for an extended period of time. (Supporting quotes here, p. B.13, and here, p. B.23.) The captain noticed that the right-side displays were working correctly and used those to fly the aircraft. This crosscheck may have been learned through experience, and potentially could be reinforced through training. (Supporting quote here, p. B.16.) The captain determined that none of the numerous ECAM caution messages required urgent action. Instead of acting upon those, he asked for help from the first officer (who was in the back during the first upset), to return to help diagnose and manage problems. The captain demonstrated effective task prioritization and good use of resources. (Supporting quote here, p. B.21.) The captain knew about and executed control checks to assess the controllability of the aircraft in preparation for landing. (Supporting quotes here, p. B.18, and here, p. B.18.)
US Airways 1549	The flightcrew selected the most appropriate checklist when neither available checklist matched the situation exactly. (Supporting quote here, p. B.40.) The captain turned on the APU by memory, earlier than it was listed in the checklist, improving the outcome. (Supporting quote here, p. B.40.) The captain relied upon his experience and perception to select a flap setting, which was not specified in the available guidance. (Supporting quote here, p. B.43.) Although this accident had novel circumstances (dual engine failure at low altitude), air carrier pilots are trained to manage engine failures. The crew was able to apply their training to the unique circumstances of their situation.
Qantas 32	The captain reframed the situation cognitively. He used his basic understanding of flight principles to figure out how to fly a badly damaged aircraft. (Supporting quote here, p. B.58.) The captain decided to fly the aircraft manually after the autopilot disconnected on its own the second time. (Supporting quote here, p. B.60.) The captain knew about and executed control checks to assess the controllability of the aircraft in preparation for landing. (Supporting quote here, p. B.65.) The entire flightcrew worked together to understand the ECAM suggestions. They decided jointly not to follow the ECAM guidance about transferring fuel, which was the correct choice because of damage to the fuel tank. (Supporting quotes here, p. B.61, here, p. B.61, and here, p. B.51.) Although this accident had novel circumstances (i.e., the failure of multiple systems in addition to the engine failure), air carrier pilots are trained to manage engine failures. The crew was able to apply their training (e.g., use of the ECAM) to the unique circumstances of their situation.

Table 4. Examples of how flightcrew experience impacted pilot response for Lion Air 610 and Ethiopian Airlines 302.

Accident	*Examples of Flightcrew Experience on Pilot Response*
Lion Air 610	The flightcrew demonstrated weak CRM and task prioritization. The crew continued to respond to routine ATC communications even as their control of the aircraft deteriorated. (Supporting quotes here, p. B.86 and here, p. B.87.) The flightcrew was unable to recall the memory items, unable to locate the airspeed unreliable checklist, and unable to complete the checklist in a timely manner. (Supporting quotes here, p. B.88 and here, p. B.85.) The captain did not communicate clearly. For example, he did not explain to the FO how he was maintaining electric trim and backpressure to manage the aircraft pitch. The FO was unable to control aircraft after he accepted handoff. (Supporting quote here, p. B.93.)
Ethiopian Airlines 302	The flightcrew did not complete the memory items associated with the initial stall warning. (Supporting quote here, p. B.121.) The flightcrew did not follow the procedures described in the emergency bulletin and airworthiness directive that was released after the Lion Air 610 accident. They also did not complete the memory items in the airspeed unreliable and/or runaway stabilizer checklists. (Supporting quotes here, p. B.130, here, p. B.124, and here, p. B.125.) The flightcrew demonstrated degraded CRM. (Supporting quotes here, p. B.109, and here, p. B.131.) The flightcrew did not appropriately complete various non-normal checklists and procedures. (Supporting quotes here, here, here, here, and here on pages B.125, B.125, B.121, B.126, and B.126, respectively). Crew training was insufficient to promote the correct crew response in the actual situation. It is not clear how this could have been prevented. (Supporting quote here, p. B.131.)

4. Summary and Suggestions for Future Research

This goal of this research was to study air carrier flightcrew response to system failures, malfunctions, and systems not functioning as expected in operational data. We completed a broad literature review of studies related to aircraft system problems, alerts and checklists, pilot training related to handling malfunctions, and studies of pilot response to system malfunctions. Past studies have made different assumptions about pilot responses and have taken different approaches to either analyze existing operational data or gather related data. Section 2 of this report explains these different assumptions and methods and summarizes several studies.

The FAA asked us to review existing operational data. We screened over 300 ASRS records and studied 20 records in detail. This sample helped us to understand the difficulties that pilots face in operations, at all stages of the situation including problem recognition, diagnosis, and management. However, data from the ASRS reports did not allow us to draw inferences about pilot training, the effectiveness of alert format and priority, or about how different alerts were related to each other.

We also reviewed five official accident reports in depth. We summarized each accident in three views. The first view provides basic facts about the accident and the alerts/malfunctions that occurred in the event (Section 3.2.1). The second view is a bulleted summary that focuses on what the pilot knew, experienced, and did in response to the situation. The most detailed view has numerous quotes from the official accident reports. The bulleted summaries and quotes are in Appendix B.

We approached this review of operational data from the perspective that pilot response to aircraft system problem(s) consists of problem recognition, problem solving, decisions, and actions in a sequence. We followed the lead of Hopf-Weichel et al. (1979) who completed a comprehensive study for the Air Force Office of Scientific Research on the cognitive skills required by military pilots to manage aircraft emergency decisions; decisions related to managing system malfunctions in particular.

The subject of this report, pilot responses to system failures, malfunctions, and systems not performing as expected, has been studied by many other researchers, across many years. It is of great interest, and it is a difficult problem to address. The literature review presents a cohesive view of this research. This specific project focused on using the technical information to help improve integration of human factors into FAA guidance on air carrier pilot training and qualification for transport category aircraft.

One topic that remains to be examined is how military pilot training has evolved over time, as a comparison point to training for transport-category airline pilots. Hopf-Weichel et al. (1979) presents a snapshot in time of training for United States Air Force pilots. Lucaccini et al. (1980) went further and developed sample training scenarios for these pilots. It would be useful to gather more current literature on how Air Force pilots are trained today.

Another observation from this study is that analysis of the data from accident and incident reports is time consuming. It requires a great deal of labor and expertise to understand these events. With the recent development of large-language model artificial intelligence systems, it may be of interest to explore whether these systems or their future versions could aid researchers. This would have to be done with care, however, to ensure that the guidance from large-language models is valid. It is not clear to us yet whether we can trust these models to help researchers without introducing biases.

Finally, based on the literature search, we find that some of the most powerful and informative studies were based on relatively simple research methods (e.g., Au, 2005 and Hopf-Weichel et al., 1979). These included, for example, low-fidelity simulations, interviews, and card sorting tasks. Fundamental aspects of human behavior were captured in these studies. Future studies should also consider these relatively low-cost, but powerful, methods.

5. Conclusions

The Hopf-Weichel et al. report, and other older reports, have wisdom that still applies today. For example, the AIA and AECMA (1998) report describes how pilot experience shifted over time with regard to exposure to aircraft engine malfunctions; newer pilots had less experience with engine malfunctions. Similarly, the situations that newer pilots experience today are changing relative to those that today's older pilots had earlier in their training. The baseline experiences and training that pilots gain naturally, through flight operations, will continue to evolve.

Hopf-Weichel et al. (1979) also comments on the need to discover root causes for human factors related deficiencies. They acknowledge how difficult it is to establish a root cause. Yet the process of searching for root causes is important if we wish to understand situations that repeat. Technical problems can be fixed in many cases, but human behavior can be harder to change. Response to emergency situations may be especially challenging to alter, given how stressful these situations are, and how uncommon they are on an individual basis.

We must continue to try to understand pilot response to aircraft malfunctions because these situations continue to occur in novel manifestations. Two recent examples include an accident over Windsor Locks, Connecticut on March 3, 2023 and an asymmetric thrust condition in Indonesia, which occurred on January 9, 2021 on PT Sriwijaya Air. It takes time and patience to draw lessons from careful study of these events, and the benefits of this work have yet to be realized. By weaving together many perspectives, this report contributes towards progress.

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Appendix A: Industry Interview Proposed Questions

The purpose of the industry discussion was to gather data from operators and OEMs about flightcrew responses to flight deck alerts and the use of corresponding checklists, procedures, and memory items.

We requested meetings with up to three air carrier operators and one OEM. The discussions would focus on gaps in pilot knowledge/training related to pilot response to system failures, malfunctions, and unexpected behavior, ways to identify those gaps, what mitigations are put in place and how mitigations are monitored/assessed for operational effectiveness, and any emerging issues.

We planned to conduct semi-structured 1-hour virtual discussions, up to three with Part 121 operators and one with an OEM. We would identify participants through managers at the airlines and OEM. We would send managers a "script" explaining the purpose of the discussion and what to expect, including the questions we planned to ask. We would ask managers to share the document with a few people in their organization who would be most suitable to answer the questions. The manager may decide who and how many people to participate in each interview. Our goal was to gather perspectives from airline training departments and OEM staff involved in monitoring and updating manuals and training.

We sent the same script/questions to operators and OEMs. We developed the questions for operators with the plan to modify them for the OEM. Some questions may not be relevant to the OEM.

The script for the discussion sessions is given in full below.

<u>Study Information</u>

Project Title: Analysis of Flightcrew Response to Aircraft System Failures, Malfunctions, and Systems Not Functioning as Expected

FAA Program Manager: Chuck Perala, NextGen Human Factors Division (ANG-C1)

FAA Technical Sponsors: AVS and AFS

Research Organization: U.S. DOT Volpe Center, Transportation Human Factors Division

Researchers (please contact for more information):
Principal Investigator: Divya Chandra, Divya.Chandra@dot.gov, (617) 494-3882
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<u>Introduction</u>

The purpose of this study is to provide the FAA with information to help inform guidance for preparing pilots of transport category aircraft to deal with aircraft systems that have failed, malfunctioned, or not performed as expected. This may include, but is not limited to, pilot response to flight deck alerts.

We want to understand what issues your organization has observed related to this topic, and how the organization mitigates those issues. We are particularly interested in changes or mitigations related to flightcrew training, flightcrew procedures (including checklists), or operator policy.

We expect this conversation to take one hour. We will follow the general script that we sent you in advance but may ask qualifying or follow-up questions as needed.

The researchers will take notes during the conversation. The information we record will be de-identified and summarized in a published government report which will be made available to the public.

Your organization will have an opportunity to review the draft writeup of its responses before the report is published. The data are being gathered purely for research purposes. The information provided will not be used for oversight or enforcement.

Do you have any questions before we begin?

Questions

First, a few introductory questions:

1. Please describe your role within the organization.
2. Did you consult with others in preparing responses to the questions below? If yes, what are their roles?

The following questions pertain to how your organization prepares pilots to deal with aircraft system failures, malfunctions, and systems not performing as expected.

1. How does your organization identify **what is needed** to train pilots about aircraft system failures, malfunctions, and systems not performing as expected?
2. How do you **identify gaps in pilot knowledge, training, or procedures** related to aircraft systems that have failed, malfunctioned, or not performed as expected?
    a. What processes or systems are in place to detect potential gaps or potential for inappropriate pilot responses?
    b. What data do you use?
3. What **gaps has your organization identified**? Please give specific examples of situations that have confused pilots or led them to make inappropriate responses. Please focus on examples that come from your own organization.
4. What is your organization's **process for addressing gaps** in pilot knowledge, training, or procedures related to this topic?
    a. What mitigations or changes have been implemented within your organization (e.g., through training, procedures/checklists, or policy)?
    b. Are there pros and cons to different types of mitigations? Discuss.
5. Once a mitigation or change is in place, how does your organization **assess its operational effectiveness**? In other words, how do you determine whether the mitigation was successful?
    a. How does the organization monitor the success of the mitigation? What audits are put in place?
    b. What data are used? How often are these data gathered/analyzed?
    c. What, if any, adjustments have to be made based on these audits?
6. What **other emerging issues that might affect pilot response**, beyond those related to system failures and malfunctions, is your organization aware of?
7. Do you have any **suggestions for improving FAA guidance** for preparing pilots to respond to aircraft systems that have failed, malfunctioned, or not performed as expected? This may include ideas for training, procedures, or policies.

Appendix B: Accident-Investigation Data

This appendix provides detailed data about each accident. First, we list the **sources** of data we reviewed, including the accident investigation report and any other external material. Next is a **bulleted summary** of the event. The bulleted summaries are approximately four pages long for each accident. Finally, there are **specific quotes** on topics of interest to the FAA (see Table 2, p. 26). The number and length of the quotes vary. We did not put a limit on the number of quotes. Even so, it is possible to read the quotes in order, one after the other; we arranged them to be readable in this way.

The bulleted summaries and quotes are aligned, meaning they present similar data, but in a different way. The bulleted summaries are intended to be read first; they provide basic information to orient a reader who may be unfamiliar with the details of the accident. They address the following questions:

- What happened, in brief?
- What was/were the malfunction(s)?
- Who were the flightcrew on board and what were their qualifications?
- What training did the flightcrew have related to this event or malfunction specifically?
- What did the flightcrew experience during the event?
- What did the flightcrew do in response to the malfunction(s)?
- What else did the flightcrew do to manage the overall situation?

The detailed quotes are intended for an audience that is already familiar with the accident. They cover the following topics:

- Overview of Event
- Description of Aircraft Systems and Alerts
- Flightcrew – General Experience
- Flight Deck Alerts During the Event
- Flightcrew Responses to Alerts
- Flightcrew Task Management
- Predictability, Reliability, and Intended Function of Systems
- Official Safety Recommendations

The quotes are organized into tables for each of these topics and subtopics are described in Table 2. The source of the quote is in the left column of the table, with the default source being the official accident report.[16] Most of the quotes are from the accident report, as these were the preferred data source. The page number of the quote is provided in the left column (relative to the total number of pages in the PDF version of the report, rather than the paper version of the report). The right column contains the text of the quote, or a brief summary of that material.

[16] The FAA writes the term "flightcrew" as one word, but many other organizations and authors write it as two words, "flight crew." In quotes from other documents, we leave the word as written in the source document. Similarly, some of the documents use British English spellings rather than American English spellings. We leave the spellings as they are in the source document. We also leave the capitalizations as is from the source document. The only edits we made to quotations from accident reports was to insert spaces between words if they were left out of the original report, for readability. Acronyms used within this appendix are also in the List of Abbreviations.

Sometimes we provide a Volpe summary to summarize lengthy content; these are clearly labeled as "Volpe Summary" in the source (left) column of each table. We also occasionally insert a Volpe comment in the data column; these are clearly marked as "Volpe comment" and are in italics. Volpe comments are the authors' interpretations of the quote.

We reviewed each accident from onset to completion, which in the Qantas 32 and US Airways 1549 accidents included passenger evacuation.

B.I Qantas 72

Source(s)

Australian Transportation Safety Board (ATSB) (December 2011) In-flight upset, 154 km west of Learmonth, Western Australia, 7 October 2008, VH-QPA, Airbus A330-303 (Report No. AO-2008-070)

Book by the captain

> Sullivan, K. (2019). *No Man's Land. The untold story of automation on QF 72.* ISBN 978 7333 3974 5.

Default references are to the PDF file of the accident investigation (313 pp).

Bulleted Summary

What happened, in brief?

The aircraft experienced two sudden and unexpected descents a few minutes apart during cruise flight. The captain flew the aircraft manually and diverted to land as soon as operationally practicable, flying cautiously in case there were other upsets.

- Just over 3 hours into the flight, at 37000 ft, the flight control system initiated a descent (8.4° pitch down, 690 ft altitude loss over 23 seconds).
- A few minutes later, a second descent occurred (3.5° pitch down, loss of 400 ft over 15 seconds). Both upsets occurred within 7 minutes.
- The upsets occurred during daylight and in clear meteorological conditions with no reported turbulence.
- The flight diverted to Learmonth, Western Australia and continued to a safe landing about an hour after the upsets.
- There were no fatalities and 12 serious injuries due to the vertical accelerations because many of the occupants were not wearing seat belts. The ATSB declared this an accident due to the extent of injuries.

What was/were the malfunction(s)?

Erroneous data spikes in AOA combined with a logic failure in the software for the flight control computer caused the upsets.

- The system that malfunctioned was the Air Data Reference (ADR). The ADR is part of the Air Data Inertial Reference Unit (ADIRU), of which there are three on the aircraft. Only one unit, ADIRU 1, malfunctioned; the other two performed normally.
- A design limitation in the flight control primary computer (FCPC) meant that this situation (multiple spikes in AOA data from a single ADIRU) could result in the FCPC commanding the aircraft to pitch down as a corrective mechanism.
- This occurrence was "the only known case of the design limitation affecting an aircraft's flightpath in over 28 million flight hours on A330/340 aircraft" and as such "the limitation was within the acceptable probability range defined in the certification requirement for hazardous effects." (p. xvi of ATSB, 2011).
- A similar event occurred with the same hardware two years earlier, in 2006, but testing found no problems. In that event, the pilots shut down the faulty unit, so there was no in-flight upset.
- Another similar event occurred on a different aircraft in the same operator's fleet in December 2008, two months after the accident. By then, a new flightcrew procedure was in place, which handled part of the problem. The procedure was updated again after the December 2008 event.

Who were the flightcrew on board and what were their qualifications?

There were three experienced pilots on board (Captain, First Officer, and Second Officer).

- The A330 was designed to be operated by two pilots (captain and first officer). Second officers were carried to relieve the captain and first officer during long sectors on some trips.
- The captain (CA) was the Pilot Flying (PF) the entire time.
- The First Officer (FO) had stepped out of the flight deck just before the first upset and the Second Officer (SO) was seated in the right seat; he acted as Pilot Monitoring (PM) during both upsets.
- The FO handled the diversion to Learmonth. The SO sat in the third seat of the flight deck for the remainder of the flight.
- The CA and FO both had Air Transport Pilot Licenses with 13,592 flight hours and 11,650 flight hours, respectively.
    - The CA had over 2400 hours in the A330. He also had flown Boeing aircraft (757/767 and 747). The CA reports that he was trained in the USAF Navy as a Top Gun F-14 pilot (Sullivan, 2019).
    - The FO also had flown Boeing 737 and 747 aircraft and had over 2000 hours in the A330.
- The SO had a Commercial Pilot License and just over 2,000 flight hours.

What training did the flightcrew have related to this event or malfunction specifically?

There was no specific training that applied to the situation. The flightcrew followed standard operating procedures, and abnormal and emergency procedures as prompted by the ECAM.

What did the flightcrew experience during the event?

The event generated multiple ECAM alerts and actions with recurring visual and aural indications. Some of the alerts were real and some were spurious.

- The event began with an autopilot disconnect approximately two minutes before the first upset. The automatic disconnect (as opposed to a voluntary disconnect by the crew) was announced with a distinct "cavalry charge" aural and a warning message (AUTO FLT AP OFF) on the ECAM, along with a red warning light indicating that immediate crew action is necessary.
- Within 5 seconds of the autopilot disconnecting, a series of caution messages began appearing on the aircraft's ECAM, each associated with a master caution chime. The first messages were for STALL and OVERSPEED, both of which have aural and visual indications.
- The investigation found that there were several spurious alerts and some real alerts, with associated aural and visual indicators and alerts. Some also had associated ECAM messages and master caution chimes.
    - The crew reported that the messages were frequently scrolling with each new caution being placed at the top of the list.
    - Some faults kept recurring, and the crew could not effectively interact with the ECAM to action and/or clear the messages.
    - Master caution chimes and visual indicators occurred frequently, along with aural warnings for stall and overspeed. For example, there were at least 10 stall warnings in the 2-minute between the autopilot disconnect and first upset. There were also at least 22 master caution chimes in the first 2-minutes from the time of the autopilot disconnect to the first pitch down.
    - The crew experienced significant workload; one of the main factors was the frequently changing ECAM messages.
- The warnings continued for the remainder of the flight.
    - The crew states these constant aural alerts, and the inability to silence them were a significant distraction.
    - The ECAM performed as it was designed to perform. However, the rules could not effectively cater for the specific failure that was encountered (the ADR unit failure).

What did the flightcrew do in response to the malfunction(s)?

Upon the initial autopilot disconnect, the CA immediately began to fly manually. The crew followed the ECAM indications, which were consistent with the Flight Crew Operating Manual (FCOM).

- As a result of the initial autopilot disconnect, the CA was hand-flying the aircraft when each upset occurred.
    - The CA applied immediate backpressure to arrest the pitch down movement, but the aircraft did not respond to the pilot's input for about 2 seconds.
    - The CA attempted to engage the Autopilot 2 system (FO's side), but it too disconnected, and then they made no further attempts to use autopilot, given their decreasing level of trust in the aircraft systems.
- The SO actioned the ECAM messages while the CA flew the aircraft manually until the FO returned.
- In addition to the warnings and cautions, the crew reported that the airspeed and altitude indications on the captain's PFD were fluctuating.
    - No such fluctuations were occurring on the first officer's PFD or the standby flight instruments.
    - Because the captain was unsure of the veracity of the information on his PFD, he used the standby instruments and the first officer's PFD to fly the aircraft.
- The CA noted that the autotrim was not working, but otherwise the aircraft was flying normally.
    - He disconnected the autothrust to minimize any potential problems associated with the erroneous air data information affecting the electronic engine control units.
    - He flew the aircraft for the remainder of the flight without the autopilot or autothrust engaged and used the standby instruments.
- The CA reported that he could see out the window in the daylight and knew the aircraft was in level flight, with stable speed and power (Sullivan, 2019, p. 54).
- The CA diagnosed the situation as "unreliable airspeed" (Sullivan, 2019, p. 56).
- The ATSB declared that "The flight crew's responses to the warnings and cautions, the pitch-down events, and the consequences of the pitch-down events, demonstrated sound judgement and a professional approach."

What else did the flightcrew do to manage the overall situation?

The crew made the decision to land as soon as possible after the FO returned to the flight deck, just after the second upset. They communicated with Maintenance, the cabin, and ATC as they prepared for the diversion. They flew the aircraft cautiously, in case of another upset.

- They initially declared PAN PAN, but upon assessment of passenger injuries, later declared MAYDAY.
- The flightcrew communicated with the passengers and with the cabin crew throughout the situation.
- During the preparation for diversion, the crew reviewed the situation and ECAM actions.
- The flightcrew contacted the operator's 24-hour maintenance for assistance by satellite communications
    - Maintenance had access to the fault messages from the aircraft.
    - Maintenance suggested the crew turn off PRIM 3 (the third FCPC), but this action had no effect on the stall or overspeed warnings.
- The crew also had several communications with ATC as they descended, to prepare for approach and landing.
- The crew worked together to prepare for the landing, which was complicated by fault messages associated with the GPS and with the cabin air pressure system, which the SO had to control manually for the descent.
    - The crew executed a cautious descent because they were not sure if/when another upset might occur.
    - The crew completed the approach checklist and completed a flight control check above 10,000 ft.
    - Due to an autobraking fault, they also had to brake manually during the landing.

Overview of Event

The aircraft experienced two sudden and unexpected descents a few minutes apart during cruise flight. The captain flew the aircraft manually and diverted to land as soon as operationally practicable, flying cautiously in case there were other upsets. The upsets were caused by erroneous data spikes in AOA combined with a logic failure in the software for the flight control computer. The first unexpected descent occurred at 37000 ft altitude, 8.4° pitch down, resulting in a 690 ft altitude loss over 23 seconds. A few minutes later, a second descent occurred (3.5° pitch down, loss of 400 ft over 15 seconds).

There were no fatalities and 12 serious injuries due to the vertical accelerations because many of the occupants were not wearing seat belts. The ATSB declared this an accident due to the extent of injuries.

Source	Data (Quote or Summary)
p. 27/313	As some of the occupants received serious injuries, the occurrence was classified as an accident. (See also, Footnote 22, which defines an accident as "an investigable matter involving an aircraft where a person dies or suffers a serious injury, or the aircraft is destroyed or seriously damaged.)
p. 51/313	The flightcrew reported that, at the time of the occurrence, the weather was fine and clear and there was no turbulence. Cabin crew and passengers provided similar reports. An examination of information from the aircraft's FDR found that the vertical acceleration data prior to and during the two in-flight upsets was not consistent with the effects of moderate or severe turbulence (section 1.11.5).

Flightcrew on Board

Source	Data (Quote or Summary)
p. 21/313	Footnote 4 The A330 was designed to be operated by two pilots (captain and first officer). Second officers were carried to relieve the captain and first officer during long sectors on some trips. On this day, the flightcrew were rostered to operate the Singapore-Perth flight and then a Perth-Singapore flight. Second officers do not normally occupy either of the control seats during landing or takeoff.
Volpe Summary	There were three pilots, the captain (CA), First Officer (FO), and Second Officer (SO). The FO stepped out of the flight deck just before both upsets, so the SO handled the plane for each upset. The FO returned to his (right-seat) position and handled the diversion to Learmonth. The SO sat in the third seat of the flight deck for the remainder of the flight.
p. 17/313	The captain was the pilot flying.
Volpe Summary	There was no information in the report about flight training the crew received that related to this event specifically.

Similarity of Event to Other Known Cases and Resolution

Source	Data (Quote or Summary)
p. 18/313	As the occurrence was the only known case of the design limitation affecting an aircraft's flightpath in over 28 million flight hours on A330/340 aircraft, the limitation was within the acceptable probability range defined in the certification requirement for hazardous effects.
p. 234/313	As of the end of 2009, A330/A340 aircraft had accumulated over 28 million flight hours. The occurrence on 7 October 2008 was the only occasion when incorrect data from an air data inertial reference unit had resulted in inadvertent elevator commands. This in-service performance was consistent with the relevant certification requirements.
p. 78-79/313 and p. 255/313 Volpe Summary	1.16.1 Previous flight control occurrences associated with ADIRU failures (p. 78/313) Appendix D: Other Data-spike occurrences (p. 255/313) A similar event occurred on the same aircraft/hardware in 2006, but testing found no problems. During the 2006 event, the pilots shut down the faulty air data unit, so no in-flight upset occurred. In the 2006 event, Autopilot 2 was engaged (rather than AP1), because the FO was PF instead of the captain and there was no autopilot disconnect or in-flight upset. Quote from Appendix D regarding 2006 event: > Discussions with maintenance watch [in-flight] could not resolve the issue. However, a scan of the overhead panel identified a very weak and intermittent ADR 1 fault light, and the crew decided to turn the ADR 1 off. Following that action, the warning and caution messages ceased and the flight continued without further incident. At no stage was there any effect on the aircraft's flight controls. (p. 255/313) The same type of event happened on another aircraft (for the same operator) on 27 December 2008 (p. 257/313), but by then there was a new crew procedure to handle it. The new procedure handled part of the problem, but not all, and was modified again after the December 2008 event.
p. 239/313	The standard was retrofitted to the operator's fleet of A330 aircraft, and completed in November 2009.

Initial and Subsequent Malfunction(s)

Source	Data (Quote or Summary)
p. 17/313	At 0132 Universal Time Coordinated (0932 local time) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA and operated as Qantas flight 72, departed Singapore…
p. 17/313	At 0440:26, while the aircraft was in cruise at 37,000 ft, ADIRU 1 started providing intermittent, incorrect values (spikes) on all flight parameters to other aircraft systems. Soon after, the autopilot disconnected and the crew started receiving numerous warning and caution messages (most of them spurious). The other two ADIRUs performed normally during the flight.
p. 9/313	Although the FCPC algorithm for processing AOA data was generally very effective, it could not manage a scenario where there were multiple spikes in AOA from one ADIRU that were 1.2 seconds apart.
p. 17/313	…due to the combination of a design limitation in the flight control primary computer (FCPC) software of the Airbus A330/A340, and a failure mode affecting one of the aircraft's three air data inertial reference units (ADIRUs). The design limitation meant that, in a very rare and specific situation, multiple spikes in angle of attack (AOA) data from one of the ADIRUs could result in the FCPCs commanding the aircraft to pitch down.
p. 122/313	Checklists are often used when developing and reviewing system requirements, and research has shown that checklists focussing on safety-related aspects can increase the chances of detecting safety-related design problems (Lutz, 1996). However, given the wide range and complexity of system designs, it is unreasonable to expect that every specific, potential problem with every type of software design could be specified in the form of checklists or guidance material. A review of a sample of guidance manuals and checklists did not identify any specific guidance that was directly applicable to the design limitation associated with the A330/A340 FCPC algorithm for processing AOA data.

Official Statements Related to Cause

Source	Data (Quote or Summary)
p. 211/313	A summary of the main factors involved in the occurrence is presented in Figure 53. In essence, a design limitation with the FCPC software combined with an ADIRU failure to falsely activate the corrective mechanisms and produce the pitch-downs. The subsequent vertical accelerations led to a large number of injuries to the aircraft's occupants, with the number and extent of these injuries being exacerbated by many of the occupants not wearing seat belts.

Source	Data (Quote or Summary)
p. 233/313	6.1 Contributing safety factors There was a limitation in the algorithm used by the A330/A340 flight control primary computers for processing angle of attack (AOA) data. This limitation meant that, in a very specific situation, multiple AOA spikes from only one of the three air data inertial reference units could result in a nose-down elevator command. *[Significant safety issue]* When developing the A330/A340 flight control primary computer software in the early 1990s, the aircraft manufacturer's system safety assessment and other development processes did not fully consider the potential effects of frequent spikes in the data from an air data inertial reference unit. *[Minor safety issue]* One of the aircraft's three air data inertial reference units (ADIRU 1) exhibited a data-spike failure mode, during which it transmitted a significant amount of incorrect data on air data parameters to other aircraft systems, without flagging that this data was invalid. The invalid data included frequent spikes in angle of attack data. Including the 7 October 2008 occurrence, there have been three occurrences of the same failure mode on LTN-101 ADIRUs, all on A330 aircraft. *[Minor safety issue]*

Official Findings related to Flightcrew Training, Procedures, and Operations

Source	Data (Quote or Summary)
p. 235/313	The flightcrew's responses to the warnings and cautions, the pitch-down events, and the consequences of the pitch-down events, demonstrated sound judgement and a professional approach.
p. 234/313	6.2 Other safety factors However, there has been limited research that has systematically evaluated how design engineers and safety analysts conduct their evaluations of systems, and how the design of their tasks, tools, training and guidance material can be improved so that the likelihood of design errors is minimised.

Description of Aircraft Systems and Alerts

Source	Data (Quote or Summary)
General	A330, 2 engines. Equipped with ECAM and Failure Warning System (FWS)

Source	Data (Quote or Summary)
Starting p. 33/313 Volpe Summary	1.6.4 Air data and inertial reference system (ADIRS) system overview The ADIRU has two components, the Air Data Reference (ADR) and Inertial Reference (IR). The ADR generates about 30 flight data parameters. The IR generates about 60. The ADR and IR can be reset/deactivated independently (see ADIRS control panel, p. 36/313).
p. 45/313	Table 3 Failure level classifications and associated indications. Text below the table on same page: For a level 3 failure, the FWS illuminated the red, flashing master warning lights that were located on both sides of the glareshield. The FWS also produced a continuous repetitive chime or other continuous aural alert. For example, a stall warning was associated with a synthetic voice stating 'STALL STALL' followed by a 'cricket' noise. The aural alert for a level 3 failure continued until the failure condition no longer existed or the crew had cancelled the warning. Some level 3 failures, such as stall and overspeed warnings, were not associated with an ECAM message. For a level 2 failure, the FWS illuminated the amber, steady master caution lights on both sides of the glareshield. It also produced a single aural chime. The master caution chimes could not be cancelled by the crew.
Starts p. 47/313	Section 1.6.11 Electronic centralized aircraft monitor (ECAM) System Overview A key principle of the ECAM's design philosophy was to present information on an 'as needed' basis. For example, when displaying fault messages, it provided the appropriate emergency/abnormal procedures in addition to associated synoptic information. (p. 48/313)
p. 49/313	Presentation of ECAM warning and caution messages Figure 18: Example of ECAM warning and caution messages There were seven lines available at the bottom of the E/WD to display warning and caution messages. The messages were displayed in a priority order, with the most important messages displayed at the top. Level 3 messages were displayed above level 2 messages, which were displayed above level 1 messages. When there were multiple messages at the same level, the most recent message had the highest priority.

Source	Data (Quote or Summary)
p. 49/313	From Footnote 37 For a small number of abnormal or emergency situations, the relevant procedure was not associated with an ECAM message. For some of those situations, flightcrew were required to complete the relevant procedure from memory and not refer to the manuals (for example, emergency descent or unreliable airspeed indications). In other situations, temporary procedures of significant importance could be promulgated as Operations Engineering Bulletins (OEBs).
p. 104/313	Section 2.3.2 Regulatory Requirements.
Volpe Summary	Discusses the relevant certification requirements and classification of hazard effects, JAR 25.671, JAR 25.1309, European AC Joint No. 1 to 25.1309, FAA AC 25.1309-1A, and DO-178A.
p. 116/313	Section 2.5.3 Safety assessment of the FCPC algorithm.
p. 174/313	Section 3.8 ADIRU safety analysis
p. 51/313	A review of technical log entries for the aircraft's relevant systems identified a previous event on 12 September 2006 that involved similar warnings and caution messages but no pitch-down events (section 1.16.2).

Flightcrew – General Experience

Source	Data (Quote or Summary)
p. 28/313 Volpe Summary	Section 1.5, Personnel Information has a table with the three pilots' flight hours and licenses. The CA and FO both had Air Transport Pilot Licenses with 13,592 flight hours and 11,650 flight hours, respectively. The SO had a Commercial Pilot License and just over 2,000 flight hours. The CA had over 2400 hours in the A330. He also had flown Boeing aircraft (757/767 and 747). The FO had over 2000 hours in the A330 and had also flown Boeing 737 and 747 aircraft. In addition to the A330, the CA also had flown Boeing aircraft (757/767 and 747). The FO also had flown Boeing 737 and 747 aircraft.

Source	Data (Quote or Summary)
Sullivan, various pages	CA was trained in the USAF Navy, Top Gun F-14 pilot in 1982 (26 years before the event). Prologue - Says that he used this training when handling the event. • e.g., time/altitude relationship, aerobatic maneuvers • Discussed management of emergencies before every flight, p. 27 • Developed 'coolness under pressure' p. 28 during initial flight training in 1977 • Fighter pilots take the airplane to its limits and beyond; need a skill set to regain control if lost. Learned to identify cues for impending stall and spins. p. 49 • Has other background on flight training experience he found formative
Sullivan, Volpe Summary	The CA was diagnosed with Post-Traumatic Stress Disorder (PTSD) after this event and was unable to continue flying as a career. (He did regain his medical and piloted a few flights, but senses he could panic multiple times.) He says his years of military experience were not as traumatic as this event.

Flight Deck Alerts During the Event

Source	Data (Quote or Summary)
p. 46/313 Volpe Summary	<u>Table 4: Summary of indications for selected types of faults</u> This table lists the summary of indications for selected faults experienced during this event. The table describes the aural alert, ECAM message and other visual indications for warnings and cautions that the crew experienced. The autopilot disconnect has an associated red Master Caution warning light, cavalry charge aural, and ECAM message. The stall and overspeed warnings also have Master Caution warning lights and associated aurals. *Volpe Comment: There is no stick shaker (tactile cue) for stall or approach to stall on Airbus aircraft. The low-speed alert on Airbus aircraft presents as an aural alert and master warning light.*
p. 54/313 Volpe Summary	<u>Table 7: Sequence of events (from the FDR)</u> The autopilot disconnected about 2 minutes before the first vertical upset. Next came several Master Warnings and Master Cautions, stall warnings, and overspeed warnings. Each of these warning had associated visual indicators and aural alerts. Some had ECAM messages as well.
p. 21/313	<u>Footnote 5</u> Consistent with an automatic disconnection (as opposed to a voluntary disconnection by the flightcrew), there was a distinctive (cavalry charge) aural signal and a warning message (AUTO FLT AP OFF) on the ECAM.

Source	Data (Quote or Summary)
p. 21-22/313	Within 5 seconds of the autopilot disconnecting, a series of caution messages began appearing on the aircraft's electronic centralized aircraft monitor (ECAM), each associated with a master caution chime.
p. 22/313	The crew also started receiving aural stall warnings and overspeed warnings, although each warning was only annunciated briefly. These cautions and warnings occurred frequently, and continued for the remainder of the flight.
p. 52-53/313	<u>Recorded Aural Alerts</u> There were no recorded warnings or cautions in the period prior to the autopilot disconnection alert at 0440:28. The disconnection alert lasted 3 seconds before it was cancelled by the crew. After that point, there were frequent occurrences of the following aural alerts: • Master caution chimes. The first master caution chime occurred at 0440:33. During the period 0440:28 (autopilot disconnection) to 0442:27 (first pitch-down) there were at least 22 master caution chimes. The chimes continued for the remainder of the flight. • Stall warnings. The first stall warning occurred at 0440:45, and there were at least 10 stall warnings in the 2-minute period between the autopilot disconnection and the first pitch-down. The warnings continued for the remainder of the flight. In all cases the stall warnings were brief; on some occasions they were truncated before the first 'STALL' was annunciated, and in all cases they were truncated before a full cycle of the warning (that is, 'STALL STALL' followed by a cricket noise). • Continuous repetitive chimes. This type of alert was used for several different types of warnings (that is, level 3 failures). Based on a comparison with the FDR data and other information sources, the only warning conditions present on the flight, other than the autopilot disconnection and the stall warnings, were overspeed warnings (also discussed in section 3.3.4). The first aural overspeed warning occurred at 0440:37, and there were at least seven warnings in the 2-minute period between the autopilot disconnection and the first pitch-down. The warnings continued for the remainder of the flight, but they were less frequent than the caution chimes and stall warnings. In all cases the aural signals were brief and they were truncated after two or less chimes.
p. 25/313	Master caution chimes associated with the ECAM messages were frequently occurring, together with aural stall warnings and overspeed warnings. The crew stated that these constant aural alerts, and the inability to silence them, were a significant source of distraction.
p. 234/313	The large number of spurious warnings and caution messages that resulted from the anomalous air data inertial reference unit behaviour created a significant amount of workload and distraction for the flightcrew.

Source	Data (Quote or Summary)
Sullivan, p. 54	CA writes "Moments before we were in stable flight; nothing in the outside environment has changed. We're lucky this is a daylight flight. I can see the horizon; one minute ago I was in straight and level flight and my cruising speed and power were stable. We're in a calm and clear air mass with no turbulence or cloud."
Sullivan, p. 56	CA writes "…I must focus on controlling the aircraft in this loud and distracting environment."
p. 68	Table 11, titled "Cockpit effect messages due to problems with ADIRU output data"
Volpe Summary	The real problems included: • Autopilot disconnect • GPWS fault • Captain's ND was not able to be displayed; red warning flag on the ND, but no ECAM message • Lat/long cross-check error between GPS and FMGES (flight management guidance and envelope system) • Loss of autobrake • Electronic information system display discrepancy • Automatic cabin pressure control lost
p. 69	Table 12: Cockpit effect messages due to spurious fault messages from ADIRU 1
Volpe Summary	The spurious alerts included: • NAV GPS 1 fault • NAV GPS 2 fault • A.ICE L CAPT STAT HEAT • NAV IR Not aligned • Other A.ICE messages for the captain's side, due to corrupted data
Sullivan, p. 56	Captain writes: "I've figured out I'm dealing with an abnormal condition that Airbus has labelled 'unreliable speed.'"…"This is not displayed as a warning or caution message because the automation doesn't make this critical assessment; it is up to the pilot to interpret."

Flightcrew Responses to Alerts

General

Source	Data (Quote or Summary)
p. 235/313	The flightcrew's responses to the warnings and cautions, the pitch-down events, and the consequences of the pitch-down events, demonstrated sound judgement and a professional approach.
p. 17/313	The flightcrew's responses to the emergency were timely and appropriate.
p. 64/313	<u>Flight crew pitch inputs</u> The inputs did not have any immediate effect on the recorded elevator position, but within 1 to 2 seconds the elevator position started to correlate with the sidestick inputs.
p. 24/313	<u>Second in-flight upset (0445:08)</u> The captain promptly applied back pressure on his sidestick to arrest the pitch-down movement. He said that, consistent with the first event, this action initially had no effect, but soon after the aircraft responded normally.
Sullivan, p. 52	The CA immediately starts troubleshooting after the autopilot disconnects. *Volpe Comment: With the autopilot disconnected, the CA was flying manually at the time of each upset.*
Sullivan, p. 61 Volpe Summary	He noticed his input on the sidestick had no effect. He resorted to his military training—"neutralize" and returned the sidestick to center, to not make any input. Then he probed the stick to check for a response and felt the computers return control to the pilot.
p. 22/313	In addition to the warnings and cautions, the crew reported that the airspeed and altitude indications on the captain's primary flight display (PFD) were fluctuating. No such fluctuations were occurring on the first officer's PFD or the standby flight instruments. The fluctuations on the captain's PFD appeared to be based on unreliable information, as there was no other indication that the aircraft was actually near a stall or overspeed condition. Because the captain was unsure of the veracity of the information on his PFD, he used the standby instruments and the first officer's PFD when flying the aircraft.

Source	Data (Quote or Summary)
p. 22/313	Footnote 7 The captain reported that he disconnected autopilot 2 as it was a required action in the event of an unreliable airspeed situation. Although the captain's airspeed values were fluctuating, there was no evidence of any problems with the other two airspeed sources during the flight.
Sullivan, p. 57	The CA realizes that some of the warnings are false. He writes: "These are serious threats that by design require immediate action, but looking out the forward cockpit window confirms we aren't under threat. These warnings *have* to be false. The cause isn't displayed and I am dealing with the results of their confused state. I won't act until the computers identify the malfunction, as we were trained to do in our Airbus course." He also writes "We haven't come across an event like this in our Airbus training." *Volpe Comment: Example of flightcrew resilient behavior because the captain uses external information to crosscheck the flight deck data.*
Sullivan, p. 79	There are other intermittent warnings that disappear before the pilots register what they were.
Sullivan, p. 75	After the first upset, CA expects automatic pitch trim to keep working, but it doesn't, and there is no corresponding error message.
p. 25/313	Footnote 15 A 'USE MAN PITCH TRIM' message was not displayed to the crew on their PFDs as, at the time of the occurrence, this message was only displayed if the flight control system was in direct law. The aircraft manufacturer advised that this problem was being addressed with a new design standard, which was certified in 2011.
p. 26/313	In a subsequent discussion, maintenance watch recommended that, at the crew's discretion, they could select PRIM 3 (or flight control primary computer 3) OFF. The crew discussed this recommendation and, at 0520, switched that computer OFF. This action had no effect on the scrolling ECAM messages, stall warnings or overspeed warnings.

Procedures

Source	Data (Quote or Summary)
p. 49/313	The operator's A330 Flight Crew Operating Manual (FCOM) was based on the aircraft manufacturer's manual. Volume 3 of the manual contained standard operating procedures and abnormal and emergency procedures. For most of the abnormal and emergency procedures, the ECAM and the FCOM presentations were consistent, with the procedures organised under the relevant ECAM warning or caution message.
p. 49/313	<u>From Footnote 37</u> …All of the procedures relevant to this occurrence were available for display via the ECAM.
p. 27/313	The crew completed the approach checklist and conducted a flight control check above 10,000 ft. *Volpe Comment: The Qantas 32 pilot also did flight control checks. This is a technique taught in the military.*
Sullivan, p. 121	CA describes "control checks." "The control check at 10,000 ft will confirm my level of controllability with the wing faps extended. This is a common consideration in military flying, as the check confirms the aircraft's speed and maneuverability at approach speed. Checking the slow speed flight capability is best determined at a safe altitude before doing it for real."

Checklists

Source	Data (Quote or Summary)
p. 25/313	Following the second in-flight upset, the crew continued to review the ECAM messages and other indications. The first ECAM message they noticed was F/CTL ALTN LAW (PROT LOST). The next messages were recurrences of the NAV IR 1 FAULT and F/CTL PRIM 3 FAULT messages. The crew reported that the IR1 FAULT light and the PRIM 3 FAULT light on the overhead panel were illuminated. No other fault lights were illuminated. The crew reported that by this time ECAM messages were frequently scrolling, with each new caution message being placed at the top of the list. The NAV IR 1 FAULT message kept recurring, together with several other messages, such as NAV GPS FAULT, and they could not effectively interact with the ECAM to action and/or clear the messages. Master caution chimes associated with the ECAM messages were frequently occurring, together with aural stall warnings and overspeed warnings. The crew stated that these constant aural alerts, and the inability to silence them, were a significant source of distraction.
p. 25/313	<u>Footnote 14</u> The crew reported that they did not recall seeing amber crosses on the PFDs, which were meant to be displayed if the flight control system was in alternate law or direct law. The aircraft manufacturer advised that there was no technical reason why these amber crosses would not have been displayed on the occurrence flight.
Sullivan, p. 77	When the systems announce they are in Alternate Law, they expect to see corresponding visual flags (amber-colored 'noughts and crosses' on the attitude indicator), but those are missing. They don't know what to believe.
p. 26/313	During remainder of flight, flightcrew noted that the NAV IR 1 FAULT and F/CTL PRIM 3 FAULT messages were still occurring, together with several other caution messages. They concluded that the ECAM was not providing them with useful information or recommended actions.
p. 50/313	Table 6: Required actions associated with selected ECAM messages

Source	Data (Quote or Summary)
p. 229/313	5.5.5 Flight crew workload Warning and Caution Messages The crew experienced a significant workload during the occurrence. One of the main factors contributing to the workload was the frequently changing ECAM messages, together with the distracting noises from the caution chimes and stall warnings. The ECAM was designed to help manage abnormal and emergency situations by providing relevant, synoptic information and recommended crew actions. Due to the frequent and repetitive nature of the messages, the crew could not effectively interact with the ECAM to determine which messages were important. As well as increasing workload, this situation would have increased the crew's unwillingness to trust the aircraft's systems. The ECAM performed as it was designed to perform. It had rules to prioritise the presentation of messages by failure level and recency, and for almost all abnormal and emergency situations these priority rules would work well. However, the rules could not effectively cater for the ADIRU data-spike failure mode, which involved a large number of messages at the same level and many of them frequently repeated. Redesigning the system to cater for this specific situation would be a major undertaking. In addition, any design change that allowed the flightcrew to stop the presentation of fault messages to minimise distractions would introduce a risk of removing potentially important information. The key problem with the fault messages for the data-spike failure mode was not the presentation of excessive or nuisance messages, but that the key message that would have resolved the problem (that is, NAV ADR 1 FAULT) was not presented in a timely manner. Improving the fault detection properties of the ADIRU would therefore seem to be more important than redesigning the ECAM to cater for a particular failure mode.

Flightcrew Task Management

General

Source	Data (Quote or Summary)
p. 17/313	The flightcrew's responses to the emergency were timely and appropriate. Due to the serious injuries and their assessment that there was potential for further pitch-downs, the crew diverted the flight to Learmonth, Western Australia and declared a MAYDAY to air traffic control. The aircraft landed as soon as operationally practicable at 0532, and medical assistance was provided to the injured occupants soon after.

Source	Data (Quote or Summary)
p. 22/313	Although the crew received numerous ECAM caution messages, none of them required urgent action, and none of them indicated any potential problems with the aircraft's flight control system. However, the captain was not satisfied with the information that the aircraft systems were providing, and he asked the second officer to call the first officer back to the flight deck to help them diagnose and manage the problems. *Volpe Comment: Example of flightcrew resilient behavior and an example of task prioritization.*
Sullivan, various pages	In addition to handling the airplane, during and right after the first upset, the pilots were multi-tasking: • CA hands aircraft control to SO so that he could put on his shoulder harness, since he had only his lap belt on, as required. • SO illuminated the "Fasten Seatbelt" sign during the pitch down. He made a quick announcement to passengers to buckle up right after the first upset. • In the flight deck heavy paper manuals floated up and hit the floor, and opened up, spreading contents all over. • Pilots heard loud bangs from the cabin as people hit the ceiling. The pilot tried to regain altitude gently, but people fell down from the ceiling as positive-g was restored. They heard moans and screams. • They mention tunnel vision, adrenaline rush, fear, fight-flight response, etc.
Sullivan, p. 103	Sullivan also mentions that the crew had trouble locating charts for the airport because their digital airport information was not working and the charts were scattered around the flight deck after the manual holding them "exploded on impact during the first pitch-down."
Sullivan, p. 67	FO needs to access a special paper checklist to reset the PRIM 3, but they could not find it amongst all the scattered paper. They have practiced this checklist in the simulator, he knows the gist, but wants to read the details. The CA hands him his own copy. (After the reset all green, but a bit later all the warnings start again.)
Sullivan, p. 74	They are also dealing with the emotional impact. CA feels "betrayed" by the automation.
Sullivan, p. 66	Captain continues flying aircraft manually (difficult task) while SO handles the ECAM messages. Captain's autopilot is not usable. While he flies manually, he also monitors the SO actions.
Sullivan, p. 67	Captain tried to use his systems knowledge, but "in vain."

Communications

Source	Data (Quote or Summary)
p. 26/313	At 0449:05, the first officer made a PAN broadcast to air traffic control, stating that they had experienced 'flight control computer problems' and that some of the aircraft's occupants had been injured. He requested a clearance to divert to and track direct to Learmonth. At 0451:25, the first officer requested further descent from air traffic control. The controller cleared the crew to leave controlled airspace and proceed direct to Learmonth. After receiving advice from the cabin of several serious injuries, the captain asked the first officer to declare a MAYDAY. At 0454:25, the first officer declared the MAYDAY and advised air traffic control that they had multiple injuries on board.
p. 26/313	In addition to communications with maintenance watch, air traffic control and the cabin, the flightcrew worked together to provide the captain with all the information he needed to fly the aircraft.
Table 29 p. 187/313	Timeline of significant cabin communications
p. 26/313	Consequently, at 0456:05, the first officer contacted the operator's, maintenance watch located in Sydney, New South Wales, by a satellite communications system (SATPHONE) to brief them on the situation and to seek assistance. There were subsequently several communications between the flightcrew and maintenance watch about the fault messages and other flight deck indications.

Timeline

Source	Data (Quote or Summary)
p. 54/313	Table 7: Sequence of events (from the FDR)
Volpe Summary	Both upsets happened within approximately 7 minutes. The crew diverted and continued to a safe landing about an hour after the sudden descents (as soon as operationally practicable).

Operations

Source	Data (Quote or Summary)
p. 230/313	Operating the aircraft without an autopilot for the remainder of the flight also increased the captain's workload. The data-spike failure mode involving ADIRU 1 affected the operation of autopilot 1 but it would not have affected autopilot 2. After autopilot 1 disconnected, the captain engaged autopilot 2, but he disconnected it shortly after. The crew made no further attempts to use autopilot 2, which was understandable given their decreasing level of trust in the aircraft's systems. Although re-engaging autopilot 2 would have reduced the captain's workload, it would not have prevented the pitch-down commands from the FCPCs. In addition, autopilot 2 would have automatically disconnected during each of the pitch-downs.
p. 17/313	Crew made the decision to land as soon as practicable.
p. 25/313	Diversion to Learmonth, planning and execution
p. 229/313	Following the decision to divert, the crew continued their attempts to diagnose the problems, and also requested assistance from the operator's maintenance watch. These efforts did not resolve the situation and, as the flight progressed, they needed to focus more of their efforts on identifying and managing the logistical issues and threats associated with the diversion and landing. They also needed to maintain communications with the cabin, air traffic control and maintenance watch. These tasks were performed with a high degree of coordination and effectiveness by the flightcrew.
p. 25/313	With the exception of the loss of autotrim, the captain reported that the aircraft was flying normally. At 0447:25, he disconnected the autothrust to minimise any potential problems associated with the erroneous air data information affecting the electronic engine control units. He then flew the aircraft without the autopilot or autothrust engaged, and using the standby instruments, for the remainder of the flight.
p. 27/313	Cautious descent In order to lose altitude for landing, the captain conducted a series of wide left orbits to maintain the aircraft's speed below 330 kts (maximum operating speed). He reported that he descended cautiously in order to prevent any potential problems associated with another unexpected pitch-down event.

Predictability, Reliability, and Intended Function of Systems

Source	Data (Quote or Summary)
p. 233/313 Volpe Summary	Section 6.1 Contributing safety factors The ATSB lists the highest priority safety item as the software logic. The sensor failure is lower priority. (See above, Official Statements Related to Cause.)
p. 22/313	Footnote 7 Although the captain's airspeed values were fluctuating, there was no evidence of any problems with the other two airspeed sources during the flight.
p. 27/313	They also needed to manage a range of problems with aircraft systems. For example, the flightcrew were unable to enter an RNAV (GNSS)21 approach into the flight management computer due to fault messages associated with the Global Positioning System (GPS) units. The second officer had to manually control the cabin pressure during the descent due to a pressurization system fault, and the crew noted that they would need to use manual braking during landing due to an autobrake fault.
p. 122/313	Checklists are often used when developing and reviewing system requirements, and research has shown that checklists focussing on safety-related aspects can increase the chances of detecting safety-related design problems (Lutz, 1996). However, given the wide range and complexity of system designs, it is unreasonable to expect that every specific, potential problem with every type of software design could be specified in the form of checklists or guidance material.

ATSB Official Safety Recommendations

There were safety actions related to FCPC issues in the ATSB report (Section 7.1), ADIRU issues (Section 7.2), Use of Seat Belts (Section 7.3), and Single Event Effects (Section 7.4). Here we detail only Section 7.1 actions, related to interim crew procedures until FCPC software retrofits were completed. The formal safety recommendations mention training crews on temporary procedures developed in response to this event (see details under Qantas below).

Source	Data (Quote or Summary)
p. 17/313	Executive Summary When the aircraft manufacturer became aware of the problem, it issued flightcrew procedures to manage any future occurrence of the same ADIRU failure mode. The aircraft manufacturer subsequently reviewed and improved its FCPC algorithms for processing AOA and other ADIRU parameters. As a result of this redesign, passengers, crew and operators can be confident that the same type of accident will not reoccur.

Airbus

Source	Data (Quote or Summary)
p. 237/313 Volpe Summary	Procedural changes were issued by Airbus (10/15/2008) after the event [OEB-A330-74-1]. The OEB said to essentially turn off the ADR. Airbus recommended operators advise their pilots without delay and insert the procedure into the flightcrew operational manual. A compatible temporary revision was issued to the MEL at the same time: "…in the event of a NAV IR [1, 2 or 3] FAULT (or an ATT red flag being displayed on either the captain's or first officer's primary flight display), the flight crew were required to select the air data reference (ADR) part of the relevant ADIRU OFF and then select the relevant inertial reference (IR) part of the relevant ADIRU OFF"
p. 238/313	The OEB procedure was subsequently amended in December 2008 to cater for a situation where the IR and ADR pushbuttons were selected OFF and the OFF lights did not illuminate. The new OEB (A330-74-3) required crews to select the IR mode rotary selector to the OFF position if the lights did not illuminate.
p. 238/313	Following the 27 December 2008 occurrence, the aircraft manufacturer issued another OEB (A330-74-4, 4 January 2009). This OEB provided a revised procedure for responding to a similar ADIRU-related event to ensure incorrect data would not be used by other aircraft systems. The procedure required the crew to select the relevant IR OFF, select the relevant ADR OFF, and then turn the IR mode rotary selector to the OFF position.
p. 238/313	When retrofit action has been completed, the aircraft manufacturer (in consultation with EASA) will cancel the relevant OEBs

EASA

Source	Data (Quote or Summary)
p. 238/313 Volpe Summary	EASA issued each of the Airbus OEBs as Airworthiness Directives shortly after Airbus released them.

Qantas

Source	Data (Quote or Summary)
p. 238/313 Volpe Summary	Procedural changes taken by the operator. Qantas issued Flight Standing Order 134/08 for A330 on 10/24/2008, replaced with 136/08 with material from the Airbus Operations Engineering Bulletin (OEB).
p. 238/313	In addition, program of focused training during simulator sessions and route checks was initiated to ensure that flightcrew undertaking recurrent or endorsement training were aware of the contents of the Flight Standing Order. Subsequent Flight Standing Orders were issued in response to the modified OEBs in December 2008 and January 2009.
p. 238/313	Footnote 202 During the 27 December 2008 occurrence, the flightcrew promptly applied the OEB 74-3 procedure. This procedure successfully stopped the transmission of ADR data from the affected ADIRU, but it did not stop the transmission of IR data. The revised procedure addressed this problem.

B.II US Airways 1549

Source(s)

National Transportation Safety Board (NTSB) (May 2010) *Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River US Airways Flight 1549*. Airbus A320-214, N106US. Weehawken, NJ, January 15, 2009.

Haines, T.B. (December 2022). Out of the pattern: Build new skills by flying beyond the horizon. *AOPA Pilot Magazine*, p. 18.

Default references are to the PDF file of the accident investigation (213 pp).

Numbered items are NTSB Findings.

Bulleted Summary

What happened, in brief?

The aircraft had an unexpected loss of thrust in both engines at low altitude, which resulted in a forced ditching in water.

- The aircraft was at 2800 ft altitude, 4.3 miles north of departure end of Runway 4 at LaGuardia airport (KLGA) when both engines ingested large birds in daytime visual meteorological weather conditions.
- From takeoff to "landing" in the Hudson River, the event took just under 4 minutes.
- The event had no fatalities and five serious injuries. The aircraft was, fortuitously, equipped for extended overwater flight and therefore had a life vest for each occupant; it was not required to be thus equipped.

What was/were the malfunction(s)?

Both engines failed as a result of the ingestion of birds.

- The onset of the failure was clearly indicated by the sound of the bird impacts.
- The birds were migratory Canadian geese weighing about 8 pounds each, larger than the birds used to test for engine failure.
- Birds are not normally active at such a high altitude, especially during the winter season.

Who were the flightcrew on board and what were their qualifications?

There were two experienced pilots.

- The captain was trained in the U.S. Air Force. He held a single- and multi-engine airline transport pilot (ATP) certificate, with type ratings in A320, Boeing 737, McDonnell Douglas DC-9, Learjet, and British Aerospace AVR-146 airplanes. He had over 19,000 flight hours total, and over 4700 in the A320.
- The First Officer held a multiengine ATP certificate with type ratings in A320,18 Boeing 737, and Fokker 100 airplanes. He had over 15,000 flight hours total, and 37 hours in the A320 as Second in Command.
- Other sources (e.g., Haines, 2022) mention that the captain also had glider training.

What training did the flightcrew have related to this event or malfunction specifically?

The flightcrew was not trained for dual-engine failures at low altitude. They had received training for dual-engine failure at high altitude and for ditching with a single engine operating at low altitude.

- Dual-engine failure training was provided in initial training in a full simulator session. The training assumed that the dual-engine failure occurred at high altitude and the crew had sufficient time to restart an engine.
- Ditching training was given as a set of slides that covered the QRH Ditching checklist. The scenario assumed that at least one engine was running.
- The pilots were trained to handle non-normal events in accordance with airline and Airbus procedures.
    - Because the FO had recently completed training, he immediately recognized that the event was an ECAM exception, and promptly located the QRH page with the dual-engine failure checklist.
    - There was a separate Ditching checklist, but the NTSB determined the Engine Dual Failure was the most applicable checklist and the flightcrew's decision to use it was in accordance with airline procedures.
    - Checklists for a dual-engine failure at low altitude were not readily available in the industry.

What did the flightcrew experience during the event?

The crew experienced multiple aural alerts and visual indications as they were preparing to ditch and searching visually for a landing location.

- The crew stated that they were saturated with visual cues, including looking out the window for a landing location.
- There was a visual low-speed indication that the crew missed because they were overloaded with other visual cues (e.g., engine parameters and outside visual references including buildings and bridges).
- There were 15 GPWS aural alerts generated between 300 ft to touchdown (since the crew did not disable this system). There was no low-energy aural speed warning generated. This alert is overridden when the GPWS is triggered.
- There was also one Traffic Alert and Collision Avoidance System (TCAS) alert with three aural messages, first "traffic traffic" then "monitor vertical speed," then "clear of conflict."

What did the flightcrew do in response to the malfunction(s)?

After considering a variety of landing options, the captain decided that a water landing was the safest course of action, rather than trying to reach a runway.

- The NTSB examined the crew's decision to land on the river through simulator tests. It concluded that, given a 35-second delay to account for real world conditions (to evaluate the engine situation and decide upon a course of action), the crew's decision to land on the river provided the highest probability that the accident would be survivable.
- During post-accident interviews the pilots said they did not have time to complete the second and third parts of the Engine Dual Failure checklist. Also, this checklist did not have an item telling the crew to disable the GPWS. (This item was in the Ditching checklist, however.)
- The captain started the APU by memory, earlier than it was listed in the checklist they used.
- The captain selected a flaps setting based on his experience and perception of the situation.
- The CA had difficulty maintaining his intended airspeed during the final approach.
    - The NTSB noted that the review and validation of Airbus operational procedures conducted during the ditching certification process did not evaluate whether pilots could attain all of the Airbus ditching parameters nor was Airbus required to conduct such an evaluation.
    - The NTSB concluded that during an actual ditching it is exceptionally difficult to meet such precise criteria when no engine power is available.
- The NTSB report praises the professionalism of the flightcrew and their excellent crew resource management, saying that it increased the survivability of the impact.

What else did the flightcrew do to manage the overall situation?

The crew declared issued a MAYDAY to inform ATC of the situation.

- ATC proposed landing options at nearby airports.
- The flightcrew and cabin crew prepared the cabin for an expedited evacuation.

Overview of Event

Unexpected loss of thrust in both engines of an A320 triggered by bird impact in both engines at 2800 ft altitude, 4.3 miles north of departure end of Runway 4 at LaGuardia airport (KLGA). From takeoff to "landing" in the Hudson River, the event took just under 4 minutes. There were two pilots. No fatalities; 5 serious injuries.

Flightcrew on Board

Source	Data (Quote or Summary)
Volpe Summary	There were two pilots on board. The PF was initially the first officer. After the bird impacts, the captain said "my aircraft" and became the PF.

Source	Data (Quote or Summary)
p. 18/213	According to the cockpit voice recorder (CVR) transcript, at 1524:54, the LGA air traffic control tower (ATCT) local controller cleared the flight for takeoff from runway 4. At this time, the first officer was the pilot flying (PF), and the captain was the pilot monitoring (PM).
p. 19/213	According to the CVR transcript, at 1527:10.4, the captain stated, “birds.” One second later, the CVR recorded the sound of thumps and thuds followed by a shuddering sound. According to FDR data, the bird encounter occurred when the airplane was at an altitude of 2,818 feet above ground level (agl) and a distance of about 4.5 miles north-northwest of the approach end of runway 22 at LGA. At 1527:14, the first officer stated, “uh oh,” followed by the captain stating, “we got one rol- both of ‘em rolling back.” At 1527:18, the cockpit area microphone (CAM) recorded the beginning of a rumbling sound. At 1527:19, the captain stated, “[engine] ignition, start,” and, about 2 seconds later, “I’m starting the APU [auxiliary power unit].”5 At 1527:23, the captain took over control of the airplane, stating, “my aircraft.”

Similarity of Event to Other Known Cases and Resolution

Source	Data (Quote or Summary)
p. 115/213	According to data from the FAA National Wildlife Strike Database, the accident was not a typical bird-strike event. Since 1960, 26 large-transport aircraft have been destroyed because of bird strikes worldwide, and 93 percent of these strikes occurred during takeoff or landing at an altitude of about 500 feet agl or less when the airplane was still near an airport. In contrast, the accident airplane struck birds at an altitude of about 2,800 feet agl about 4.3 miles from LGA, occurring at a higher altitude and further away from an airport than where most strikes occur.
p. 116/213	Therefore, the likelihood of an airplane striking a resident goose is substantially higher than striking a migratory goose. However, the Canada geese struck by the accident airplane were determined to be migratory geese by the Smithsonian Institute. The NTSB concludes that this accident was not a typical bird-strike event; therefore, this accident demonstrates that a bird strike does not need to be typical to be hazardous.
Volpe Summary	The likelihood of this scenario was expected to be lower than the likelihood of the scenarios the crews were trained for (i.e., dual-engine failure at high altitude, or ditching with one engine operating).

Initial and Subsequent Malfunction(s)

Source	Data (Quote or Summary)
p. 17/213	…the ingestion of large birds into each engine, which resulted in an almost total loss of thrust in both engines and the subsequent ditching on the Hudson River.

Official Statements Related to Cause

Source	Data (Quote or Summary)
p. 136/213	6. Both engines were operating normally until they each ingested at least two large birds (weighing about 8 pounds each), one of which was ingested into each engine core, causing mechanical damage that prevented the engines from being able to provide sufficient thrust to sustain flight.
p. 33/213 Volpe Summary	1.6.6.1 Bird-Ingestion Certification Requirements 1.6.6.1.1 Requirements at the Time of Certification At the time the aircraft was certified, bird-ingestion requirements required testing with ingestion of one 4-pound bird and multiple smaller birds (3 ounces or 1.5 pound).
p. 17/213 and p. 140/213	Contributing to the fuselage damage and resulting unavailability of the aft slide/rafts were (1) the Federal Aviation Administration's (FAA) approval of ditching certification without determining whether pilots could attain the ditching parameters without engine thrust, (2) the lack of industry flight crew training and guidance on ditching techniques, and (3) the captain's resulting difficulty maintaining his intended airspeed on final approach due to the task saturation resulting from the emergency situation.

Official Findings related to Training, Procedures, and Operations

Source	Data (Quote or Summary)
Starts p. 136/213	<u>Section 3.1 Findings</u> This section has a detailed list of findings, including findings related to training, procedures, and operations. We include these in the appropriate sections below, with their numbers from the report.

Source	Data (Quote or Summary)
p. 17/213 and p. 140/213	Contributing to the survivability of the accident was (1) the decision-making of the flight crewmembers and their crew resource management during the accident sequence; (2) the fortuitous use of an airplane that was equipped for an extended overwater flight, including the availability of the forward slide/rafts, even though it was not required to be so equipped; (3) the performance of the cabin crewmembers while expediting the evacuation of the airplane; and (4) the proximity of the emergency responders to the accident site and their immediate and appropriate response to the accident.

Description of Aircraft Systems and Alerts

Source	Data (Quote or Summary)
General	A320, certified for extended overwater operations (ETOPS) and ditching.
p. 68/213	The airplane was equipped with an electronic centralized aircraft monitor (ECAM) system, which presented data on the engine/warning and system display located in the cockpit. If the flight warning computer (FWC) detects an airplane system failure, the failure type and the flightcrew actions to be taken are displayed on the ECAM displays in the cockpit. In certain instances, an abnormal event cannot be sensed by the airplane's systems. For events that cannot be sensed by, or presented on, the ECAM system, pilots were to use the US Airways QRH, which contained abnormal and emergency procedures for such events. The QRH also contained six procedures, referred to as "ECAM Exceptions," which were to be used instead of the ECAM action. The back cover of the QRH listed the six ECAM exceptions and immediate action items and the page numbers where each checklist was located within the QRH.
p. 37/213	Certification for ditching is optional since not all airplane types will be used to conduct EOW operations. The accident aircraft was certificated for ditching.
p. 55/213	Footnote 72 In addition, because the airplane was used for EOW operations, it also had to meet the operational requirements of 14 CFR 121.339, "Emergency Equipment for Extended Overwater Operations," which states, in part, that an EOW-equipped airplane must be equipped with a life vest for each airplane occupant.
p. 17/213	Contributing to the survivability of the event was … (2) The fortuitous use of an airplane that was equipped for an extended overwater flight, including the availability of the forward slide/rafts, even though it was not required to be so equipped;

Flightcrew – General Experience

Source	Data (Quote or Summary)
p. 23/213	[The captain] flew McDonnell Douglas F-4 airplanes for the U.S. Air Force. At the time of the accident, he held a single- and multi-engine airline transport pilot (ATP) certificate, issued August 7, 2002, with type ratings in A320, Boeing 737, McDonnell Douglas DC-9, Learjet, and British Aerospace AVR-146 airplanes. …the captain had accumulated 19,663 total flight hours, including 8,930 hours as pilot-in-command, 4,765 hours of which were in A320 airplanes. … search of FAA records revealed no accident or incident history, enforcement action, pilot certificate or rating failure, or retest history.
p. 25/213	[The First Officer] held a multiengine ATP certificate, issued December 31, 2008, with type ratings in A320,18 Boeing 737, and Fokker 100 airplanes. …the first officer had accumulated 15,643 total flight hours, including 8,977 hours as second-in-command (SIC). The first officer had 37 hours in A320 airplanes, all as SIC. A search of FAA records revealed no accident or incident history, enforcement action, pilot certificate or rating failure, or retest history.
External Sources	Online, found that Captain Sullenberger holds a commercial pilot glider license. “Sullenberger's "C" badge is the third in a series of ABC ratings, received after gliding for at least an hour without an instructor, and landing within a relatively small area (500 ft) with an instructor.” His glider training is also mentioned in Haines, T.B. (December 2022). Out of the pattern: Build new skills by flying beyond the horizon. *AOPA Pilot Magazine*, p. 18.

Flightcrew – Training Related to Event

Source	Data (Quote or Summary)
p. 76/213	None of the contacted A320 operators included in their training curricula a dual-engine failure scenario at a low altitude or with limited time available. The A320 operators indicated that the training scenarios generally presented situations for which the course of action and landing location were clear and sufficient time was available to complete any required procedures before landing. The only low-altitude scenarios presented during training were single-engine failures at, or immediately after, takeoff. The A320 operators also indicated that dual-engine failure training was generally only provided during initial, not recurrent, training.

Source	Data (Quote or Summary)
p. 77/213	Section 1.17.3.2 Ditching Training US Airways provided ditching training during ground school. The training consisted of a PowerPoint presentation that reviewed the US Airways QRH Ditching checklist, which assumed that at least one engine was running. Ground school also included training on airplane-specific equipment; the use of slides, life vests, and life rafts; and airplane systems related to ditching. The US Airways Flight Operations Manual (FOM) TM included nonairplane-specific guidance on ditching procedures and techniques. In addition, the FOM TM addressed ditching when power was not available…[guidance follows] Ditching scenarios were not included in either the US Airways or Airbus simulator training curriculum. The US Airways ditching guidance was similar to military ditching guidance and ditching guidance contained in the FAA Aeronautical Information Manual (AIM), both of which state that, if no power is available, the approach speed used during a ditching should be greater than normal down to the flare to provide the pilot with a speed margin to break the glide earlier and more gradually, thus allowing the pilot time and distance to "feel for the surface."

Source	Data (Quote or Summary)
Starts p. 110/213)	Section 2.5.1 Dual-Engine Failure Training US Airways' dual-engine failure training, which was provided during initial training in a full-flight simulator session, was consistent with the training provided by Airbus. During informal discussions, A320 operators indicated that their dual-engine failure training was conducted at high altitudes in accordance with Airbus recommendations and industry practices. The dual-engine failure scenario was presented at 25,000 feet, included two engine restart attempts, and was considered complete after the restart of one engine, typically at an altitude from about 8,000 to 10,000 feet. During the training scenarios, at least one engine was always restarted; therefore, the pilots never reached the point of having to conduct a forced landing or ditching. No dual-engine failure training scenarios were presented at or near traffic pattern altitudes, and no scenarios were used to train pilots to conduct a possible ditching or forced landing. The scenarios were focused on restarting an engine in flight. Dual-engine failure scenarios were not presented during recurrent training. The operators revealed that the training scenarios were intended to simulate a high-altitude engine failure and train pilots on the available methods to restart an engine in flight, not to simulate a catastrophic engine failure for which a restart was unlikely. None of the contacted A320 operators included a dual-engine failure scenario at a low altitude in their training curricula. The A320 operators indicated that the training scenarios generally presented situations for which the course of action and landing location were clear and sufficient time was available to complete any required procedures before landing. The A320 operators also indicated that dual-engine failure training was generally only provided during initial, not recurrent, training.
p. 74/213	The US Airways QRH contained an Evacuation checklist, which included the following procedures for the captain: select parking brake ON, turn engine master switches 1 and 2 to OFF, and initiate the evacuation command. The checklist included the following procedures for the first officer: notify ATC; after the engine master switches are OFF, push fire (engine and APU) pushbuttons; and discharge fire agents, if required. The procedures further stated that, after all possible assistance has been rendered, the captain and first officer should leave the airplane by any suitable exit and direct passengers away from the airplane.

Training Suggestions from NTSB Report

Source	Data (Quote or Summary)
p. 111/213	The NTSB is concerned that pilots are not taught how to handle low-altitude abnormal events or to use critical thinking, task shedding, decision-making, and proper workload management to achieve a successful outcome when such events occur.
p. 138/213	(21) Training pilots how to respond to a dual-engine failure occurring at a low altitude would challenge them to use critical thinking and exercise skills in task shedding, decision-making, and proper workload management to achieve a successful outcome.
p. 138/213	(22) The flightcrewmembers would have been better prepared to ditch the airplane if they had received training and guidance about the visual illusions that can occur when landing on water and on approach and about touchdown techniques to use during a ditching, with and without engine power.
p. 138/213	(24) Training pilots that sidestick inputs may be attenuated when the airplane is in the alpha-protection mode would provide them with a better understanding of how entering the alpha-protection mode may affect the pitch response of the airplane.

Flight Deck Alerts During the Event

Source	Data (Quote or Summary)
p. 29-30/213	1.6.4 Low-Speed or -Energy Warning The A320 also incorporated an aural warning, which was available when the airplane was operating in normal law, to enhance the pilot's awareness of a low-speed or -energy condition. This warning is only available when the airplane is in CONF 2, CONF 3, or full flaps. The Airbus FCOM states the following An aural low-energy "SPEED SPEED SPEED" warning, repeated every 5 seconds, warns the pilot that the aircraft's energy level is going below a threshold under which he will have to increase thrust, in order to regain a positive flight path angle through pitch control. However, the low-energy warning is overridden when the airplane is below 100 feet radio altitude or when a GPWS alert is triggered. According to CVR and FDR data, GPWS alerts were triggered repeatedly during the descent, and no low-energy level alert was generated.

Source	Data (Quote or Summary)
p. 107/213	1.3.3 Descent and Ditching Airspeed To alleviate a pilot being overloaded by aural warnings, Airbus designed alert prioritizations to determine when cues are made available to pilots. However, in this accident, the low-speed warning was inhibited by the GPWS warnings, so that the flightcrew was not made aware of the low-speed state. (See section 2.6.1.) Although a visual low-speed indication was available on the airspeed tape, the NTSB acknowledges that the flight crewmembers were overloaded with other visual cues (for example, engine parameters and outside visual references, such as buildings and bridges), which might have affected their ability to continuously monitor the airspeed tape. *Volpe Comment: The NTSB report does not mention an overload of warning lights or visual alerts.*
p. 113/213	Under normal circumstances, the black and amber strip is sufficient to alert pilots visually that they have entered alpha-protection mode. However, in emergency situations, when visual resources are overloaded, pilots may inadvertently overlook the airspeed tape.
p. 114/213	Although the A320 airplane does not provide tactile cues that a low-speed or -energy condition exists, it does have an aural speed warning, which repeats every 5 seconds and is available when the airplane is configured with full flaps, flaps 2, or flaps 3. However, the system is designed such that the warning is inhibited when the airplane is below 100 feet radio altitude or when a GPWS alert is triggered. The A320 was designed with an alert prioritization hierarchy that considered inputs from various airplane systems, including the GPWS, FWC, TCAS, and radar and the GPWS-triggered alerts had priority over a low-speed warning. CVR and FDR data indicated that 15 GPWS alerts were triggered during the descent from 300 feet to touchdown and that no low-speed aural alert was triggered during this time. Considering the alert prioritization hierarchy, low-speed warnings were likely inhibited by the GPWS alerts. *Volpe Comment: The dual-engine failure checklist the crew used did not have a step telling them to disable the GPWS alerts.*
p. 136/213	If the accident engines' electronic control system had been capable of informing the flight crewmembers about the continuing operational status of the engines, they would have been aware that thrust could not be restored and would not have spent valuable time trying to relight the engines, which were too damaged for any pilot action to make operational. *Volpe Comment: There was no message to inform pilots that the engines were too damaged to restart. See (7) under Procedures below.*

Source	Data (Quote or Summary)
p. 192-193/213	Volpe Summary from CVR transcript. There was a one TCAS alert with three aural messages, first “traffic traffic” then “monitor vertical speed,” then “clear of conflict.”

Flightcrew Responses to Alerts

General

Source	Data (Quote or Summary)
p. 68-69/213	The US Airways A319/320/321 Pilot Handbook (PH), Chapter 9, “Non-Normal Operations,” contains non-normal procedures and methodology. The PH states, in part, that, when a non-normal situation is evident, the pilots should methodically accomplish the following steps: 1. PF - maintain aircraft control; 2. Identify the non-normal situation, PM - cancel the warning or caution, if applicable; 3. PM - determine if situation requires an Immediate Action or if it is an ECAM Exception; 4. PM - accomplish Immediate Action Items, if applicable; 5. Captain - assigns PF; 6. PM - accomplish non-normal procedure; and 7. PM - accomplish ECAM followup procedures, if applicable.
p. 69/213	The expanded step 3 items stated that, once the airplane flightpath and configuration are properly established and the airplane is not in a critical phase of flight (for example, takeoff or landing), the PM should determine and verbalize whether the non-normal situation is an immediate action item or an ECAM exception and refer to the immediate action and ECAM exception indexes on the back cover of the QRH. The ECAM exception index indicated that a dual-engine failure was an ECAM exception and directed the PM to the Engine Dual Failure checklist procedures contained in the QRH.
p. 68/213	Footnote 90 The US Airways QRH was developed in accordance with the Airbus QRH
p. 93/213	Section 1.18.5 NASA Research on the Challenges of Abnormal and Emergency Situations Footnote 127 See B.K. Burian, I. Barshi, and K. Dismukes, *The Challenge of Aviation Emergency and Abnormal Situations*, NASA Technical Memorandum 2005-213462 (Moffett Field, California: National Aeronautics and Space Administration, 2005).

Procedures

Source	Data (Quote or Summary)
p. 136/213	(7) If the accident engines' electronic control system had been capable of informing the flight crewmembers about the continuing operational status of the engines, they would have been aware that thrust could not be restored and would not have spent valuable time trying to relight the engines, which were too damaged for any pilot action to make operational.
p. 138/213	(25) The review and validation of the Airbus operational procedures conducted during the ditching certification process for the A320 airplane did not evaluate whether pilots could attain all of the Airbus ditching parameters nor was Airbus required to conduct such an evaluation.
p. 138/213	(26) During an actual ditching, it is possible but unlikely that pilots will be able to attain all of the Airbus ditching parameters because it is exceptionally difficult for pilots to meet such precise criteria when no engine power is available, and this difficulty contributed to the fuselage damage.

Checklists

Source	Data (Quote or Summary)
p. 69/213	Engine Dual Failure checklist was originally developed "based on the highest probability in time of exposure that a dual engine failure would occur." Because Airbus airplanes spend much more time at higher altitudes and, therefore, a dual-engine failure had the highest probability of occurring at a high rather than a low altitude, Airbus designed the Engine Dual Failure checklist for the occurrence of a dual-engine failure above 20,000 feet.
p. 76/213	The discussions with A320 operators also indicated that low-altitude, dual-engine failure checklists are not readily available in the industry.
p. 69/213	The first officer indicated that, because he had just completed training, he immediately recognized that the event was an ECAM exception; therefore, he was able to promptly locate the procedure listed on the back cover of the QRH, turn to the appropriate page, and start executing the checklist. *Volpe Comment: Maybe an example of resilient pilot behavior*
p. 110/213	The NTSB recommends that the FAA develop and validate comprehensive guidelines for emergency and abnormal checklist design and development.

Source	Data (Quote or Summary)
p. 114/213	NTSB recommends that the FAA require Airbus operators to amend the ditching portion of the Engine Dual Failure checklist and any other operators to amend the ditching portion of the Engine Dual Failure checklist and any other applicable checklists to include a step to select the GPWS and terrain alerts to OFF during the applicable checklists to include a step to select the GPWS and terrain alerts to OFF during the final descent.
p. 114/213	The NTSB acknowledges that the flightcrew did not have sufficient time to accomplish the ditching portion of the Engine Dual Failure checklist. Regardless, the NTSB believes that the ditching procedures should be consistent in all applicable checklists.
p. 137/213	(12) Although the Engine Dual Failure checklist did not fully apply to the accident event, it was the most applicable checklist contained in the quick reference handbook to address the event, and the flightcrew's decision to use this checklist was in accordance with US Airways procedures.
p. 137/213	(13) If a checklist that addressed a dual-engine failure occurring at a low altitude had been available to the flightcrewmembers, they would have been more likely to have completed that checklist.) *Volpe Comment: A checklist that did not exist*
p. 137/213	(14) Despite being unable to complete the Engine Dual Failure checklist, the captain started the auxiliary power unit, which improved the outcome of the ditching by ensuring that a primary source of electrical power was available to the airplane and that the airplane remained in normal law and maintained the flight envelope protections, one of which protects against a stall. *Volpe Comment: Captain turned on the APU by memory. It was listed later in the checklist, but he turned it on earlier. Example of resilient behavior.*
p. 138/213	(20) Comprehensive guidelines on the best means to design and develop emergency and abnormal checklists would promote operational standardization and increase the likelihood of a successful outcome to such events.
p. 138/213	(23) The guidance in the ditching portion of the Engine Dual Failure checklist is not consistent with the separate Ditching checklist, which includes a step to inhibit the ground proximity warning system and terrain alerts.

Flightcrew Task Management

Source	Data (Quote or Summary)
p. 137/213	(15) The captain's decision to ditch on the Hudson River rather than attempting to land at an airport provided the highest probability that the accident would be survivable.
p. 137/213	(19) The professionalism of the flight crewmembers and their excellent crew resource management during the accident sequence contributed to their ability to maintain control of the airplane, configure it to the extent possible under the circumstances, and fly an approach that increased the survivability of the impact.
p. 58/213	The captain and first officer assisted the flight attendants with the evacuation of the airplane. The captain stated in interviews that he and the first officer noted that a number of passengers had evacuated the airplane without life vests; therefore, they obtained some life vests from under the passenger seats in the cabin and passed them out to passengers outside of the airplane. He further stated that, following the evacuation, he and the first officer inspected the cabin to ensure that no more passengers or crewmembers were on board. Subsequently, the captain and first officer exited the airplane onto the 1L slide/raft.

Communications

Source	Data (Quote or Summary)
p. 19/213	Footnote 7 The "mayday, mayday, mayday" portion of the captain's statement was not transmitted to the air traffic controller because another pilot was transmitting on the same frequency at the same time.
p. 106/213	During the emergency, the flightcrew was faced with a series of GPWS and TCAS aural alerts and many ATC communications, which can also present distractions during an emergency.
Starting p. 186 Volpe Summary	CVR transcript, starting from sound of bird impacts ATC conveyed various landing options at LGA and TEB. There were no irrelevant remarks, queries, or instructions.

Source	Data (Quote or Summary)
p. 21/213 Volpe Summary	Footnote 14 Just before ditching, the flight crew confirmed that they had activated the cabin emergency notification switch, which provides a signal to the cabin crewmembers indicating that an emergency has occurred. Within seconds after the ditching, crewmembers and passengers began the evacuation on the Hudson River.

Timeline

Source	Data (Quote or Summary)
Starting on p. 186 Volpe Summary	CVR transcript, starting from sound of bird impacts From sound of bird impacts (just after 1527:10.4) to ditching in the river (CVR recording ended at 1530:43.7), time elapsed was just over 3.5 minutes. (Volpe Summary)
p. 67/213	In post-accident simulations, pilots who were fully briefed on the maneuver were able to turn immediately and land on a runway successfully, but not when they were given a 35 second delay; that landing was unsuccessful. Footnotes 88 and 89: 88 - The immediate turn made by the pilots during the simulations did not reflect or account for real-world considerations, such as the time delay required to recognize the bird strike and decide on a course of action. 89 - The 35-second delay accounted for real-world considerations, such as the time delay required to recognize the extent of the engine thrust loss and decide on a course of action.
p. 70/213	During post-accident interviews, the pilots stated that, because of the low altitude and limited time available, they were unable to initiate Parts 2 and 3 of the Engine Dual Failure checklist.

Operations

Source	Data (Quote or Summary)
p. 137/213	(15) The captain's decision to ditch on the Hudson River rather than attempting to land at an airport provided the highest probability that the accident would be survivable. *Volpe Comment: Resilient behavior; assessing risky tradeoffs and making sacrificing decision.*

Source	Data (Quote or Summary)
p. 137/213	(16) The captain's difficulty maintaining his intended airspeed during the final approach resulted in high angles-of-attack, which contributed to the difficulties in flaring the airplane, the high descent rate at touchdown, and the fuselage damage.
p. 137/213	(17) The captain's difficulty maintaining his intended airspeed during the final approach resulted, in part, from high workload, stress, and task saturation.
p. 137/213	(18) The captain's decision to use flaps 2 for the ditching, based on his experience and perception of the situation, was reasonable and consistent with the limited civilian industry and military guidance that was available regarding forced landings of large aircraft without power. *Volpe Comment: Resilient behavior; continuous risk assessment; sacrificing decision*
p. 137/213	(19) The professionalism of the flight crewmembers and their excellent crew resource management during the accident sequence contributed to their ability to maintain control of the airplane, configure it to the extent possible under the circumstances, and fly an approach that increased the survivability of the impact. *Volpe Comment: Resilient behavior, crew coordination*
p. 74/213	The pilots stated in interviews that, after the ditching, the first officer initiated the Evacuation checklist. The captain stated that he considered completing his part of the checklist but that he realized that the items would not help the situation. He stated that he could not make an announcement over the PA system because of the loss of electrical power after the ditching,[99] so he opened the cockpit door and issued a verbal "evacuate" command. He added that, when he exited the cockpit, the cabin crew had already started evacuating passengers from the airplane. [99]According to Airbus, the [public address] PA system is designed to function under these circumstances.

NTSB Official Safety Recommendations

Source	Data (Quote or Summary)
Starting on p. 141/213	4. Safety Recommendations There are several for the FAA, and some for other agencies, including EASA. The status of the Safety Recommendations is tracked here: DCA09MA026.aspx (ntsb.gov).
Volpe Summary	The FAA declined to implement several of the recommendations, including revisions to the checklists and guidance for approving checklists (A-10-66, A-10-67, and A-10-68) so these actions were marked as "closed – unacceptable" by NTSB. (The FAA cited Information for Operators (InFO) memorandum 10002, "Industry Best Practices Reference List," which is out of date and not easy to locate.)

Source	Data (Quote or Summary)
Volpe Summary	A-10-68 requested development of "comprehensive guidelines for emergency and abnormal checklist design and development." It was closed in 2012 because the FAA essentially said that memory items on checklists are necessary for the most time-critical situations. FAA guidelines to have three or fewer memory items is in AC 120-71B, which was published in 2017.
Volpe Summary	For A-10-73, NTSB writes to the FAA: We note that on January 5, 2016, you issued Notice N8900.339, "Actions Required to Identify and Correct Discrepancies Between Airplane Flight Manuals and Flight Deck Quick Reference Handbooks." The notice alerts principal operations inspectors (POIs) that discrepancies may exist between some AFMs and their associated QRHs, and directs the POIs to review the QRHs for compliance with the FAA-approved abnormal/emergency procedures checklists found in the AFMs. The notice also defines POI actions in the event that discrepancies are found. Although the notice expires on January 5, 2017, we note that, on March 15, 2016, FAA Order 8900.1, "Flight Standards Information Management System," volume 3, chapter 3, sections 5 and 12, was revised to include the guidance contained in the notice.

B.III Qantas 32

Source(s)

ATSB (27 June 2013) In-flight uncontained engine failure - overhead Batam Island, Indonesia – 4 November 2010 – VH-OQA, Airbus A380-842. (Report No. AO-2010-089)

Book by captain:

de Crespigny, R. & M. Abernathy. (2012). QF32. http://qf32.aero

Default references are to the accident investigation PDF file (305 pp). References to the book material are Volpe summaries unless inside quotation marks.

Bulleted Summary

What happened, in brief?

One of four engines failed on climb out, damaging the aircraft structure and systems. There were multiple ECAM actions from the initial failure through the landing and evacuation.

- A sudden engine fire/failure in Engine 2 (left side, inboard) occurred about 6 minutes out of Singapore airport while climbing out of 7000 ft altitude.
- The crew actioned initial ECAM messages for 50 minutes while holding near the airport.
- Although the aircraft suffered significant damage to its structure and systems, the crew was able to continue safe flight to landing back at the departure airport.
- The flight landed 1 hour and 50 min after the failure. The crew was unable to shut down Engine 1 after landing, so evacuation on the runway was delayed another 50 min.
- There were no injuries to the crew or passengers.
- Because of the long duration of the event, the flight deck voice recording did not capture the beginning of the event; the recording was limited to 2 hours.

What was/were the malfunction(s)?

The initial uncontained engine malfunction caused malfunctions of many critical systems.

- It is not clear how to count the number of malfunctions; the first malfunction caused several others.
- The investigation found that the intermediate pressure turbine disc of Engine 2 burst into a least three main fragments that penetrated the leading edge of the left wing and spar as well as the fuselage belly fairing.
- Damage to the wiring looms in the left wing and belly fairing resulted in the loss of a number of redundant systems, including damage to the fuel system, loss of fire protection and means of shutting down Engine 1, loss of function of the Green hydraulic system, and loss of the fuel transfer system.
- There were also several problems that resulted in an abnormal landing configuration, which in turn affected the landing-distance calculation. The landing distance performance software was overly conservative and needed to be revised for landings with multiple system failures

Who were the flightcrew on board and what were their qualifications?

There were five pilots working together in the flight deck (the CA, FO, SO, Check Captain, and Supervising Check Captain), all of whom were highly experienced.

- The CA had over 15,000 flight hours; FO had over 11,000 flight hours; the SO had over 8,000 flight hours; the Check CA had over 20,000 flight hours; the Supervising Check CA had over 17,000 flight hours. All of them also had type ratings on both Boeing and Airbus aircraft.
- The ASTB determined that the additional flightcrew on the flight deck were a valuable resource because they gathered information that assisted in decision making. Had they not been present, the safety of flight would not have been affected, but the airborne time may have been prolonged, and the primary crew may have shed tasks that were not essential to flight safety.
- The CA's book mentions that he had previous experience with handling in-flight engine failures (on three separate occasions), military flight experience, and experience as a test pilot. He also had experience as a software developer outside of his flying duties.

What training did the flightcrew have related to this event or malfunction specifically?

The flightcrew operated in accordance with standard operating procedures and practices.

- They followed the ECAM procedures as described in the Flight Crew Training Manual (FCTM) – Operating Philosophy. For example, the FCTM indicated that if an ECAM messages disappeared before they could action the procedure, or while they were actioning the procedure, the crew could consider that warning or caution as no longer applicable.
- The pilot who was not handling the aircraft controls managed the ECAM procedures and sought confirmation from the PF as required.

What did the flightcrew experience during the event?

The event began suddenly with two coincident loud bangs, and then multiple ECAM warnings and cautions.

- The crew was not aware of the extent of the damage during the event.
- Passengers saw a fuel leak from Engine 2 and the company received messages from Airborne Communication Addressing and Reporting System (ACARS).
- Multiple ECAM warnings and cautions notified the crew of other failures after the initial failure.
    - For example, Engines 1 and 4 were operating in a degraded mode, the Green hydraulic system had low system pressure and low fluid level, flight controls were operating in alternate law, wing slats were inoperative and many other problems.
    - As part of the investigation, Airbus determined that all these warnings were valid.

What did the flightcrew experience during the event? (continued)

- The ECAM includes four master warning and caution lights and four loudspeakers.
  - Each warning is annunciated by an audio alert, a visual alert, a local light and/or the automatic display of the applicable system page.
  - When many ECAM messages are generated, the priority logic ensures that the most important messages are shown first. Less important messages may not be visible in the queue, due to the length of the more important procedures.
- During the final approach, three flight envelope protection alerts were activated.
  - The first two were low energy aural alerts: SPEED SPEED.
  - The third warning was for stall associated with the AOA at 3 ft Radio Altimeter altitude, just prior to touchdown.
  - All three warnings were found to be genuine in the post-accident analysis.
- After the aircraft landed and its speed went below 80 kts, several ECAM messages that were previously inhibited were displayed.

What did the flightcrew do in response to the malfunction(s)?

The crew took approximately 50 minutes to complete the initial procedures associated with the ECAM messages. After doing so, they prepared for landing and performed the approach and landing.

- Immediately upon failure of the engine, the captain selected altitude and heading hold mode on the autoflight system control panel in order to reduce thrust on the engines. He wanted to reduce thrust to reduce stress on the engines and airframe. He noticed that the autothrust system was no longer active, so he manually retarded the thrust levers instead.
- The flightcrew discussed the available options early on, including an immediate return to Singapore, climbing, or holding.
  - Because the aircraft remained controllable and there was ample fuel on board, they decided to hold at the present altitude while they processed the ECAM messages and procedures.
  - The flightcrew recalled frequently reviewing this decision and assessing the amount of fuel on board.
- The ATSB report contains a reconstructed ECAM sequence based upon the crew's recollection and other documentation.
  - At first, the Engine 2 warnings changed between overheat and fire. When the crew deployed the fire extinguisher, they did not receive confirmation that it had discharged, twice.
  - A number of ECAM procedures were recorded on more than one occasion during the sequence as a result of the particular ECAM being marked as RESET before the triggering conditions reoccurred.

What did the flightcrew do in response to the malfunction(s)? (continued)

- When the crew noticed that the Yellow hydraulic system was affected, but all the damage was on the left side of the aircraft (where the Green hydraulic system was located), they questioned the validity of the ECAM messages.
    - The crew reported that after assessment of multiple fuel system ECAM messages, they elected not to further transfer fuel because they were unsure of the integrity of the fuel system.
    - The investigation concluded that had the crew initiated this fuel transfer, approximately half the fuel in the trim tank would have been lost due to transfer to the damaged tank.
- The crew manually selected the APU page and started the unit roughly 45 minutes after the engine failure.
    - After the APU was running, the crew manually selected system display pages (rather than following an ECAM suggested sequence).
    - The crew was trying to understand what damage had occurred and what systems were still functional.
- Due to the many failures associated with the flight controls (i.e., ailerons, spoilers, and wing slats), and the inability of the crew to view these controls from the flight deck, the only way the crew could determine whether the aircraft was controllable was to monitor the displayed deflection of the flight control on their systems page as they maneuvered the aircraft.
- The crew manually selected various system pages to determine whether the aircraft was controllable as they reconfigured it for landing.
- The crew identified the overly conservative landing calculations and used their own judgement to modify the calculations to get a better estimate of the landing distance.
- During the approach, after the autopilot disconnected for the second time (at about 800 ft) the captain elected to leave it disconnected and manually fly the aircraft.
- The CA responded appropriately to the SPEED alert during final approach by adding thrust.
- After landing, only one VHF radio was working, so the pilots used mobile phones to seek assistance in shutting down Engine 1.
- The ATSB concurred with the crew's decision to wait for disembarkation by stairs as it likely provided the safest option.

What else did the flightcrew do to manage the overall situation?

The flightcrew initially focused their attention on the ECAM actions and later communicated with the cabin crew, ATC, passengers, and others.

- The flightcrew declared PAN PAN to ATC during the first 30-second monitoring period for the engine restart.
- The flightcrew was busy managing ECAM messages initially.
    - The cabin crew could not reach the flightcrew even with the "emergency" selection on the cabin phone system. The crew received an aural that sounded like the flight deck horn and they associated that aural with the ECAM warnings instead of the cabin crew, so they canceled it. This was not unsafe, but it delayed communication with the cabin.
    - The operator also attempted to contact the flightcrew through ACARS, but the flightcrew only had time to acknowledge, but not respond, to the operator's message.
- As the event progressed, the flightcrew made several public address announcements to keep the cabin crew and passengers informed.
- The operator's customer service manager and the cabin crew were also informed to prepare for the possibility of a runway overrun and evacuation.
- The flightcrew advised ATC that they would require emergency services on the ground and that fuel was leaking from the left wing.
- The flightcrew was performing at the level of a competent team, including in its interactions with cabin crew and passengers.

Overview of Event

A sudden engine fire/failure in Engine No. 2 occurred about 6 minutes out of Singapore (Changi) airport while climbing out of 7000 ft. The failure damaged the aircraft structure and multiple systems. The crew was able to continue safe flight to landing back at departure airport. They actioned initial ECAM messages for 50 minutes while holding near the airport. The aircraft landed 1 hour and 50 minutes after the failure. The crew as not able to shut down Engine No. 1 after landing, so the evacuation on the runway was delayed another 50 minutes. There were no injuries to the crew or passengers.

Source	Data (Quote or Summary)
p. 151/305	Although there was significant damage to the aircraft structure and systems, the aircraft was capable of continued safe flight and landing. Furthermore, the flightcrew operated in accordance with standard operating procedures and practices. Therefore, this analysis is focused on the failure of the No. 2 engine and the factors that lead to the failure.
p. 48/305	There were no injuries as a direct result of the uncontained engine failure and the cabin environmental systems remained functional during the occurrence and return to Changi Airport.

Source	Data (Quote or Summary)
p. 37/305	No significant weather was observed within the vicinity of the airport. Weather radar images indicated that there were no areas of precipitation between Singapore and Batam Island during the occurrence. The flight crew reported weather conditions that were consistent with the recorded data, and that the flight was conducted in visual conditions.

Flightcrew on Board

Source	Data (Quote or Summary)
Volpe Summary	There were five pilots working together in the flight deck. The five pilots were: Captain, First Officer (FO), Second Officer (SO), Check Captain, and Supervising Check Captain. The role of the Check Captain is to monitor the captain's performance for a proficiency check. The role of the Supervising Check Captain is to monitor the performance of the Check Captain, who was also in training (de Crespigny, p. 139-140).

Similarity of Event to Other Known Cases and Resolution

Source	Data (Quote or Summary)
Volpe Summary	<u>Section 7.2 Subsequent safety actions</u> Upon inspection of the engine failure, it was determined that the component that failed had a quality control problem. Numerous other engines within the Trent 900 fleet were also found to contain a critical reduction in the oil feed stub pipe wall thickness. The design specification for the wall thickness was increased. Quality control processes were also improved at a subcontractor for the engine manufacturer.
p. 173/305	As a result of this action, 40 engines were removed from service having been identified with an oil feed stub pipe wall thickness of less than 0.5 mm.
p. 179/305	The calculation method in the aircraft manufacturer's landing distance performance application was overly conservative and this could prevent the calculation of a valid landing distance at weights below the maximum landing weight with multiple system failures. Airbus has developed a product improvement with the in-flight landing distance application…

Initial and Subsequent Malfunction(s)

Source	Data (Quote or Summary)
Volpe Summary	Appendix B: Detailed Damage Description There was an uncontained engine rotor failure (UERF) due to a manufacturing issue. The intermediate pressure turbine disc separated from its shaft. The aircraft sustained damage from a large number of disc fragments, affecting its structure and many systems and backups to those systems. The event began with Engine fire/failure (Engine No. 2, left side towards fuselage). There was a clear and sudden onset of the problem. The crew heard two coincident loud bangs. Passengers saw the fuel leak. ACARS messages were received by company systems.
p. 201/305	Figure B1: Trajectory of the major disc segments. Two main fragments impacted the wing. A smaller, high energy fragment followed a different ballistic trajectory and penetrated the fuselage belly fairing structure.
p. 25/305	The inoperative wing leading edge lift devices, reduced braking function, reduced number of operational spoilers and inactive left engine thrust reverser resulted in an abnormal landing configuration, which in turn affected the landing distance calculation.
p. 201-202/305	Damage to wiring looms located in the left wing and the fuselage belly fairing resulted in the loss of a number of redundant systems that used segregated control wiring. Those systems included: • loss of the fuel isolation valves (LPSOV) for the No. 1 and No. 2 engine, • loss of the fire protection system for the No. 1 engine • all means of shutting down the No. 1 engine • loss of function of the Green hydraulic system • loss of fuel transfer system.
p. 249/305	Damage to the fuel system resulted in [among other items]: • the restriction of the trim tank fuel transfer capability to the manual transfer of fuel to the inner feed tanks after the provision of a low fuel warning to the crew. Had the flightcrew initiated this procedure, approximately half of the fuel in the trim tank would have been lost due to its transfer to the damaged Feed Tank 2. *Volpe Comment: Crew judgement; resilient behavior.*

Source	Data (Quote or Summary)
p. 31-32/305	The following systems were affected either as a direct result of the damage from the engine failure, or due to actions taken by the flightcrew as part of the ECAM procedures: Hydraulic power, as a result of: — the loss of function to the aircraft's green hydraulic system — reduced redundancy within the aircraft's other (yellow) hydraulic system. Electrical power, resulting from: — a loss of electrical power generation at engines No. 1 and 2 — the loss of one of the aircraft's four alternating current (AC) systems — the inability to connect the aircraft's auxiliary power unit (APU) generators on the ground. Flight controls, through: — reduced aileron and spoiler function — the loss of wing leading edge slats and droop nose function. Engine control, as a result of: — loss of autothrust function — reduction in the automatic control function to engines No. 1, 3 and 4. The landing gear normal extension function was no longer available. Braking, through a: — reduction of function in the right wing gear brakes (including anti-skid) — loss of function to the left wing gear brakes. Partial loss of bleed air, resulting from damage to the: — left wing system ducting — APU bleed air ducting. Fuel system, resulting from: — fuel leakage from the No. 2 engine feed tank — a loss of function to the engines No. 1 and 2 low pressure fuel shutoff valves — the loss of function to the No. 1 engine high pressure shutoff valve — loss of function of numerous fuel system components (valves and/or pumps) — degradation of the fuel quantity management system — a reduction in capability of the automatic and manual fuel transfer function — disabling the fuel jettison system. Engine fire protection, as a result of a loss of function to one of the two extinguisher bottles in engines No. 1 and 2.

Official Statements Related to Cause

Source	Data (Quote or Summary)
p. 5/305	…sustained an uncontained engine rotor failure (UERF) of the No. 2 engine, a Rolls-Royce Trent 900. Debris from the UERF impacted the aircraft, resulting in significant structural and systems damage.
p. 163-165/305 Volpe Summary	Section 6.1 Contributing Safety Factors. This section describes three items, none of which are related to flightcrew performance. Section 6.2 Other Safety Factors This section has three additional items, one of which is related to flightcrew performance, Section 6.2.3, on the landing distance performance application (see full quote below, from p. 165/305).

Official Findings related to Training, Procedures, and Operations

Source	Data (Quote or Summary)
p. 58/305	Although the additional flightcrew were a valuable resource, had they not been available the primary flightcrew would have likely responded to the situation in a similar manner. However, the gathering of information to assist in decision making would have required the use of alternative resources and methods. This may have resulted in prolonging the airborne time before landing or it is also possible that the flightcrew may have shed tasks not essential to flight safety. This was unlikely to have affected the safety of the flight because the crew's training and the aircraft manufacturer's procedures required them to complete prescribed tasks before attempting to land.
p. 165/305	Section 6.2.3 Landing distance performance application. The calculation method in the aircraft manufacturer's landing distance performance application was overly conservative and this could prevent the calculation of a valid landing distance at weights below the maximum landing weight with multiple system failures. [Safety issue]
p. 166/305	Section 6.3 Other Key Findings The crew's decision to perform a precautionary disembarkation via the stairs likely provided the safest option, particularly given the low immediate safety threat and the elevated risks associated with an emergency evacuation into a potentially hazardous external environment. *Volpe Comment: Crew judgement; resilient behavior.*

Description of Aircraft System and Alerts

Source	Data (Quote or Summary)
General	A380, Four engines. ECAM.
p. 187/305	ECAM Alerts There were three levels of warnings and cautions within ECAM, each based upon the associated operational consequences of the detected failure. These levels of failure included: • Level 3 – the highest level of failure indicating an impact on the safety of the aircraft. This failure indication was colour coded red and had an associated aural warning (master warning). The recommended crew action was to respond immediately to the warning. • Level 2 – this failure indication defined an abnormal condition to the crew. It was colour coded amber with a different aural warning to that of a Level 3 failure (master caution). The recommended crew action was to be aware of the condition and then take appropriate action. • Level 1 – defined as a degradation in an aircraft system, this failure indication was also colour coded amber but there was no associated aural warning (master caution visual only). The recommended crew action was to be aware of the condition. When multiple failures or out-of-limits conditions were detected by ECAM they were prioritised according to the programmed ECAM logic. In that event, the highest priority procedure relating to the sensed condition was displayed first. When ECAM detects multiple system failures and has displayed them to the crew (abnormal procedure), the in-built ECAM logic meant that the crew are presented with the most important procedures first. Airbus operational philosophy means that each abnormal procedure, in order of importance, has to be completed by the flightcrew before they move onto the next procedure. If the flightcrew were attending to a lower priority ECAM, a higher priority ECAM would cease that procedure and display the higher priority ECAM for action. If an ECAM message disappeared either before the crew could action the procedure or while they were actioning the procedure, the Flight Crew Training Manual (FCTM) – Operating Philosophy – Abnormal operations and ECAM section indicated that the crew could consider that the warning or caution was no longer applicable.

Source	Data (Quote or Summary)
p. 185/305	ECAM integrates this information from a number of onboard systems, including (Figure A3): • two flight warning systems (FWS) • one ECAM control panel (ECP) • four master warning and caution lights • four loudspeakers. The information is displayed to the crew via the: • EWD for normal checklists, abnormal and emergency procedures, aircraft limitations and memos
p. 186/305	To minimise distractions during specific important flight phases (such as during takeoff and the initial climb), many abnormal and emergency procedures detected by ECAM are inhibited from being displayed. There are 12 separate flight phases on the A380, commencing when electrical power is first switched on and ending 5 minutes after the last engine is shut down at the end of the flight. [Certain flight phases can inhibit the warning. See footnote 109]
p. 191/305	When a large number of ECAM messages are generated, the priority logic ensures that the crew see the most important ones first. Less important ones may be at the end of the queue and therefore not initially visible to the crew due to the length of the preceding procedures on the ECAM display.
p. 52/305	The onboard information system (OIS) could be operated through an onboard information terminal (OIT) that was incorporated into the captain’s and first officer’s instrument panels, or through synchronised laptop computers stowed at each of the flightcrew stations (Figure 24). The OIS included an operations library application that supported a complete suite of aircraft operations documentation, navigation charts, and performance applications. The performance applications enabled the flightcrew to determine aircraft performance data including take-off and landing data. The program for determining landing performance was referred to as the landing performance application (LPA). Certain OIS functions, including the LPA, were also available on a third laptop computer stowed at the rear of the cockpit.
de Crespigny p. 119	“On the A380 the flight control computers (FCCs) are designed so there’s always at least one of the seven computers in control.” “Hundreds of computers monitor 250,000 sensors throughout the plane.”

Source	Data (Quote or Summary)
de Crespigny p. 120-121	"If an A380 engine fails after getting airborne, and the pilots keep their hands off the sidesticks, the FCCs automatically introduce rudders to balance the aircraft, and ailerons to stop it rolling, and the aircraft flies away beautifully with a small 5-degree roll and a bit of drift. The FCCs could have been designed to fly the aircraft through the failure without yaw or a heading change, but in this case, the pilot might not even recognize the engine failure and might have trouble identifying the failed engine."
de Crespigny p. 122	"The ECAM system only ever gives the flight crew a simplified or 'veiled' version of what is actually going on in the aircraft…" "…there is enough information to overwhelm a pilot…an engineer told me that Airbus computers only every allow the pilot to see 15 per cent of the information."
de Crespigny p. 255	The book describes the laptop for the landing calculations: "These laptops are stored on either side of the two pilots and are connected to the aircraft's networks by a 2 metre-long umbilical cord." *Volpe Comment: Figure 24 in accident report (p. 52/305) shows built-in devices to the sides, but the pilots who used the laptops to compute landing performance were the check airmen, one seated in the SO position.*

Flightcrew – General Experience

Source	Data (Quote or Summary)
p. 34-35/305 Volpe Summary	CA had 15,140.4 flight hours total; 570.2 in the A380. CA held an Airline Transport Pilot (Aeroplane) Licence (ATPL(A)) and was endorsed on and operated Boeing 747, 747-00, and Airbus 330 aircraft. FO had 11,279.5 flight hours total; 1,271.0 in the A380. The FO held an ATPL(A) and was endorsed on and had operated Boeing 747, 767, Airbus A330 and A340 aircraft. SO had 8,153.4 flight hours total; 1,005.8 in the A380. The SO held an ATPL(A) and was endorsed on and had operated Boeing 747 aircraft. Check Captain had 20,144.8 flight hours total; 806.4 in A380. The check captain held an ATPL(A) and was endorsed on and had operated Boeing 747, 747-400 and 767 aircraft. Supervising Check Captain had 17,692.8 flight hours; 1,345.9 in A380. The supervising check captain held an ATPL(A) and was endorsed on and had operated Boeing 747, 747-400, 767 and Airbus A330 aircraft

Source	Data (Quote or Summary)
de Crespigny various pages	CA had 35 years of flight experience (p. 167). The CA had experienced three engine failures as a crewmember and two as a passenger (p. 102). The CA had military flight experience, and experience as a test pilot. He was the second Qantas pilot trained on the A380 (p. 131). He also had experience as a software developer outside of his flying duties.
de Crespigny p. 242-3	CA was taught "control checks" in the RAAF (Royal Australian Air Force). He developed his own basic procedure based upon standards test pilots use to certify aircraft stalling speeds.

Flight Deck Alerts During the Event

Source	Data (Quote or Summary)
Starting on p. 183/305	Appendix A Electronic Centralised Aircraft Monitoring Process Workflow and Timeline. Describes the procedures based upon crew recollection and other documentation.
p. 190/315	The flightcrew recalled the following systems warnings and inoperative system messages on ECAM after the failure of the No. 2 engine: — engines No. 1 and 4 were operating in a degraded mode — Green hydraulic system – low system pressure and low fluid level — Yellow hydraulic system – engine No. 4 pump errors — failure of the alternating current (AC) electrical No. 1 and 2 bus systems — flight controls operating in alternate law — wing slats inoperative — flight controls – ailerons partial control only — flight controls – reduced spoiler control — landing gear control and indicator warnings — multiple brake system messages — engine anti-ice and air data sensor messages — multiple fuel system messages, including a fuel jettison fault — centre of gravity messages — autothrust and autoland inoperative — No. 1 engine generator drive disconnected — left wing pneumatic bleed leaks — avionics system overheat.
p. 190/315	Airbus (OEM) determined that all these warnings were valid.

Source	Data (Quote or Summary)
p. 191/305	The FCOM indicated the annunciation of each warning to the crew in terms of whether there was an audio alert, a visual alert, a local light and/or the automatic display of the applicable system page.)
p. 191/305	A number of ECAM procedures were recorded on more than one occasion during the sequence as a result of the particular ECAM being marked as RESET before the triggering conditions reoccurred.
de Crespigny p. 217	ECAM warnings come with flashing lights and colors and sounds. The noise of the piercing alerts was "like being in a military stress experiment."
de Crespigny p. 212	First hour of flight, about 100 significant errors and checklists on ECAM. Held for 1 hour 10 minutes while addressing failures, before beginning approach.
de Crespigny starting p. 218	CA describes 5 phases of ECAM • Phase 1: Actions/checklists. Fix the broken items or shut them down, stabilize the aircraft to remain safely in flight. • Phase 2: What is the state of the affected systems after all the checklists have been run? Review diagnostic displays for each failed system (fuel, hydraulics, electrics, pneumatics) • Phase 3: Housekeeping. Identical for every checklist, provides procedural checks that might be a remedy, e.g., system resets. • Phase 4: Transition from trying to fix errors to accepting the failures and provide advice to mediate threats (information and guidance items). Normally just a few, in this case, multiple pages. ECAM displays redundant systems that have failed. (3 pages of faults, 2-columns each page, a lot). • Phase 5: Landing preparation (using the landing performance application on the OIT), 10 minutes *Volpe Comment: These are not Airbus-defined phases, just the CA's description.*
de Crespigny p. 212	"By inverting our logic and looking at what was working, we were able to build our basic Cessna aircraft from the ground up with sufficient bits to build a basic fuel system, flight controls, brake, landing gear and electrical supplies."
p. 53/305	Flight envelope protection alerts during the final approach Reports from the flightcrew and data from the FDR indicated that the aircraft activated three flight envelope protection alerts during the approach and landing. The first two were 'low energy' aural alerts, with the first being triggered as the aircraft passed 1,000 ft radio altitude (RA) and the second at 362 ft RA. On each occasion the captain appropriately responded by increasing thrust. The third warning, a stall warning associated with the aircraft's angle of attack, was generated at 3 ft RA, immediately prior to the aircraft touching down on the runway.

Source	Data (Quote or Summary)
p. 54/305	As a result of the damage to the aircraft systems, primarily the loss of the leading edge slats, the aircraft's control system reverted from NORMAL to ALTERNATE 1A law. Although this included an ECAM message to advise the crew that the flight envelope protections had been lost, the only protection lost was alpha floor. Under ALTERNATE 1A law, the stall warning was restored. Post-accident analysis by Airbus identified that, as a result of the control system laws and the damage to the aircraft, all three warnings were genuine and that the flight envelope margins were maintained.
de Crespigny p. 236	The CA describes the alerts received on final approach as: "a loud aural warning, 'SPEED, SPEED', that interrupts everything else.... If you ignore this warning and continue to slow, then a very loud 'STALL, STALL' deafens your senses..."
p. 198/305	After the aircraft landed and the speed passed below 80 kt, a number of ECAM messages that were previously inhibited by the flight phase were displayed to the crew.

Flightcrew – Training Related to Event

Source	Data (Quote or Summary)
p. 187/305	ECAM training If an ECAM message disappeared either before the crew could action the procedure or while they were actioning the procedure, the Flight Crew Training Manual (FCTM) – Operating Philosophy – Abnormal operations and ECAM section indicated that the crew could consider that the warning or caution was no longer applicable. The normal operating philosophy was that the pilot who was not handling the aircraft's controls managed the ECAM procedures and sought confirmation from the handling pilot as required. (p. 189/305) Some procedure items required the correct switch or control to be positively identified by both crew members before being activated.
de Crespigny	Crew trained for engine failures regularly.
various pages	Comments that the dangers of too many pilots include distraction, group think; captain tried to deliberately counteract these.

Flightcrew Responses to Alerts

General

Source	Data (Quote or Summary)
p. 23/305	While the flight crew continued to process the ECAM messages and associated procedures, the second officer went into the cabin to visually assess the damage. As the second officer moved through the cabin, a passenger, who was also a pilot for the operator, brought his attention to a view of the aircraft from the vertical fin-mounted camera that was displayed on the aircraft's in-flight entertainment system. That display showed a fuel leak from the left wing.
p. 25/305	Autopilot The autopilot disconnected twice during the approach—these were automatic disconnections in response to pre-set functions within the autopilot system relating to the aircraft's angle of attack. When the autopilot disconnected for the second time (at about 800 ft) the captain elected to leave it disconnected and manually fly the aircraft for the remainder of the approach.

Procedures and Checklists

Source	Data (Quote or Summary)
Starting on p. 183/305	Appendix A Electronic Centralised Aircraft Monitoring Process Workflow and Timeline.
Volpe Summary	The flightcrew takes seconds to minutes in between failures and checklists to assess stability and scan the instruments. *Volpe Comment: Pilot resilient behavior.*
p. 190/305	When the flightcrew noticed that the YELLOW Hydraulic system was affected, yet all the damage was on the side of the aircraft in which the GREEN hydraulic system was located, they questioned the validity of the ECAM messages being presented to them. Discussion ensued, but crew agreed to follow ECAM actions. *Volpe Comment: Pilot judgement; resilient behavior.*
p. 22/305	Contrary to their expectation, the flightcrew did not receive confirmation that the fire extinguisher bottle had discharged. They repeated the procedure for discharging the fire extinguisher and again did not receive confirmation that it had discharged.

Source	Data (Quote or Summary)
p. 194/305	The crew reported that whenever a fuel-related ECAM displayed, and due to the extensive damage to the fuel system and number of problems displayed on the associated FUEL system page, they took considerable time understanding the ECAM procedure and the action in response.
p. 24/305	The flightcrew reported that during their assessment of subsequent multiple fuel system ECAM messages, they elected not to initiate further fuel transfer as they were unsure of the integrity of the fuel system. In addition, the flightcrew could not jettison fuel due to damage to the fuel management system. *Volpe Comment: Pilot judgement; resilient behavior.*
de Crespigny p. 217	Crosschecked and verified ECAM with synoptic displays before actioning a checklist.
de Crespigny, Volpe Summary	At some point, ECAM started giving them incorrect advice. It was trying to balance the fuel, for example, by transferring from the good engine side to the bad side. Captain and other pilots all overruled ECAM. This happened a second time, where ECAM recommended they transfer fuel from a rear tank to a forward tank; pilots overruled. Pilots eventually looked up their manual for the CG flight envelope and decided they were okay without rebalancing fuel. At one point, ECAM told them to transfer fuel, then said the transfer system was inoperative. The pilots started doubting ECAM. *Volpe Comment: Pilot knowledge and judgement; resilient behavior.*
p. 196/305	The crew manually selected the APU page and started the unit at 02:45:22 (Figure A10). Once the APU was running, the system display pages changed to those being manually selected, rather than being automatically displayed as part of the ECAM function. That was consistent with the crew progressing through a number of different systems and their recollection of seeking to understand what damage had occurred, and what systems functionality remained. *Volpe Comment: Timeline starts at 02:00, so this happened 45 minutes after the engine failure.*

Flightcrew Task Management

Communications

Source	Data (Quote or Summary)
de Crespigny, p. 163	Flightcrew contacted ATC with PAN PAN during 30-sec monitoring period for engine restart: "This pause gave me the ideal opportunity to notify air traffic control of our problem and to make a PAN call….'PAN PAN PAN Qantas 32, engine failure, maintaining 7400, and current heading." "Shortly after that I made another call: 'QF32 Engine 2 appears failed. Heading 150, maintaining 7400 ft we'll keep you informed and will get back to you in five minutes.' This call made it clear that we were now giving instructions, not asking for them, and that, when it suited us, we would make other demands."
p. 22-23/305	The flightcrew contacted ATC and advised that they would need about 30 minutes to process the ECAM messages and associated procedures and requested an appropriate holding position…
p. 38/305	Cabin crew unable to reach the flightcrew. Tried using the cabin interphone system, but unsuccessful. Then they tried using the "emergency" contact selection on cabin phone system, but the crew got an alarm that sounded like the flight deck horn. They associated the sound with warnings from ECAM and canceled the horn without recognizing its association with the cabin phone system. Not unsafe, but delayed transfer of information.
p. 24/305	The flightcrew also received an aircraft communications addressing and reporting system (ACARS) message from the aircraft operator that indicated that multiple failure messages had been received from the aircraft by the operator. At the time, the flightcrew were busy managing the ECAM messages and procedures, and only had time to acknowledge but not respond to that ACARS message.
p. 25/305	The flightcrew advised ATC that on landing they required emergency services, and that the aircraft was leaking fuel from the left wing. The captain called the CSM [customer service manager] on the interphone to advise him of the potential for a runway overrun and evacuation, and the CSM and cabin crew prepared the cabin for this possibility.
p. 25/305	The captain and the supervising check captain made a number of public address (PA) announcements during the flight to inform the cabin crew and passengers of the situation and to provide updates when required.

Timeline

Source	Data (Quote or Summary)
p. 13/305	About 4 minutes after take-off, while the aircraft was climbing through about 7,000 ft, the flight crew heard two 'bangs' and a number of warnings and cautions were displayed on the electronic centralised aircraft monitor (ECAM).
p. 21/305 Volpe Summary	Flight departed at 1:56:47 UTC. Engine No 2 failed about 6 minutes out of Singapore airport, 7000 ft altitude
p. 24-26/305 Volpe Summary	It took about 50 minutes for the flightcrew to complete all of the initial procedures associated with the ECAM messages. Event Stages • Initial ECAM actions • Managing the situation • Observation of physical damage from cabin • Completion of ECAM procedures • Preparation for landing • Approach and landing • Events on ground after landing
p. 191/305	Reconstruction of ECAM sequence The voice recording of crew actions and dialogue immediately following the engine failure was not available to the ATSB due to limitations of the 2 hour cockpit voice recorder and the extended duration of the ground operations. The available recorded voice commenced after the crew had completed all of the applicable ECAM actions and the aircraft was on approach to Changi Airport, Singapore. The ATSB used other data sources and the crew's recollection of events to recreate the ECAM timeline and associated workflow.

Operations

Source	Data (Quote or Summary)
p. 21/305	Following a normal takeoff, the crew retracted the landing gear and flaps and changed the thrust setting to climb. At about 02:01, while maintaining 250 kt in the climb and passing 7,000 ft above mean sea level (AMSL), the crew heard two, almost coincident 'loud bangs'. The captain immediately selected altitude and heading hold mode on the auto flight system control panel. The captain stated that he expected the aircraft's autothrust system to reduce thrust on the engines to maintain 250 kt as the aircraft levelled off. However, the autothrust system was no longer active, so he manually retarded the thrust levers to control the aircraft's speed.
de Crespigny p. 159 Volpe Summary	Decision to hold altitude upon initial failure, captain says he knew they would stay safely above nearby mountains, and by staying level, would reduce thrust and reduce stress on the engines and airframe. He learned this technique from a fellow Qantas pilot and ex-US Navy F-14 top-gun pilot during a different engine failure in 2001 (while flying as a passenger). He asked that pilot after the event how he had shut down the thrust so fast. 'I didn't,' he said. 'I just hit the altitude hold button.' The engines did not go to idle after hitting altitude hold, speed was increasing; then he realized that the A/T had failed. *Volpe Comment: Example of resilient behavior/knowledge. This action stabilized the situation quickly.*
p. 22/305	The flightcrew discussed the available options to manage the situation, including an immediate return to Singapore, climbing or holding. As the aircraft remained controllable, and there was ample fuel on board, it was decided that the best option would be to hold at the present altitude while they processed the ECAM messages and associated procedures. The flightcrew recalled frequently reviewing this decision and assessing the amount of fuel on board. *Volpe Comment: Example of resilient behavior/knowledge. Good CRM.*
de Crespigny p. 171	"Armstrong Spiral" idea to climb and then spiral down, strongly rejected by others in the flight deck.

CRM

Source	Data (Quote or Summary)
Section 1.17 starting on p. 57/305	The flightcrew was "performing at the level of a competent team." The report provides several examples of this performance, including interactions with cabin crew and passengers.

Source	Data (Quote or Summary)
p. 58/305 Volpe Summary	Effective use of the additional pilots on the flight deck, but they were not required to handle the situation.
General Volpe Summary	Good crew coordination. Discussed options. Had plenty of time to revisit options. Asked for holding pattern close to airport. Determined that aircraft remained controllable prior to landing; checked controllability after each configuration change prior to landing. Pilots used mobile phones to contact operator to seek assistance regarding shutting down engine No. 1 (because only one VHF radio was working).

Preparation to Land: Controllability Checks

Source	Data (Quote or Summary)
de Crespigny p. 242	"The decision to do control checks would be controversial to 90 per cent of commercial pilots." CA says flight control checks are not referenced in any Airbus manual. It is not referenced in Qantas literature, manuals, or SOPs. There is no mention from CASA either.
de Crespigny p. 243 Volpe Summary	The captain devised his own basic procedure to determine the required approach speed as accurately as he possibly could, knowing it was critical due to the length of the runway. He did this based on standards that test pilots use to certify aircraft stalling speeds.
p. 197/305	Footnote 111 The actual flight controls (ailerons, spoilers, elevators and rudders) are not directly viewable from the cockpit. The only way that a crew can assess control functionality is to select the applicable F/CTL system page and monitor the displayed deflection of each control as they manoeuvre their aircraft.
p. 197/305	Figure A13 shows the system page display as the crew manually selected various system displays to further enhance their understanding of the condition of the aircraft and its systems.) The crew reported that the selections of the flight control page were to further assess the aircraft's controllability during reconfiguration.

Predictability, Reliability, and Intended Function of Systems

Source	Data (Quote or Summary)
p. 53/305	Landing calculations They [the flightcrew] manually entered data including the aircraft's maximum landing weight, the runway and weather conditions and nine inoperative aircraft systems. In calculating the landing distance, the LPA applied the additional operational coefficient, and therefore the inherent conservatism nine times, reflecting the number of inoperative aircraft systems entered. The landing distance calculated was greater than the landing distance available and the LPA provided a 'no result' message. The crew recalculated the landing performance data, but this time used the actual aircraft weight. This revised calculation indicated that a landing on runway 20C was feasible, with 100 m of runway remaining. The crew elected to proceed on that basis. *Volpe Comment: Resilient knowledge.*
Volpe Summary	After landing, aircraft electrical system went to configuration similar to emergency electrical power mode; only one VHF radio was working. Flightcrew was unable to shut down engine No. 1 after landing.

ATSB Official Safety Recommendations

Source	Data (Quote or Summary)
p. 167-168/305	**Qantas** Grounded the A380 fleet immediately on 4 Nov 2010. Recommenced operations on 27 Nov 2010 with the caveat that only flights that did not require use of max engine thrust were permitted, based on advice from the engine manufacturer. **EASA** On 10 November 2010, the European Aviation Safety Agency (EASA) issued emergency airworthiness directive EASA AD: 2010-0236-E in respect of the operation of the Rolls-Royce RB211 Trent 900 series engines. The EASA emergency AD was superseded on 22 November 2010 by AD 2010-0242-E that incorporated the contents of Rolls-Royce NMSB 72-AG590 (Revision 2). **ATSB** Issued safety recommendation to Rolls Royce (ATSB safety recommendation AO-2010-089-SR-012) **CASA** (Civil Aviation Safety Agency) On 2 December 2010, CASA issued a maintenance direction to Qantas under Regulation 38 of the Civil Aviation Regulations 1988. This required Qantas to comply with Rolls Royce bulletin, inspect all engines (within two cycles) and submit a report to CASA. **Airbus** On 9 December 2010, in conjunction with the release of the Trent 900 IPTOS as advised in Rolls-Royce NMSB RB.211-73-AG639, Airbus released service bulletin A380-73-8011 to operators of Trent 900 equipped A380 aircraft. This bulletin required the IPTOS to be installed across the Trent 900-equipped fleet.
p. 179/305	The calculation method in the aircraft manufacturer's landing distance performance application was overly conservative and this could prevent the calculation of a valid landing distance at weights below the maximum landing weight with multiple system failures. Airbus has developed a product improvement with the in-flight landing distance application OIS 2B+, available to A380 Operators 4 October 2011 with SB A380-46-8046, that ensures consistency of computation results whatever the landing weight A further product improvement will be introduced with future OIS standards planned to be available by the third quarter of 2013 that will optimize performance calculation and therefore improve consistency of in-flight landing distance prediction to actual aircraft capability.

Source	Data (Quote or Summary)
p. 40/305	The CVR recording capability met the 2 hour requirement; however, in this occurrence this was not adequate to record both the engine failure event and the subsequent ground operations. CVR audio prior to and around the time of the engine failure would have been extremely useful to this investigation in examining the crew resource management response to the event and exact ECAM sequences. The CVR audio would have been able to provide a correlation with other sources of flight information allowing the ATSB to more quickly develop an understanding of the technical issues and the flight crew's response. The overwriting of the CVR in this event was cited in a Working Paper presented by the ATSB to the ICAO flight recorder working panel in October 2012, to support the panel proposal for increased CVR duration. This proposal resulted in a recommendation by the panel to the ICAO Air Navigation Committee in January 201312 to extend the mandated CVR recording capability to 15 hours.

Details on ECAM Actions from the Qantas (QF) 32 Book

Source	Data (Quote or Summary)
Phase 1	Engine overheat, then engine fire, contact ATC (PAN PAN), back to checklists Engine 2 failed, but all three other engines were degraded too. No data on thrust from No. 3 and 4. Order of checklists: Engine, flight controls, hydraulics, electrics, fuel *[slightly different order p. 211]* Sea of red lights and red synoptic displays, problems with fuel tanks and hydraulics were growing; becoming overwhelming Decision to return to Singapore. Timing unclear. Not sure how much fuel (i.e., flying time) they had. Considered increasing altitude to 10000 ft (for a glide/spiral unpowered to airport), but 4 of 5 pilots said no. Too risky to climb with damaged engines. (See p. 22/305 of ATSB report) After completing several checklists, did a visual inspection from cabin to supplement ECAM info. Did not know how many ECAM checklists were queued up (p. 188). They kept coming. Trying to sort out engine status and fuel status. Several times a higher priority checklist interrupted their flow. At one point, ECAM alert says Fuel: Wings not balanced (p. 190) and the captain's instincts said this was wrong. Decided not to transfer fuel towards the leaking wing. Ignored checklist. *Volpe Comment: Resilient behavior/judgment* Another checklist they doublechecked was the Fuel: Nom + Alt XFR Fault (p. 191). They had transferred some fuel earlier, but some of those steps had not worked. Returned to synoptics page to confirm fuel imbalance. Fuel imbalance across outer tanks was well outside published limit. Not sure how well the aircraft would turn or land. p. 194, ECAM was not helping. It said CG out of limits for landing, asked to transfer fuel aft, but then said the trim tank was unusable and the transfer system was inoperative. Started to have doubts about ECAM. Asked a spare pilot to use the laptop to look up the FCOM graph of the CG envelope. After reviewing the graph, concluded the CG was within acceptable range. (p. 195)
Phase 3 p. 211	Called for abnormal checklist for overweight landing
Phase 4 starts p. 223	n/a

Source	Data (Quote or Summary)
Phase 5 p. 225	Landing performance Came in overweight with several failed systems. CA asked the Check Captain and Supervising Check Captain to do the calculations on the laptop (p. 225) At first used an incorrect assumption, working slats, and calculated incorrect approach speed of 145 kts, which the FO caught as too low based on his *judgement*. One pilot realized the landing performance software defaulted to wet runway and added 15% to landing distance. *Volpe Comment: Resilient behavior/judgment* Carefully briefed potential for a go-around, which was highly undesired. Had to meet an exact approach speed, ±1 kt, very precise, better than certification tests. Had to minimize flare to minimize landing distance

B.IV Lion Air 610

Source(s)

Komite Nasional Keselamatan Transportasi (KNKT) Republic of Indonesia (October 2019). Final Aircraft Accident Investigation Report PT. Lion Mentari Airlines [Lion Air] Boeing 737-8 (MAX); PK-LQP tanjong Karawang West Java, Republic of Indonesia, 29 October 2018.

Default references are to the PDF file of the accident investigation (322 pp).

Numbered items are official investigation findings.

Bulleted Summary

What happened, in brief?

Inputs from a defective AOA sensor to the Speed Trim System (STS) produced multiple warnings beginning with the stick shaker on the left (captain's) side.

- The left stick shaker activated as nose gear lifted off the runway. Within a few seconds, multiple warnings triggered including Takeoff Configuration, Indicated Air Speed (IAS) Disagree, Altitude (ALT) Disagree and Feel Differential Pressure warnings.
- The CA called for the Non-Normal Airspeed Unreliable checklist, but the FO was confused about memory items and the location of the checklist. After approximately 4 minutes, they began the Non-Normal Airspeed Unreliable checklist working through it over approximately 2.5 minutes. They did not complete the checklist.
- After the crew retracted the flaps, the Maneuvering Characteristics Augmentation System (MCAS) started to generate repeated aircraft nose down trim commands.

What happened, in brief? (continued)

- From the time the flaps were set to zero until the end of the recording there were at least 26 automatic trim down commands generated by MCAS and at least 34 manual electric trim up inputs (generated by the flightcrew).
- The multiple alerts and indications increased crew workload and obscured the problem. The flightcrew could not arrive at a solution, such as performing the runaway stabilizer (cut-out) procedure or continuing to use electric trim to reduce control column forces.
- The crew followed ATC heading instructions and did not declare an emergency.
- There was no AOA DISAGREE message available on the aircraft, reducing crew situation awareness.
- The flight lasted approximately 11 min. All on board fatally injured.

What was/were the malfunction(s)?

A defective AOA sensor was installed in the aircraft.

- The installed left AOA sensor had a 21° bias which was not detected during the installation test the day before the accident.
- The AOA differences between left and right were constant, at about 21°, from the time the aircraft accelerated for take-off until the end of recording.
- The stick shaker was active during the entire duration of the previous flight (96-min) but, in that case, the flightcrew shut off the stabilizer trim (deactivating MCAS) and completed the flight using manual trim to control the stabilizer position. The crew of this previous flight report some malfunctions (IAS and ALT DISAGREE, plus the FEEL DIFF PRES light) but did not specify the stick shaker activation or the stabilizer trim cutout.

Who were the flightcrew on board and what were their qualifications?

There were two pilots. Both had negative remarks on their training records, the FO more so than the captain.

- Captain (CA) was Pilot Flying (PF) for first 10 minutes of flight. First Officer (FO) was (PF) for last one minute of flight.
- The CA had over 6000 flight hours total, with 5176 on the B737.
- The FO had over 5000 flight hours total, with 4286 in the B737.
- The captain’s training record notes from 2017 and 2018 include negative comments on his technique for recovery from stall on approach, and negative comments about his teamwork and CRM.

Who were the flightcrew on board and what were their qualifications? (continued)

- Numerous deficiencies were noted in the FO's management of procedures, flight control, situation awareness, and workload from 2013 through 2018. For example:
  - In April 2017, there was a remark indicating that he had the "wrong concept of the basic principal for stall recovery."
  - In July 2014, a note said that the FO missed identifying the non-normal checklist on the FMS assessment item.

What training did the flightcrew have related to this event or malfunction specifically?

Although the crew did not have information about MCAS, they did have training on recognizing non-normal events and applying non-normal checklists.

- The crew had no information about MCAS through any training or manual and they had no procedures to mitigate erroneous data from an AOA.
- The crew did have training for the B737 on recognition of abnormal situations and appropriate crew actions.
  - The inability for the FO to perform memory items and locate the [airspeed unreliable] checklist in the QRH in a timely manner indicated that the FO was not familiar with the NNC.
  - The reappearance of difficulty in aircraft handling identified during training in the accident flight indicated that the Lion Air training rehearsal was not effective.
- The procedure of runaway stabilizer was not reintroduced during transition training and there was no immediate indication available to the flightcrew to be able to directly correlate the uncommand nose down stabilizer to the procedure.

What did the flightcrew experience during the event?

The stick shaker continued through most of the flight. There were also aural warnings from the Enhanced Ground Proximity Warning System (EGPWS) and other indications.

- The left control column stick shaker activated just after the aircraft became airborne.
  - It temporarily stopped at about 2322 UTC when the aircraft descended with flaps extended.
  - About 15 seconds later the left control column stick shaker activated again and was continuously active until the end of recording.
- The IAS Disagree indication appeared on PFD shortly after takeoff and continued until end of recording.
- There were multiple aural warnings from the EGPWS.
- The FEEL DIFF PRESS light on the overhead panel illuminated.

What did the flightcrew do in response to the malfunction(s)?

The flightcrew was unable to manage the multiple alerts and MCAS activations.

- Airspeed unreliable checklist
    - The CA asked the FO to perform the memory items for the airspeed unreliable checklist about 1 minute after takeoff. The FO told the CA, "standby." A minute later the FO said there is no airspeed unreliable checklist.
    - The CA prompted the FO for memory items again, and there were a few short exchanges. The FO finally found the checklist, over a minute later.
    - The FO continued to read the checklist over the next 2.5 minutes with multiple interruptions from ATC.
- The flaps were retracted two minutes after takeoff, at which point the MCAS activations began.
    - The flaps were later moved to 1, then to 5, then back to 1. Since MCAS does not activate until the flaps are retracted, when these flaps settings were in effect, MCAS should have stopped activating.
    - Eventually, the flaps were retracted and the MCAS activations began again.
- The flightcrew confirmed disengagement of the autothrottle at the start of the Unreliable Airspeed non-normal checklist. Based on flight data, one of the pilots had reduced or power to approximately 50-55% N1 before the checklist called for a power reduction to about 75% N1.
- The captain and FO did not have a shared mental model of the situation as exhibited by their lack of clear and effective communication.
    - For example, the FO did not conduct memory items for the airspeed unreliable NNC when asked by the captain and the captain did not verify that the FO did not conduct the memory items when asked.
    - The captain also did not verbalize information regarding the aircraft state or the need to trim out increased column forces when he transferred control to the FO near the end of the flight.
- There were no recorded indications of autopilot engagement during the flight.

What else did the flightcrew do to manage the overall situation?

The crew was consumed with attempting to complete the unreliable airspeed checklist while managing backpressure and trim inputs to counter the MCAS activations.

- The captain did not verbalize allocation of crew duties and did not clearly verbalize a plan to hold or to troubleshoot the aircraft problems.
- The crew did not declare either urgency (PAN PAN) or an emergency (MAYDAY). They did not ask for special handling from ATC nor did they object to heading instructions from ATC, even though these instructions increased workload.
    - They eventually told ATC that they had "a flight control problem," but that was not considered as an emergency condition according to the air traffic service.
    - The crew also requested ATC to tell them their altitude, not realizing that ATC only had access to the same data they had.
- The captain at one point asked for help from a flight engineer seated in the passenger area and someone entered the flight deck, but there was no clear effect.

Overview of Event

An approximately 21° difference between left and right AOA sensors initiated the indications. The left stick shaker activated as the nose gear lifted off the runway. Within a few seconds, multiple warnings triggered including Takeoff Configuration, Indicated Air Speed (IAS) Disagree, Altitude (ALT) Disagree and Feel Differential Pressure warnings. The Maneuvering Characteristics Augmentation System (MCAS) activated after the flaps were retracted. The two pilots were confused about memory items and the location of related checklists. They began, but did not complete, the Non-Normal Airspeed Unreliable checklist. The flight lasted approximately 11 min. All on board fatally injured.

Flightcrew on Board

Source	Data (Quote or Summary)
Volpe Summary	Captain (CA) was Pilot Flying (PF) for first 10 minutes of flight. First Officer (FO) was (PF) for last one minute of flight
p. 81/322	The FO advised the captain that this flight was not his actual schedule. The FO was called at 4 o'clock in the morning and informed the revision of the original schedule. [Flight was scheduled for 5:45 am and departed about 6:20 am.] The CA advised the FO that he was having flu. The CVR recorded the CA coughed about 15 times within an hour during the preflight.

Similarity of Event to Other Known Cases and Resolution

Source	Data (Quote or Summary)
Volpe Summary	An AOA sensor was defective. This was a single source of bad data with propagating effects. The Technical Advisory Board report provided guidance on returning aircraft to service, including changes to MCAS and crew training.
p. 213/322	58. The LNI043 flight that experienced multiple malfunctions were considered caused or could have caused difficulties in controlling the aircraft. According to the ICAO Annex 13, CASR part 830 and OM-part A, the flight is classified as serious incident which required investigation by the KNKT in accordance with the Aviation Law Number 1 of 2009 and Government Decree Number 62 of 2013.

Aircraft Flight History

Source	Data (Quote or Summary)
p. 20/322	On 26 October 2018 [three days before accident], the SPD (speed) and ALT (altimeter) flags on the Captain's primary flight display first occurred on the flight from Tianjin, China to Manado, Indonesia. Following reoccurrence of these problems, the left angle of attack (AOA) sensor was replaced in Denpasar on 28 October 2018 [the day before the accident]. The installed left AOA sensor had a 21° bias which was undetected during the installation test in Denpasar. The erroneous AOA resulted in different indications during the flight from Denpasar to Jakarta, including IAS (indicated airspeed) DISAGREE, ALT (altitude) DISAGREE, FEEL DIFF PRESS (feel differential pressure) light, activations of Maneuvering Characteristics Augmentation System (MCAS) and left control column stick shaker which were active throughout the flight [LNI043]. The flightcrew was able to stop the repetitive MCAS activation by switched the stabilizer trim to cut out. After [LNI043] landed in Jakarta, the flightcrew reported some malfunctions, but did not include the activation of stick shaker and STAB TRIM to CUT OUT. The AOA DISAGREE alert was not available on the aircraft therefore, the flightcrew did not report it. The reported problem would only be able to rectify by performing tasks of AOA Disagree.
p. 38/322	Thereafter, the aircraft departed from Denpasar to Jakarta with flight number LNI043 and arrived in Jakarta at 1556 UTC (2256 LT). The flightcrew reported on AFML page number B3042855 that the aircraft had problems of "IAS and ALT Disagree shown after take-off" and "FEEL DIFF PRESS light illuminated".

Source	Data (Quote or Summary)
p. 176/322	2.1.1 Situation Awareness and Handling of Flight Deck Indications The Captain's initial response [LNI043], as the PF, to the activation of stick shaker during lift-off and subsequent response of numerous caution lights was to continue rotation by maintaining pitch 15 degrees and existing take-off thrust. After the Captain transferred control to the FO, he cross-checked the flight instruments and determined his instruments were erroneous. The Captain action of transferring the control prior to crosscheck of the instruments may have indicated that the Captain generally was aware of the repetitive previous problem of SPD and ALT flags and the replacement of the left AOA sensor on this aircraft.
p. 71/322	On the flight from Denpasar to Jakarta (DPS-1), the data for these parameters remained valid. However, the DFDR recorded differences in altitude and speed between left and right instruments. It also recorded differences in angle of attack between left and right AOA sensor which were not recorded on any of the previous flights.
p. 208/322	(14) The flightcrew of LNI043 eventually observed and recognized the un-commanded stabilizer movement and moved the stabilizer trim cutout switches to the cutout position. Stopping the stabilizer movement enabled the flightcrew to continue the flight using manual trim wheel to control stabilizer position. On that flight, stabilizer cutout was used to counter the repetitive MCAS-commanded stabilizer. Boeing reasoning that the stabilizer cutout is available but not required is incorrect.
p. 169/322	The Captain [of LNI043] reported that he performed three Non-Normal Checklists (NNCs) consisting of Airspeed Unreliable, Altitude DISAGREE, and Runaway Stabilizer. None of the NNCs performed contained the instruction "Plan to land at the nearest suitable airport". The Captain decided to continue the flight since none of the NNCs gave instructions to land at the nearest suitable airport and despite the degraded flight instrumentation, flying without autopilot and auto-throttle, and a continuous activation of stick shaker, he convinced himself that the aircraft was able to fly to the scheduled destination. The Captain did not inform the Lion Air ground station in Denpasar about the problems as he assumed that the aircraft would be able to continue the flight to Jakarta.
p. 176/322	The Captain's initial response, as the PF, to the activation of stick shaker during lift-off and subsequent response of numerous caution lights was to continue rotation by maintaining pitch 15 degrees and existing take-off thrust. After the Captain transferred control to the FO, he cross-checked the flight instruments and determined his instruments were erroneous. The Captain action of transferring the control prior to crosscheck of the instruments may have indicated that the Captain generally was aware of the repetitive previous problem of SPD and ALT flags and the replacement of the left AOA sensor on this aircraft.

Source	Data (Quote or Summary)
p. 177/322	After being transferred to Upper West Semarang, the flight crew [of LNI043] restated their problem with additional information and during the descent to destination they requested uninterrupted descent path profile. This action suggested that the flight crew were aware of their existing flight condition (continuous stick shaker, manual flying, manual trimming, FO PFD was the primary instrument) required a simplified flight path management until approach and landing.
p. 178/322	The LNI043 flightcrew decision to continue with stick shaker active is not common in comparison to previous events of erroneous stick shaker. When combined with the runaway stabilizer situation recognized by the flightcrew, the decision to continue was highly unusual.
p. 197/322	The accident flight was the first flight of the day therefore after powering up the aircraft, the left FCC acted as the operating Speed Trim System (STS) channel and received input from left AOA sensor. The DFDR showed that on the accident flight, the left AOA sensor had a high bias 21° when compared to the right AOA sensor.

Initial and Subsequent System Malfunction(s)

Source	Data (Quote or Summary)
p. 73/322	On the accident flight, the DFDR recorded differences in altitude of about 200 to 500 feet and differences in speed of about 10 to 15 knots between left and right instruments from the beginning of the flight until the end of the recording. The DFDR recorded differences between left and right AOA of about 21°.
p. 79-80/322	Figure 29 (DFDR plot) From the time the flaps were set to zero until the end of the recording there were at least 26 automatic trim down commands and at least 34 manual electric trim up inputs.
p. 80/322	The AOA differences between left and right were constant, about 21°, from the time the aircraft accelerated for take-off until the end of recording.
p. 197/322	The MCAS software uses input from a single AOA sensor only. Certain failure or anomalies of the AOA sensor corresponding to the master FCC controlling STS can generate an unintended activation of MCAS.

Official Statements Related to Cause

Source	Data (Quote or Summary)
p. 217/322	Section 3.2 Contributing Factors Contributing factors defines as actions, omissions, events, conditions, or a combination thereof, which, if eliminated, avoided or absent, would have reduced the probability of the accident or incident occurring, or mitigated the severity of the consequences of the accident or incident. The presentation is based on chronological order and not to show the degree of contribution. 1. During the design and certification of the Boeing 737-8 (MAX), assumptions were made about flight crew response to malfunctions which, even though consistent with current industry guidelines, turned out to be incorrect. 2. Based on the incorrect assumptions about flight crew response and an incomplete review of associated multiple flight deck effects, MCAS's reliance on a single sensor was deemed appropriate and met all certification requirements. 3. MCAS was designed to rely on a single AOA sensor, making it vulnerable to erroneous input from that sensor. 4. The absence of guidance on MCAS or more detailed use of trim in the flight manuals and in flight crew training, made it more difficult for flight crews to properly respond to uncommanded MCAS. 5. The AOA DISAGREE alert was not correctly enabled during Boeing 737-8 (MAX) development. As a result, it did not appear during flight with the mis-calibrated AOA sensor, could not be documented by the flight crew and was therefore not available to help maintenance identify the mis-calibrated AOA sensor. 6. The replacement AOA sensor that was installed on the accident aircraft had been mis-calibrated during an earlier repair. This mis-calibration was not detected during the repair. 7. The investigation could not determine that the installation test of the AOA sensor was performed properly. The mis-calibration was not detected. 8. Lack of documentation in the aircraft flight and maintenance log about the continuous stick shaker and use of the Runaway Stabilizer NNC meant that information was not available to the maintenance crew in Jakarta nor was it available to the accident crew, making it more difficult for each to take the appropriate actions. 9. The multiple alerts, repetitive MCAS activations, and distractions related to numerous ATC communications were not able to be effectively managed. This was caused by the difficulty of the situation and performance in manual handling, NNC execution, and flight crew communication, leading to ineffective CRM application and workload management. These performances had previously been identified during training and reappeared during the accident flight.

Source	Data (Quote or Summary)
p. 209/322	(23) During the accident flight erroneous inputs, as a result of the misaligned resolvers, from the AOA resulted in several fault messages (IAS DISAGREE, ALT DISAGREE on the PFDs, and Feel Differential Pressure light) that affected the flightcrew's understanding and awareness of the situation.

Official Findings related to Flightcrew Training, Procedures, and Operations

Source	Data (Quote or Summary)
p. 207/322	(12) Multiple alerts and indications occurred which increased flightcrew's workload. This obscured the problem, and the flightcrew could not arrive at a solution during the initial or subsequent automatic aircraft nose down stabilizer trim inputs, such as performing the runaway stabilizer procedure or continuing to use electric trim to reduce column forces and maintain level flight. Safety Recommendation 04.M-2018-35.11 (p. 229/322) has similar wording (see below).
p. 210/322	(31) The aircraft should have included the intended AOA DISAGREE alert message functionally, which was installed on 737 NG aircraft. Boeing and the FAA should ensure that new and changed aircraft design are properly described, analyzed, and certified. (32) The absence of an AOA Disagree message made it more difficult for the flightcrew to diagnose the failure and for maintenance to diagnose and correct the failure.
p. 183/322	Being unaware of multiple problems that occurred on the previous flight, including the stick shaker activation and uncommanded AND [aircraft nose down] trim lead to the inability of the flightcrew to predict and be prepared to mitigate the events that might occur.
p. 211/322	(46) After LNI043 [the previous flight] was airborne, the left control column stick shaker was active and several messages appeared. The Captain of LNI043 was aware to the aircraft condition after discussion with the engineer in Denpasar. This awareness helped the captain to make proper problem identification.

Source	Data (Quote or Summary)
p. 214/322	(66) Just after liftoff, the left stick shaker activated and numerous messages on the PFD were displayed, repetitive MCAS activation after the flaps were retracted and the ATC communication increased the flightcrew workload. (67) The FO asked the controller of the aircraft altitude and the indicated speed on the ATC radar display in an attempt to obtain another source of information. However, the ATC radar receives altitude data transmitted by the aircraft therefore, no additional data may be acquired. Being unable to determine reliable altitude and airspeed might increase stress to the flightcrew. (71) The controller provided eight heading instructions after the flightcrew reported that the aircraft was experiencing a flight control problem, which was not considered as an emergency condition according to ATS SOP of AirNav Indonesia branch JATSC. There was also no objection by the flightcrew to the heading instructions and the flightcrew did not declare an emergency. These conditions increased the flightcrew workload.
p. 215/322	(73) The AOA DISAGREE message was inhibited on the accident aircraft therefore, flightcrews would not be aware that this message would not appear if the AOA DISAGREE conditions were met. This would contribute to flightcrew being denied valid information about abnormal conditions being faced and lead to a significant reduction in situational awareness by the flightcrew.

Description of Aircraft Systems and Alerts

Source	Data (Quote or Summary)
Volpe Summary	General B737-800 (MAX) The Lion Air 610 report does not describe the B737 notification system. There was no centralized notification system for failures/malfunctions. Refer to the Ethiopian Airlines 302 report for description of the B737-800 MAX notification system as it applied to that flight.
p. 43/322	Airspeed Low Alert The AIRSPEED LOW annunciation alerts flightcrew for low air speed. The alert is an aircraft operational alert that is calculated by the Enhance Ground Proximity Warning System (EGPWS) and the MAX Display System (MDS) which occurs when the computed airspeed (from the ADIRU) falls below a threshold airspeed between the minimum maneuver speed and stick shaker speed.

Source	Data (Quote or Summary)
p. 43/322	IAS Disagree and ALT Disagree IAS disagree and ALT disagree are visual warnings on the PFD, as shown in Figure 4.
p. 50/322	Feel Differential Pressure Master Caution and light Master Caution for Feel Diff Press is defined (Section 1.6.5.3). The elevator feel computer provides simulated aerodynamic forces on the control column using total pressure from two dedicated pitot probes mounted on the vertical stabilizer and stabilizer position. Feel force is transmitted to the control columns by the elevator feel and centering unit - thus column forces are adjusted relative to the airspeed. Elevator Feel Shift (EFS) modifies the column forces at high angles-of-attack. The FEEL DIFF PRESS light on the overhead panel will illuminate if EFS operates continuously for more than 30 seconds. The FEEL DIFF PRESS light is not recorded on the DFDR, but will result in activation of Master Caution which is recorded on the DFDR.
p. 50/322	Speed Trim System (STS) The Speed Trim System (STS) provides speed stability augmentation and pitch stability augmentation. Speed stability augmentation is provided by the Speed Trim Function. Pitch stability augmentation is provided by the MCAS function.
p. 45/322	Angle of Attack (AOA) Sensors The Boeing 737-8 (MAX) has two independent angle-of-attack (AOA) sensors, one on each side of the forward fuselage. The AOA sensors consist of an external vane which rotates to align with the local airflow connected to two internal resolvers which independently measure the rotation angle.

Source	Data (Quote or Summary)
p. 50-51/322	MCAS The MCAS is a function within the STS and, when activated, moves the stabilizer during non-normal flaps up, high angle of attack maneuvers to provide a desirable increase in stick force gradient and a reduced pitch up tendency. Similar to the Speed Trim Function, the MCAS function is also a flight control law contained within each of the two FCCs. As originally delivered, MCAS became active during manual, flaps-up flight (autopilot not engaged) when the AOA value received by the master FCC exceeded a threshold based on Mach number. When activated, the MCAS provided a high rate automatic trim command to move the stabilizer AND [aircraft nose down]. The magnitude of the AND command was based on the AOA and the Mach. After the non-normal maneuver that resulted in the high AOA, and once the AOA fell below a reset threshold, MCAS would move the stabilizer ANU [aircraft nose up] to the original position and reset the system. At any time, the stabilizer inputs could be stopped or reversed by the pilots using their yoke-mounted electric stabilizer trim switches, which also reset the system after a 5 second delay.
p. 206/322	Section 3.1, Findings (1) MCAS is designed to function only during manual flight (autopilot not engaged), with the aircraft's flaps up, at an elevated AOA. As the development of the 737-8 (MAX) progressed, the MCAS function was expanded to low Mach numbers and increased to maximum MCAS command limit of 2.5° of stabilizer movement.
p. 55-56/322	Takeoff Configuration Warning Light Takeoff configuration warning is armed when the aircraft is on the ground and either forward thrust lever is advanced for takeoff. The Takeoff configuration warning activates if the aircraft is not correctly configured for takeoff. One such condition is that that the leading edge devices are not in the normal takeoff position. An intermittent warning horn sounds and the TAKEOFF CONFIG warning light illuminates when the takeoff configuration warning activates.
Starting p. 106/322	*Volpe Comment: This section has lengthy quotes from the Lion Air Flight Crew Operations Manual, Checklist Instructions.* Section 1.17.1.5 Quick Reference Handbook (QRH). Most checklists correspond to a light, alert or other indication. In most cases, the MASTER CAUTION and system annunciator lights also illuminate to indicate the non-normal condition. (p. 107/322) If the MASTER CAUTION and system annunciator lights illuminate, all related amber lights are reviewed to assist in recognizing the cause(s) of the alert. (p. 108/322)

Flightcrew – General Experience

Source	Data (Quote or Summary)
Volpe Summary	Report offers no insight about either the captain or First Officer's first 800 hours and training programs, ab-initio or other.
p. 30-31/322	Captain
Volpe Summary	Total 6028 flight hours, 5176 flight hours on the B737 (no other type ratings listed). Air Transport Pilot License (ATPL) license obtained in 2016. His nationality is listed as "India." Report noted the CA training record notes from 2017 and 2018 • 12 May 2015, in the assessment item of "stall on final approach", the remark was lack of appropriate technique that resulted in a second stick shaker activation. • 25 May 2017, the remark was the Crew Resource Management (CRM) needed to be improved. • 23 May 2018, in the assessment item "teamwork exercise" the remark was to use standard signal for effective communication and good teamwork during abnormal or emergency situation. Details of the CA's training record are in Section 6.9.1, starting p. 303/322

Source	Data (Quote or Summary)
p. 31-33/322 Volpe Summary	FO Total 5174 hours, 4286 in B737 (no other type ratings listed). Commercial Pilot License (CPL) issued 1997. His nationality is listed as "Indonesia." Report noted training record notes from 2013 through 2018 Numerous deficiencies were noted in procedures, flight control, situation awareness, and workload management (p. 32-33). For example: • 14 July 2013, the new-hire training records indicated: need more detail on procedures, after 4th attempt of engine failure after takeoff the result was satisfactory, during single engine operation need improvement of rudder usage during power up or down, need more discipline to follow F/D during single engine non precision and precision approach. In general, "tends fixation so awareness less." Corrective training performed by briefing. • 2 June 2014, …the FO had "major problem" to focus on short-final, too rush, and needed gentle handling on control column with small correction for pitch and attitude and must be patient with the result. The FO also needed to manage stress while aircraft attitude was changing such as pitch due to external aspect (wind, etc.). • 6 July 2014, …On the assessment item "Flight Management System (FMS)" the remark was the FO missed identifying the Non-Normal Checklist (NNC). Details of the FO's training record are in Section 6.9.2, starting p. 307/322 *Volpe Comment: FO did not have an Air Transport License.*

Flightcrew – Training Related to Event

Source	Data (Quote or Summary)
p. 207/322	(11) The procedure of runaway stabilizer was not reintroduced during transition training and there was no immediate indication available to the flightcrew to be able to directly correlate the uncommand nose down stabilizer to the procedure.
p. 209/322	(30) Flight crew training would have supported the recognition of abnormal situations and appropriate flightcrew action. Boeing did not provide information and additional training requirements for the 737-8 (MAX) since the condition was considered similar to previous 737 models.

Source	Data (Quote or Summary)
p. 214/322	(68) The inability for the FO to perform memory items and locate the checklist in the QRH in a timely manner indicated that the FO was not familiar with the NNC. This condition was reappearance of misidentifying NNC which showed on the FO's training records. (70) The reappearance of difficulty in aircraft handling identified during training in the accident flight indicated that the Lion Air training rehearsal was not effective. (72) The absence of a declaration of urgency (PAN PAN) or emergency (MAYDAY), or asking for special handling, resulted in the ATCo not prioritizing that flight. With priority, ATC would not require LNI610 to maneuver repeatedly.
p. 215/322	(74) No information about MCAS was given in the flightcrew manuals and MCAS was not included in the flightcrew training. These made the flightcrew unaware of the MCAS system and its effects. p. 183/322 adds: There were no procedures for mitigation in response to erroneous AOA.

Flight Deck Alerts During the Event

Source	Data (Quote or Summary)
p. 80/322	The left control column stick shaker activated just after the aircraft became airborne. It temporarily stopped about 2322 UTC when the aircraft descended with flaps extended. About 15 seconds later the left control column stick shaker activated again and was continuously active until the end of recording.
p. 22/322 Volpe Summary	IAS Disagree indication appeared on PFD shortly after takeoff and continued until end of recording.
p. 24-29/322 Volpe Summary	<u>Aural Warnings</u> EGPWS • BANK ANGLE, BANK ANGLE • AIR SPEED LOW – AIR SPEED LOW (The DFDR recorded the indicated airspeed on the Captain's PFD indicated as 306 knots and on the FO's PFD indicated 318 knots.) • TERRAIN -TERRAIN • SINK RATE Other • Overspeed clacker

Source	Data (Quote or Summary)
p. 199/322	The stick shaker activated continuously after lift-off and the noise could have interfered with the flightcrew hearing the sound of the stabilizer trim wheel spinning during MCAS operations. Therefore, the movement of stabilizer wheel might not have been recognized by the flightcrew.
p. 82-83/322	From the CVR 23:22:12 The FO advised to the Captain "Feel Differential". 23:23:17, The FO: "Feel differential already done…" 23:24:05 The FO: "Feel differential pressure". *Volpe Comment: The first statement occurred approximately 1 min and 40 seconds after takeoff. It appears to refer to the FEEL DIFF PRESS light (Feel Differential Pressure) illuminating on the overhead panel based upon the FDR data for the Master Caution alert activation shown in Figure 29 (p. 79/322).* *In the last statement, the FO might be referring to the Feel differential pressure checklist as he is searching for the Unreliable Airspeed checklist, but it is unclear, because earlier he says that the item is "done."*
p. 86/322	At 23:29:31 in the CVR (p. 86/322), the FO mentions "off schedule descend."
Volpe Summary	*Volpe Comment: We think that the OFF SCHED DESCENT annunciator light on the Cabin Pressure Control section of the overhead panel would have been associated with a Master Caution as shown in the DFDR plot (p. 79/322, Figure 29).*

Flightcrew Responses to Alerts

General

Source	Data (Quote or Summary)
p. 217/322	(Contributing Factor #9) The multiple alerts, repetitive MCAS activations, and distractions related to numerous ATC communications were not able to be effectively managed. This was caused by the difficulty of the situation and performance in manual handling, NNC execution, and flightcrew communication, leading to ineffective CRM application and workload management. These performances had previously been identified during training and reappeared during the accident flight.

Source	Data (Quote or Summary)
p. 181/322	Despite the flightcrew's attempt to execute of the NNC, due to increase workload, and distractions from the ATC communication, the NNC was unable to be completed in that situation. Similar statement on p. 214/322, official finding: (69) Despite the flightcrew's attempt to execute the NNC, due to increased workload, and distractions from the ATC communication, the NNC was unable to be completed in that situation. The unfinished NNC made it difficult for the flightcrew of LNI610 to understand the aircraft problem and how to mitigate the problem.
p. 181/322	The FO was unable to control the aircraft as the repetitive MCAS activations were not countered by adequate trim up input.
p. 86/322 Volpe Summary	CA called flight attendant to come to flight deck. CA asked flight attendant to call an engineer seated in the passenger area to flight deck. FO repeated request. Someone entered the flight deck. CA said "look what happened."
p. 206/322	(6) The flightcrew did not react to MCAS activation but to the increasing force on the control column. Since the flightcrew initially countered the MCAS command using control column, the longer response time for making electric stabilizer trim inputs was understandable.

Procedures and Checklists

Source	Data (Quote or Summary)
p. 111/322	Figure 33 shows the Airspeed Unreliable Checklist page 1 from the Lion Air Flight Crew Operations Manual

Source	Data (Quote or Summary)
p. 180-181/322	<u>Section 2.3.1 Report summary of checklist confusion</u> After the IAS DISAGREE had been identified, the Captain instructed the FO to perform memory items of Airspeed Unreliable, and the FO did not perform them. The first four items of the Airspeed Unreliable NNC are memory items to be performed by memory and must be done before reading the checklist. The Captain repeated the command about two minutes after without mentioning the NNC title and the FO was confused of the memory items to be performed. About 1 minute later, the FO asked to the Captain of the memory item to be performed to which the Captain responded "Airspeed Unreliable". The FO acknowledged and started to locate the checklist. About 1 minute later, the FO found the checklist and started to read the checklist. The Airspeed Unreliable procedure is one of the checklists which are listed on the Quick Action Index. The Quick Action Index is available on the cover page of the QRH and the Airspeed Unreliable is on the second line of the list. The inability for the FO to perform memory items and locate the checklist in the QRH in a timely manner indicated that the FO was not familiar with the NNC. This condition was reappearance of misidentifying NNC which showed on the FO's training records. *Volpe Comments:* *1) The FO could not find checklist initially then responded with the page number (10.1) when he found it (CVR, p. 82-84/322).* *2) Both pilots appeared confused about the airspeed unreliable checklist and memory items.* *3) The FO spent approximately 2.5 minutes from discovery of Airspeed Unreliable checklist until final mention in CVR, completing the first 8 or 9 steps out of 17.* *4) The FO attempted to complete Airspeed Unreliable Checklist while handling numerous ATC instructions.*
p. 79/322 and 84/322 Volpe Summary	<u>Autothrottle Disengagement and Power Settings</u> The CVR indicates that the autothrottle was confirmed disengaged at the start of the Airspeed Unreliable checklist by the CA at 23:25:41 (p. 84/322) Figure 29 (p. 79/322) shows that the power setting was at approximately 50% for several seconds before the captain confirmed that autothrottle was disengaged. Then it rose to approximately 75% N, just after the FO read that value from the airspeed unreliable checklist (at 23:25:46). There is no verbal callout on the CVR by either pilot indicating that the power setting was reduced prior to this checklist item. The power setting later returned to the lower value (approximately 50% N1), but then increased, decreased, and then increased again towards the end of the recording.
p. 83/322 Volpe Summary	The FO mentions the Feel Differential Pressure condition, and may have referenced or completed the short checklist, it is unclear. The checklist has just one item and one note.

Source	Data (Quote or Summary)
p. 119/322 Volpe Summary	Figure 44: Feel Differential Pressure Non-Normal checklist The Feel Differential Pressure Non-Normal checklist says "Column forces can be significantly higher than normal, particularly during landing flair. The autopilot can disengage when pitch changes are commanded. Do not attempt an autoland." *Volpe Comment: The checklist focuses on landing and would not have been useful at the time the FO called for it.*

Flightcrew Task Management

Communications with ATC

Source	Data (Quote or Summary)
p. 184/322	The Lion Air OM-part A describes that during abnormal and emergency situations, ATC communication is the task of PF which in this flight was the captain, while completing procedure is the task of PM. During this flight, the ATC communication and completing checklist were handled by the FO as PM. *Volpe Comment: The crew deviated from their standard roles. The FO should not have been handling the ATC communications while he was completing the non-normal procedure.*
p. 182/322	The flightcrew workload increased with the ATCo communication when the controller provided eight heading instructions after the flightcrew reported that the aircraft was experiencing a flight control problem. The ATCo considered a flight control problem was not an emergency condition which was consistent with ATS SOP of AirNav Indonesia branch JATSC. There was also no objection by the flightcrew to the ATCo heading instruction and the flightcrew did not declare an emergency. The absence of a declaration of urgency (PAN PAN) or emergency (MAYDAY), or asking for special handling, resulted in the ATCo not prioritizing that flight. With priority, ATC would not require LNI610 to maneuver repeatedly. *Volpe Comment: There was no objection by the flightcrew to the ATC heading instructions.*

Source	Data (Quote or Summary)
p. 22/322 p. 82/322 Volpe Summary	Approximately 30 seconds after takeoff (and stick shaker, takeoff config, and IAS disagree warnings) Tower controller instructed LNI610 to contact Terminal East (TE) controller. FO acknowledged. TE controller identified aircraft on RADAR and cleared to 27,000 feet. FO asked TE controller their RADAR altitude FO requested from TE controller any point to hold per CA direction. TE controller asked nature of problem. FO responded they are experience flight control problem. TE controller did not respond to FO's request. TE controller advised aircraft was descending (1,700 to 1,600 feet) and asked the intended altitude. FO advised TE controller 5,000 feet. TE controller issued climb to 5,000 and 050 heading. FO asked TE controller their speed on RADAR display. TE responded 322 knots.
p. 26/322 p. 85/322 Volpe Summary	TE controller issued six heading changes over the next four minutes. One was for traffic. TE controller asked if they "have some problem…". FO advised they had a flight control problem. TE issued maintain previous heading and change to Arrival (ARR) frequency. FO contacted ARR controller and advised of flight control problem. ARR gave runway and new heading. After aircraft control switch, Captain requested direct to ESALA waypoint due to weather and was approved. Captain advised ARR controller aircraft altitude could not be determined. ARR responded "LNI610 no restriction". Captain requested block altitude 3,000 feet and above. ARR asked what altitude flightcrew wanted. Captain responded, "FIVE THOU...". ARR approved. Flight ended 20 seconds later.

Timeline

This section summarizes key points from the CVR transcript (p. 81-87/322).

Source	Data (Quote or Summary)
p. 21/322	At takeoff: At 23:20:16 UTC, the FO called 80 knots and the DFDR recorded the airspeed indicator on Captain's Primary Flight Display (PFD) indicated 79 knots while on the First Officer's (FO) PFD indicated 81 knots. The DFDR also recorded difference angle between left and right Angle of Attack (AOA) sensor, which was about 21° which continued until the end of recording. The DFDR indicated that the Flight/Director (F/D) on the Captain Primary Flight Display (PFD) showed 1° down, while on the first officer PFD showed 13° up.
p. 81-87/322 Volpe Summary	Flight took off at 23:20:33 UTC, which is 6:20 local time (daytime). Scattered clouds with bases likely at 2,000 feet. Total time from rotation to end was 11 minutes 22 seconds.
p. 82/322 Volpe Summary	Three seconds after V1 and rotate calls, stick shaker started, plus IAS/ALT Disagree warnings soon after. CA asked FO to perform memory items for airspeed unreliable for the first time about one minute after takeoff. Flaps retracted two minutes after takeoff then MCAS AND activates. CA instructs FO to select flaps 1 shortly after.
p. 23/322 Volpe Summary	Flaps later moved to 5 and back to 1 without discussion.
p. 25/322 Volpe Summary	At 23:25:13 flaps returned to up with no discussion noted on CVR. MCAS activates multiple times, approximately 22 times when CA was PF, and four or five times when FO was PF.
p. 82/322 Volpe Summary	Approximately four minutes after takeoff, FO attempts to find airspeed unreliable checklist. The CA first asks for the checklist at 23:24:11, the FO says to standby. At 23:25:11 (one minute later), the FO says there is no airspeed unreliable checklist, after turning pages. Finally, at 23:25:17, the FO gives the page number for the checklist and starts reading it 3 seconds later. It took well over one minute to locate the checklist. Over the next 2.5 minutes the FO continues to read the checklist with multiple controller interruptions.
p. 85/322 Volpe Summary	Crew interacts with flight attendant and asks to call engineer to flight deck.

Source	Data (Quote or Summary)
p. 87/322 Volpe Summary	Ten minutes after takeoff captain again asks FO to take over aircraft control for a while and FO accepts (as of 23:30:54 UTC). *Volpe Comment: CA did not mention how he had been maintaining control before switch.*
p. 29/322	At 23:31:15 UTC, MCAS activated for about 3 seconds until it was interrupted at 23:31:17 when the FO commanded ANU trim for 1 second, the pitch trim changed to 2.9 units and the FO's column sensor force recorded 65 lbs. of back pressure. At 23:31:27 UTC, MCAS activated for 8 seconds, the pitch trim changed to 1.3 units and the FO's control column sensor force recorded 82 lbs. At 23:31:36 UTC, the FO exclaimed the aircraft was flying down which then the Captain responded: "it's ok". At 23:31:43 UTC, MCAS activated for 4 seconds, the pitch trim changed to 0.3 units and the FO's control column sensor recorded 93 lbs.
p. 79/322 Volpe Summary	Figure 29 (DFDR plot). FO experiences four or five MCAS aircraft nose-down trim events after taking control of aircraft.

Operations

These points are summarized in Sections 2.3.2 "Flight Crew Workload" (p.182/322), 2.3.3 "Flight Crew Awareness" (p.183/322), and 2.3.4 CRM (p.184/322).

Source	Data (Quote or Summary)
p. 80/322	There were no recorded indications of autopilot engagement during the flight.
p. 82 & 87/322 Volpe Summary	CA requested to transfer control to FO twice. • First time, about 2 minutes into the flight, the FO responded with "standby" and continued responding to ATC • Second time, about 10 minutes into the 11-minute flight), the FO was unable to control aircraft after he accepted handoff

Source	Data (Quote or Summary)
p. 184/322	The Lion Air OM-part A describes that during an abnormal situation, “the PIC must allocate the crew duties to ensure that the highest level of situation awareness is maintained in the cockpit and cabin. This will prevent all attention being totally directed at resolving the emergency or abnormal situation to the detriment of safe flight. Any ambiguities, confusion, unresolved discrepancies or use of improper procedures must be discussed immediately, and if necessary, a missed approach initiated to allow remedial action at safe altitude.” The Captain did not verbalize allocation of the crew duties and did not clearly verbalize the plan to hold or to troubleshoot the aircraft problems. The Captain and FO did not have a shared mental model of the situation as exhibited by their lack of clear and effective communication. For example, the FO did not conduct memory items for the airspeed unreliable NNC when asked by the Captain and the Captain did not verify that the FO did not conduct the memory items when asked. The Captain also did not verbalize information regarding the aircraft state or the need to trim out increased column forces when he transferred control to the FO near the end of the flight.
p. 181/322	Despite the flightcrew’s attempt to execute of the NNC, due to increase workload, and distractions from the ATC communication, the NNC was unable to be completed in that situation. The unfinished NNC made it difficult for the flightcrew of LNI610 to understand the aircraft problem and how to mitigate the problem.
p. 182/322	Typical markers for high workload include dropped task, reduced task performance, and reduced verbalization. High workload for the Captain could be identified by his short responses to the FO, his difficulty to maintain an assigned heading and altitude due to repetitive MCAS activation, and his failure to manage speed and thrust, and call out flap retraction points. *Volpe Interpretation: Crew responded with short answers or did not respond to each other’s communications.*
p. 185/322	The Captain did not verbalize to the FO the difficulty in controlling the aircraft and the need for repeated aircraft nose up trim. Subsequently, the FO was not able to anticipate the need for repeated pitch corrections and nose up trim and did not use adequate electric trim to counter repetitive MCAS activations while controlling the aircraft [near the end of the flight]. Similar statement in official findings (p. 215/322): (76) During the multiple MCAS activations, the Captain managed to control the aircraft altitude. The Captain did not verbalize to the FO the difficulty in controlling the aircraft and the need for repeated aircraft nose up trim. The FO was preoccupied with completing the NNC and not monitoring the flight progress. Subsequently, the FO did not provide adequate electric trim to counter multiple MCAS activations.

Source	Data (Quote or Summary)
p. 215/322	(75) Both flightcrew of LNI610 being preoccupied with individual tasks indicated that the crew coordination was not well performed. The Captain and FO did not have a shared mental model of the situation as exhibited by their lack of clear and effective communication. Most of the components of effective crew coordination were not achieved, resulting in failure to achieve the common goal of flying the aircraft safely.
p. 182/322	The absence of a declaration of urgency (PAN PAN) or emergency (MAYDAY), or asking for special handling, resulted in the ATCo not prioritizing that flight. With priority, ATC would not require LNI610 to maneuver repeatedly.

Predictability, Reliability, and Intended Function of Systems

Source	Data (Quote or Summary)
p. 183/322	The activation of stick shaker indicated that the aircraft was about to stall while the cockpit instrument indicated the pitch was relatively level and the speed relatively high. The cockpit instrument did not indicate that the aircraft was close to stall condition which contradicted to the stick shaker activation.

FAA Approval Issues

Source	Data (Quote or Summary)
p. 206/322	(5) Boeing conducted the Functional Hazard Analysis (FHA) assessment based on the FAA guidance and was also based on an assumption that the flightcrew was highly reliable to respond correctly and in time within 3 seconds. 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.
p. 207/322	(9) In the event of multiple MCAS activations with repeated electric trim inputs by flightcrew without sufficient 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. The cumulative mis-trim could not be countered by using elevator alone which is contrary to the Boeing assumption during FHA.
p. 217/322	(Contributing Factor 1) During the design and certification of the Boeing 737-8 (MAX), assumptions were made about flightcrew response to malfunctions which, even though consistent with current industry guidelines, turned out to be incorrect.
p. 217/322	(Contributing Factor 2) Based on the incorrect assumptions about flightcrew response and an incomplete review of associated multiple flight deck effects, MCAS's reliance on a single sensor was deemed appropriate and met all certification requirements.

Source	Data (Quote or Summary)
p. 209/322	(25) The aircraft design should provide the flightcrew with information and alerts to help them understand the system and know how to resolve potential issues.
p. 210/322	(33) For the safety assessment of aircraft systems, the 14 FAR 25.1309 set the requirements for the design and installation of systems which include analysis of effects and probabilities of single, multiple and combined failures of systems. It assumed that flightcrew would correctly respond to flight conditions in case of such failures. Human error is not included in the probability analysis, even though the flightcrew is often used as a means to mitigate a failure condition.
p. 210/322	(34) When performing safety assessments to comply with 14 FAR 25.1309, Boeing followed the procedures set in FAA AC 25.1309-1A and the SAE ARP 4761 as the acceptable means of compliance. When doing the analysis, Boeing assumed that the flightcrew are completely reliable and would respond correctly and appropriately to the situations in time. During the accident and previous LNI043 flights, some of these assumptions were incorrect, since the flightcrew responded differently from what was expected.
p. 210/322	(35) 14 FAR 25.671 (c) requires that probable malfunctions of the flight control system must be capable of being readily counteracted by the flightcrew. This necessitates that normal flightcrew should be able to readily identify problems and respond quickly to mitigate them. However, during the accident flight multiple alerts and indications concealed the actual problem and made it difficult for the flightcrew to understand and mitigate it.
p. 210/322	(36) The Flight Standardization Board (FSB) process for the Boeing 737-8 (MAX) utilized airline line pilots to help ensure the requirements are operationally representative. The FAA and OEMs should re-evaluate their assumptions for what constitutes an average flightcrew's basic skill and what level of systems knowledge a 'properly trained average pilot' has when encountering failures.

Official Safety Recommendations

There are safety recommendations for the airline, the maintenance company, Boeing, Collins, Indonesian AirNav (ATC), FAA, and Directorate General of Civil Aviation (Indonesian CAA?)

Boeing

Source	Data (Quote or Summary)
p. 229/322	**04.M-2018-35.11** During the accident, multiple alerts and indications occurred which increased flightcrew's workload. This obscured the problem, and the flightcrew could not arrive at a solution during the initial or subsequent automatic AND stabilizer trim input, such as performing the runaway stabilizer procedure or continuing to use electric trim to reduce column forces and maintain level flight. Therefore, KNKT recommends that the aircraft manufacture to consider the effect of all possible flight deck alerts and indications on flightcrew recognition and response; and incorporate design, flightcrew procedures, and/or training requirements where needed to minimize the potential for flightcrew actions that are inconsistent with manufacturer assumptions.
p. 230/322	**04.M-2018-35.12** During certification phase, compliance was demonstrated by flight test pilots which normally have exceptional skill and experience. Flight test pilots generally have more knowledge about the aircraft design characteristics than normal pilots. This level of competence usually cannot be translated to most pilots… The FAA and OEMs should re-evaluate their assumptions for what constitutes an average flightcrew's basic skill and what level of systems knowledge a 'properly trained average flightcrew' has when encountering failures. Therefore, KNKT recommends that Boeing include a larger tolerance in the design is required to allow operability by a larger population of flight-rated pilots.
p. 233/322	**04.R-2018-35.23** 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 flightcrew was unable to maintain altitude. Therefore, KNKT recommends that Boeing and the FAA more closely scrutinize the development and certification process for systems whose malfunction has the ability to lead to loss of control of the airplane. (Repeated in **04.M-2018-35.13** (p. 230/322)
p. 230/322 p. 233/322	**04.M-2018-35.14,** p. 231, **04.R-2018-35.25** The flightcrew should have been provided with information and alerts to help them understand the system and know how to resolve potential issues. Flight crew procedures and training should be appropriate. Therefore, KNKT recommends to Boeing to develop the guidance for the criteria of information which should be included in flightcrew and engineer's manuals.

Source	Data (Quote or Summary)
p. 231/322 p. 233/322	**04.M-2018-35.15,** p. 231, **04.R-2018-35.26** The aircraft should have included the intended AOA DISAGREE alert message functionally, which was installed on 737 NG aircraft. Boeing and the FAA should ensure that new and changed aircraft design are properly described, analyzed, and certified. Therefore, KNKT recommends to Boeing that they ensure that certified and delivered airplanes have intended system functionality.

Lion Air

Source	Data (Quote or Summary)
p. 228/322	**04.O-2018-35.4** The investigation considered that the duration of hazard identification topic on the SMS training syllabus was insufficient. This may reduce the ability of employees to define and report a hazard. Consistently, the Lion Air safety report on December 2018 mostly consisted of occurrence report and only about five percent of hazard report. Therefore, KNKT recommends that Lion Air review the SMS training material and the duration of training.
p. 228/322	**04.O-2018-35.5** The LNI043 flight that experienced multiple malfunctions were considered caused or could have caused difficulties in controlling the aircraft. According to the ICAO Annex 13, CASR part 830 and OM-part A, the flight is classified as serious incident which required investigation by the KNKT in accordance with the Aviation Law Number 1 of 2009 and Government Decree Number 62 of 2013. Therefore, KNKT recommends that Lion Air improve their hazard report management enabling identifying the hazard and provides proper mitigation.

FAA

Source	Data (Quote or Summary)
p. 232/322	**04.R-2018-35.20** In the accident flight, the system malfunction led to erroneous information that initiated a series of events that were not correctly recognized and responded to by the flightcrew. This exposed issues that were not identified if FAR 25.1302 and 25.1309 were each considered separately in which system malfunction was followed by flightcrew limitation in identifying and mitigating the problem. There could be a potential gap between the two requirements when system malfunction is followed by crew fallibility. Therefore, KNKT recommends to review the requirements of the applicable FARs to consider any issue that may be overlooked when the requirements are considered separately.

Source	Data (Quote or Summary)
p. 228/322	**04.R-2018-35.21** In the accident flight, the system malfunction led to a series of aircraft and flightcrew interactions which the flightcrew did not understand or know how to resolve. This exposed issues that were not identified if FAR 25.1302 and 25.1309 were each considered separately in which system malfunction was followed by flightcrew limitation in identifying and mitigating the problem. There could be a potential gap between the two requirements when system malfunction is followed by crew fallibility. Therefore, KNKT recommends to review the requirements of the applicable FARs to consider any issue that may be overlooked when the requirements are considered separately.
p. 228/322	**04.R-2018-35.23**, See Boeing **04.M-2018-35.13** identical recommendations (p. 230/322).
p. 233/322	**04.R-2018-35.24** During the accident and previous LNI043 flights, the flightcrew initially responded in the same way, by pulling back on the control column. However, they did not consistently trim out the resulting column forces as had been assumed. As a result Boeing assumption was different from the flightcrew behavior and reaction time in responding to MCAS activation. Therefore, the KNKT recommends that the FAA work with international regulatory authorities to review assumptions on flightcrew behavior used during design and revise certification processes to ensure assumptions used during the design process are validated.
p. 233/322	**04.R-2018-35.25,** See Boeing **04.M-2018-35.14,** identical recommendations. (p. 231/322)
p. 233/322	**04.R-2018-35.26,** See Boeing **04.M-2018-35.15,** identical recommendations. (p. 231/322)

AirNav Indonesia

Source	Data (Quote or Summary)
p. 229/322	**04.A-2018-35.9** The flightcrew of LNI610 asked to the TE controller of the aircraft altitude detected on the ATC radar display which might be an effort to obtain other source of information. The asking of aircraft altitude to the controller will not get any additional information as the ATC radar display is received data from aircraft transponder which transmitting the cockpit indications. Therefore, KNKT recommends providing information to the flightcrew that the altitude indication on the ATC radar display was repeating data from the aircraft.

NTSB Safety Recommendations

Source	Data (Quote or Summary)
p. 226/322 Also in NTSB Report ASR-19-01	Section 4.7 The NTSB recommendations to FAA are as follows: a. 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) b. Require that for all other US 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) c. 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) d. 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) e. 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)

B.V Ethiopian 302

Source(s)

Ethiopian Aircraft Accident Investigation Bureau (EAIB) Final Report (December 23, 2022). Ethiopian Airlines Group B737-8 (MAX) Registered ET-AVJ 28 NM Southeast of Addis Ababa, Bole International Airport, March 10, 2019. (Report No. AI-01/19)

Additional information about the accident was gathered from the following public documents:

- NTSB (January 13, 2023). *Response to Final Aircraft Accident Investigation Report.* Ethiopian Airlines Flight 302; Boeing 737-8 MAX, ET-AVJ; Ejere, Ethiopia; March 10, 2019.
- NTSB (May 12, 2022). *US Comments on Draft Aircraft Accident Investigation Report.* Ethiopian Airlines Flight 302; Boeing 737-8 MAX, ET-AVJ; Ejere, Ethiopia; March 10, 2019.
- Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA). *BEA Main Comments on the draft Final Report for the accident that occurred on 10th March 2019 to the Boeing 737-8 MAX registered ET-AJV operated by Ethiopian Airlines.* https://bea.aero/en/investigation-reports/notified-events/detail/accident-to-the-boeing-737-registered-et-avj-and-operated-by-ethiopian-airlines-on-10-03-2019-near-bishoftu-investigation-led-by-eaib-ethiopia/#onglet1-ong (Retrieved January 3, 2023.)[17]

Default references are to the PDF file of the final report (331 pp).

Bulleted Summary

What happened, in brief?

Shortly after takeoff, the AOA sensor failed. This produced multiple warnings beginning with the stick shaker on the left (captain's) side.

- The left stick shaker activated a few seconds after takeoff and lasted throughout the short (5-minute) flight.
- The Master Caution and Anti-Ice warnings activated initially. Several other warnings and some confusing indications appeared at various points in time (e.g., GPWS alerts, overspeed clacker, IAS Disagree, pitch flight director bars disappearing).
- The crew were expected to be familiar with and to follow the procedures released after the Lion Air accident (five months earlier) to prevent potential repeated nose down trim inputs from the flight control computer (FCC). Still, they were not able to manage the situation.
- The FCC MCAS function activated four times.

[17] Our analysis is based on a file posted online by the BEA in January 2023. This material has since been updated but stayed the same in substance. The September 2023 BEA website information matches the NTSB report more closely than the January 2023 version.

What happened, in brief? (continued)

- During the third MCAS activation, the crew had put the stabilizer trim in the cutout position, so it did not produce another nose down command. Later, the crew returned the stabilizer trim to normal function and resumed use of electric trim. After that, MCAS activated for the fourth and final time.
- All on board fatally injured.

What was/were the malfunction(s)?

The AOA sensor failed due to impact with a foreign object, most likely a bird.

- The AOA sensor also failed in the Lion Air 610 flight. However, the difference between the left and right AOA sensors reached as high as 59° for Ethiopian Airlines 302, while there was consistent 21° bias for the Lion Air flight.
- The NTSB determined such a large a bias for Ethiopian Airlines 302 was consistent with the separation of the AOA vane from the airplane due to impact with a foreign object.
  - The NTSB conclusions were not included in the final report as required by ICAO, which is why NTSB released its own statement after the final report was released.
  - The EAIB has an alternate explanation of the AOA failure that the NTSB discounts.
  - The NTSB specifically disputes the EAIB findings No. 20, 50, 54, 55, 64, and 65, which are related to the root cause of the AOA sensor failure.

Who were the flightcrew on board and what were their qualifications?

There were two pilots. The FO was relatively inexperienced.

- The CA had over 8000 flight hours total, over 4000 hours in the 737/7-8, and 103 hours on the 737 MAX.
- The FO had 361 flight hours total, of which 207 were in the 737/7-8 and MAX.
- The CA was PF entire time (though FO attempted to assist captain resist control forces per captains' direction).

What training did the flightcrew have related to this event or malfunction specifically?

Both crew members had received recurrent training on the events that occurred in the accident within the past few months. The training covered stick shaker activation, IAS DISAGREE, runaway stabilizer, use of trim wheel, reaction to multiple non normal events, and task prioritization.

- The stick shaker activation training would have covered the procedures for approach to stall or stall recovery.

What training did the flightcrew have related to this event or malfunction specifically? (continued)

- The crew had received the AD and Bulletin with guidance that resulted from the Lion Air accident. However, it is not clear how well they understood this guidance.
    - It was pushed to them electronically (via email and an internal system, called Logipad).
    - The EAIB believes the AD was not clear about whether to use the autopilot and about the flap setting needed for MCAS activation. EAIB speculates this guidance might have been misinterpreted, to account for some of the crew's actions. The NTSB discounts this speculation, saying that the information about cutting out the stabilizer trim and keeping it cut out, was clear.
- The EAIB also speculates that the crew did not realize how much force would be needed for manual trimming, but the NTSB states that the FCOM had sufficient information.
    - The FCOM says: "In extreme cases it may be necessary to aerodynamically relieve the air loads to allow manual trimming. Accelerate or decelerate towards the in-trim speed while attempting to trim manually."
    - The NTSB states that the EAIB report "misses an opportunity to evaluate the effectiveness of air carrier training related to the relationship between airspeed and manual trim control forces and make safety recommendations, as appropriate, to improve industry training."
- The crew had taken a computer-based differences-training course for the 737 MAX but this training did not cover MCAS.

What did the flightcrew experience during the event?

The event began with a stick shaker on the left side (captain's), followed by multiple visual and aural alerts.

- The stick shaker, a tactile alert, continued for the duration of the flight.
- The Master caution and right side (FO) annunciator illuminated with indications about the AOA vane and anti-ice protection systems. The NTSB finding that the AOA vane separated from the aircraft is consistent with these warnings.
- The left and right-side airspeed and altitude indications diverged, although the crew did not mention noticing the discrepancy.
- The GPWS aural alert sounded multiple times.
- The overspeed warning sounded.
- The pitch flight directors went out of view due to the divergence between the left and right side. The divergence was due to the erroneous AOA value from the left side.
- According to calculations, the IAS and ALT DISAGREE alerts should have appeared, although the crew conversation does not mention them. It is not clear whether the crew noticed the alerts.

What did the flightcrew experience during the event? (continued)

- The flightcrew attempted to control the pitch by exerting backpressure on the control column, but the forces required were too great to manage.
    - The autothrottle remained engaged, which was a factor in the excessive control column forces.
    - The autothrottle remained responsive to the erroneous AOA input, and as a result remained at takeoff thrust.

What did the flightcrew do in response to the malfunction(s)?

The flightcrew attempted to maintain control of the pitch primarily by exerting backpressure on the control column, but the force required was excessive. There were a number of actions the crew should have taken that they did not.

- The crew did not apply the Stall recovery procedure in response to the stick shaker, which is a memory item. In particular, they did not disengage the autopilot and autothrottle, they only applied nose-down input.
- The expected crew response was to take manual control of the thrust, but this was not done.
- The crew did not identify the lack of transition of autothrottle from the ARM mode to N1.
- The CA ordered four attempts to engage the autopilot. The autopilot engaged briefly, for 32 seconds, on the third attempt. However, the stall recovery procedure required the autopilot to be disengaged.
- The flightcrew cutout the stabilizer trim briefly, but then turned it on again. The available evidence for this accident did not indicate why the crew performed this action. The bulletin and emergency AD direct crews to ensure that the switches "stay in the CUTOUT position for the remainder of the flight."
- The CA used the electric trim to counteract the MCAS nose down commands several times, but he never applied the trim inputs for sufficient duration to relieve the high control column forces.
    - It is not clear why the CA's inputs did not last long enough.
    - In observations made during simulator sessions for the investigation, pilots felt it was instinctive to use the electric trim to counter the nose down situation.
- The CA asked the FO to trim the aircraft manually at one point, but the FO was unable.
- The flightcrew did not discuss the IAS and ALT DISAGREE messages, so the BEA concludes the crew did not see these messages.

What did the flightcrew do in response to the malfunction(s)? (continued)

- The flightcrew did not mention or attempt to use any checklist or non-normal procedure.
    - The NTSB comments that the crew did not appropriately follow non-normal procedures in response to the unreliable airspeed, stall warning, and runaway stabilizer.
    - The crew also did not respond as expected to the overspeed warning by disconnecting the autothrottle and reducing power.
    - The crew did not apply the Approach to Stall or Stall Recovery maneuver checklist in response to the stick shaker activation.
- The flightcrew did not discuss any issue related to the stick shaker.
- There are gaps in understanding of the crew response. These areas were not fully examined by the investigation board.

What else did the flightcrew do to manage the overall situation?

The crew's efforts were focused on maintaining backpressure to increase pitch. They did not communicate clearly with ATC or others about their situation.

- The flightcrew continued to communicate with ATC normally even as the stick shaker was active; they did not declare a PAN PAN or emergency at any point. ATC did not query them about their condition.
- There is no mention of communications with the cabin crew, passengers, or airline operations during the event.

Overview of Event

Shortly after takeoff (8:38 am Local time, daylight, visual flight conditions), the left AOA sensor malfunctioned resulting in multiple erroneous indications on the captain's PFD. The left stick shaker activated a few seconds after takeoff and lasted throughout the short (5-minute) flight. The Master Caution and Anti-Ice warnings activated initially. Several other warnings and confusing indications appeared at various points (e.g., GPWS alerts, overspeed clacker, IAS Disagree, pitch flight director bars disappearing).

The Flight Control Computer (FCC) Maneuvering Characteristics Augmentation System (MCAS) function activated four times. The crew cut out the electronic stabilizer trim at one point, but they turned it back on again later. All on board were fatally injured.

NTSB and BEA Responses to EAIB Final Accident Report

Four days after the EAIB released its final report, the NTSB released a statement about the EAIB final report noting that it did not include earlier NTSB comments as an attachment as required by ICAO Annex 13. The NTSB found that the final report included significant changes from its last draft and that the final report contained new information that the NTSB had not reviewed before it was issued.

NTSB released comments on the final EAIB accident report on January 13, 2023. Overall, the NTSB concurs with the EAIB's investigation of the MCAS and related systems and the roles that they played in the accident. However, the NTSB states the EAIB's claimed initial cause of the left AOA sensor failure is not supported. In addition, the NTSB notes that many operational and human performance issues present in this accident were not fully developed as part of the EAIB investigation. These issues include flightcrew performance, CRM, task management, and human-machine interface. The NTSB specifically disputes the EAIB findings No. 20, 50, 54, 55, 64, and 65, which are related to the root cause of the AOA sensor failure. NTSB also found EAIB finding No. 78 (regarding information available to the crew about the flaps setting and MCAS) to be misleading.

Regarding flightcrew performance, the NTSB faults the EAIB for not covering several aspects of performance related to CRM, including:

- Division of duties
- Operator CRM training
- Expected/as-trained CRM performance
- Flight deck communication
- First officer's limited flight experience
- Potential authority gradient

On January 3, 2023 the BEA released a statement with six comments, most of which are related to flightcrew response. The BEA generally agrees with the analysis of the crew performance for the latter two phases of the accident scenario, from the time the stab trim cutout switches were in the cutout position to the end of the flight. However, the BEA considers that some aspects of the analysis of the crew performance in the earlier phases of the flight are insufficiently developed and could improve the understanding of what could have been done by the crew to modify the outcome of the flight.

Flightcrew on Board

Source	Data (Quote or Summary)
Volpe Summary	There were two pilots. The captain was PF entire time though FO attempted to assist captain resist control forces per captains' direction.

Similarity of Event to Other Known Cases and Resolution

Source	Data (Quote or Summary)
Volpe Summary	Similar to Lion Air 610 (and Lion Air 43) events, an AOA sensor malfunctioned This was a single source of bad data with propagating effects. According to the NTSB, the AOA most likely failed in this accident due to impact from a foreign object such as a bird. The EAIB has an alternate explanation that the NTSB discounts. The AOA sensor also failed in the Lion Air 610 flight. However, the difference between the left and right AOA sensors reached as high as 59° for Ethiopian Airlines 302, while there was consistent 21° bias for the Lion Air flight. The NTSB determined such a large a bias for Ethiopian Airlines 302 was consistent with the separation of the AOA vane from the airplane due to impact with a foreign object. The Ethiopian Airlines 302 accident occurred within 5 months of the Lion Air Flight 610 accident. The Technical Advisory Board report provided guidance on returning aircraft to service, including changes to MCAS and crew training.

Initial and Subsequent Malfunction(s)

Source	Data (Quote or Summary)
p. 17/331	Shortly after liftoff, the left Angle of Attack sensor recorded value became erroneous and the left stick shaker activated and remained active until near the end of the recording. In addition, the airspeed and altitude values from the left air data system began deviating from the corresponding right side values. The left and right recorded AOA values began deviating. Left AOA decreased to 11.1° then increased to 35.7° while the right AOA indicated 14.94°. Then after, the left AOA value reached 74.5° in ¾ seconds while the right AOA reached a Maximum value of 15.3°, the difference between LH and RH AOA was 59°and near the end of the recording it was 49°.
NTSB Comments 1/13/2023 p. 2/7	The final report does not provide any details to support the EAIB's statements about the existence of an electrical problem related to the left AOA sensor. The US team found that the erroneous AOA sensor output was caused by the separation of the AOA sensor vane due to impact with a foreign object, which was most likely a bird. During the accident investigation, the NTSB provided the EAIB with the evidence supporting this finding. In fact, each set of NTSB comments detailed this evidence.

Source	Data (Quote or Summary)
NTSB Comments 1/13/2023 p. 3-5/7	For the following reasons, the US team believes that an electrical failure affecting the left AOA sensor did not occur before the left AOA vane's impact with a foreign object:… [list follows]
p. 228/332	The airplane's left Angle of Attack (AOA) Sensor failed immediately after takeoff sending faulty data to the flight control system. The erroneous data in turn triggered the Maneuvering Characteristics Augmentation System (MCAS) which repeatedly pitched the nose of the airplane down until the pilots lost control.

Official Statements Related to Cause

There are 88 numbered Findings items in the Final Report findings starting on p. 246/331.

Here we extracted Findings related to cause of the event that were not disputed by NTSB.

Source	Data (Quote or Summary)
p. 255/331	3.2 Probable cause of the accident Repetitive and uncommanded airplane-nose-down inputs from the MCAS due to erroneous AOA input, and its unrecoverable activation system which made the airplane dive with the rate of -33,000 ft/min close to the ground was the most probable cause of the accident.
NTSB Comments on EAIB Draft report 5/12/2022 p. 2/9	However, the draft probable cause indicates that the MCAS alone caused the airplane to be "unrecoverable," and we believe that the probable cause also needs to acknowledge that appropriate crew management of the event, per the procedures that existed at the time, would have allowed the crew to recover the airplane even when faced with the uncommanded nose-down inputs. We propose that the probable cause in the final report present the following causal factors to fully reflect the circumstances of this accident: • uncommanded airplane-nose-down inputs from the MCAS due to erroneous AOA values and • the flightcrew's inadequate use of manual electric trim and management of thrust to maintain airplane control.

Source	Data (Quote or Summary)
p. 255-256/331	3.3 Contributing Factors 1. The MCAS design relied on a single AOA sensor, making it vulnerable to erroneous input from the sensor; 2. During the design process, Boeing failed to consider the potential for uncommanded activation of MCAS, but assumed that pilots would recognize and address it through normal use of the control column, manual electric trim, and the existing Runaway Stabilizer NNC. The OMB and Emergency AD issued after the Lion Air accident included additional guidance but did not have the intended effect of preventing another MCAS-related accident; 3. While Boeing considered the possibility of uncommanded MCAS activation as part of its FHA, it did not evaluate all the potential alerts and indications that could accompany a failure leading to an uncommanded MCAS; 4. The MCAS contribution to cumulative AOA effects was not assessed; 5. The combined effect of alerts and indications that impacted pilot's recognition and procedure prioritization were not evaluated by the Manufacturer; 6. Absence of AOA DISAGREE warning flag on the flight display panels (PFD); 7. The B737 MAX Crew difference CBT training prepared by Boeing and delivered to Pilots did not cover the MCAS system; 8. Failure by the manufacturer to design simulator training for pilots with regards to safety critical systems like MCAS with catastrophic consquences during undesired activation. 9. The manufacturer failed to provide procedures regarding MCAS operation to the crew during training or in the FCOM; 10. Failure by the manufacturer to address the safety critical questions raised by the airline which would have cleared out crew confusion and task prioritization
NTSB Comments on EAIB Draft report 5/12/2022 p. 2/9	In addition, we propose that the following contributing factors be included: • the operator's failure to ensure that its flightcrews were prepared to properly respond to uncommanded stabilizer trim movement in the manner outlined in Boeing's flightcrew operating manual (FCOM) bulletin and the FAA's emergency airworthiness directive (AD) (both issued 4 months before the accident) and • the airplane's impact with a foreign object, which damaged the AOA sensor and caused the erroneous AOA values.

Source	Data (Quote or Summary)
p. 247/331	(13) Erroneous AOA Sensor data ultimately triggered the Maneuvering Characteristics Augmentation System (MCAS) which repeatedly pitched the nose of the airplane down until the pilots lost control. (24) The activation of MCAS followed by GPWS aural alert with ongoing stick shaker, coupled with no failure flag or warning to indicate that the auto throttle has failed to transition to climb thrust at the critical phase of flight indicate that multiple happenings taking place simultaneously because of the overlapping effects of the erroneous AOA inputs;

Official Findings related to Flightcrew Training, Procedures, and Operations

There are 88 numbered Findings items in the Final Report findings starting on p. 246/331.

Here we extracted Findings that were not disputed by NTSB related to flightcrew training, procedures, and operations.

Source	Data (Quote or Summary)
BEA Comments p. 4/5	The following contributing factor, which emerges from the analysis is not precisely stated in the report: Degradation of the CRM which started immediately after the AOA vane failure and which didn't help the crew take the necessary actions to keep the plane under control although they had received an adequate recurrent training on situations that occurred in the accident flight.
BEA Comments p. 4/5	The BEA notes that the process of information dissemination and training at the airline level appears to have been insufficient to make it sure that the flightcrews had acquired the required knowledge on the MCAS described in the Boeing Multi Operator Message (MOM) issued by the manufacturer after the Lion Air accident in Indonesia.
p. 247/331	13. …Compounding factors included the pilots lack of awareness and training associated with MCAS, confusing alerts, and the startle factor.

Source	Data (Quote or Summary)
p. 250-254/331	(49) There was CBT training for a few hours long which was supposed to cover the difference between MAX and NG but there was no information related to MCAS description in the CBT (51) There was no information related to MCAS either in the FCOM provided by Boeing or in the AFM (72) Boeing's consideration regarding crew action to meet MCAS did not consider the cumulative effect of different flight deck alerts and warning as in the accident flights; (73) On ET 302 accident, the system failure led to a complicated series of events and flightcrew response did not match the assumptions used in the initial design process upon which the FHA classification of Major was based; (79) The absence of MCAS description in the FCOM, in the flightcrew training manual, and the absence of an AOA indicator made it difficult for the flightcrew to identify the problem on the accident Airplane and find the corrective measure to solve (86) The difference training from B737NG to B737MAX provided by the manufacturer was found to be inadequate
p. 258/331	Section 4.2 EAIB Interim Report Safety Recommendations (4) The difference training should also include simulator sessions to familiarize with normal and non-normal MCAS operation. The Training simulators need to be capable of simulating AOA failure scenarios.

Description of Aircraft Systems and Alerts

Source	Data (Quote or Summary)
General	A B737-8 (MAX)
Volpe Summary	There was no centralized notification system for system failures/malfunctions. The system in the aircraft is described in this section.

Source	Data (Quote or Summary)
p. 50/331 Volpe Summary	Master Caution Indicator and Probe Heat Panel Figure 9 shows the Master Caution and Anti-ICE warnings. There is a main MASTER CAUTION button that illuminates (yellow) on either side of the flight deck. On the FO side, there is a list of 6 possible systems to the left of the Master Caution light, one of which is the ANTI-ICE system. On the CA side, there is a similar box, but it lists different systems.  FIGURE9: MASTER CAUTION ANTI-ICE  FIGURE10: PROBE HEAT PANEL Figures 10 shows the Probe Heat Panel. To further diagnose the ANTI-ICE system error, the pilot must look at the overhead panel, where there are additional (visual/light) indicators, one of these is for the (left/right) vane heating monitor.
p. 69/331	The MCAS is a function within the Speed Trim System and, when activated, moves the stabilizer during nonnormal, flaps up, manual flight, high angle of attack maneuvers to provide a desirable increase in stick force gradient and improved static longitudinal pitch stability. Similar to the Speed Trim function, the MCAS function is also a flight control law contained within each of the two FCCs. Only one FCC at a time is permitted to send Speed Trim System commands to the stabilizer trim motor. At Airplane power-up, the master FCC defaults to the left side FCC; and will then alternate between the left and right FCC by flight.
p. 92/331 Volpe Summary	No discrete parameter records the MCAS activation. MCAS activation was detected from the FDR using the following conditions: Autopilot not engaged, flaps retracted, nose down trim activated.
p. 198/331	As the development of the 737 MAX- 8 progressed, the MCAS function was expanded to low Mach numbers to comply with the stall characteristics requirements specified in FAR 25.201 and FAR 25.203. MCAS is designed to function only during manual flight (autopilot not engaged), with the Airplane's flaps up, at an elevated AOA.

Source	Data (Quote or Summary)
p. 299/331	D.3 Stabilizer Trim Cutout Switches: There are two stabilizer trim cutout switches located next to each other on the aisle stand just aft of the flap lever. They are identified as the STAB TRIM PRI (stabilizer trim primary) cutout switch and the STAB TRIMB/U (stabilizer trim back up) cutout switch. If either switch is positioned to CUTOUT, power is removed from the stabilizer trim motor and neither main electric trim nor automatic trim can move the stabilizer.
p. 308/331	F.1 Autopilot The control column force must be less than 5 lbs. and the control wheel force must be less than 3 lbs. for the autopilot to engage. If the forces exceed these values, then attempting to engage the autopilot results in an autopilot disconnect warning. Upon autopilot disconnect, the autopilot disengage light on the Autoflight Status Annunciator will indicate disconnect by flashing red. The annunciator is located just above both the Captain's and First Officer's Secondary EFIS displays. This will be accompanied by an aural warning. The pilot may reset the warnings by pressing the autopilot disengage switch on the wheel or the light on the Warn Annunciator. The warning will continue for 2 seconds regardless of how quickly the pilot might reset the warning.
p. 25/331	GPWS DON'T SINK is an aural warning that sounds for 3 seconds.
Volpe Summary	PULL UP is the associated visual indicator, shown on the PFD.
p. 74/331	Figure 23 shows the visual IAS disagree and ALT disagree warnings on the PFD.
p. 54/331	737-8 (MAX) display system software did not correctly implement the AOA DISAGREE alert requirements. As with the Boeing 737 NG, the Boeing display system requirements for the Boeing 737-8 (MAX) called for the activation of the AOA DISAGREE alert as a standard feature on all Airplanes. The software delivered to Boeing, however, linked the AOA DISAGREE alert to the AOA position indicator, which is an optional feature on the Boeing 737 (MAX) series. Accordingly, the software activated the AOA DISAGREE alert only if an airline opted for the AOA indicator. At the time of the accident, Boeing advised that the AOA indicator had been selected by approximately 20% of airlines. Ethiopian Airlines did not select the optional AOA indicator feature on the PFD of their 737-MAX8 Airplane; therefore as a result, the AOA DISAGREE did not appear on ET-AVJ Airplane, even though the necessary conditions were met.

Flightcrew – General Experience

Source	Data (Quote or Summary)
p. 32/138	The captain graduated from Ethiopian Aviation Academy on July 23, 2010. ...he received his 737-800 First Officer type rating on January 31, 2011 and completed his PIC type rating for the 737-800 October 26, 2017, B737MAX differences training on 03 July, 2018.
Captain's Experience Summarized from table p. 32-33/331	Total 8122 hours; 4017 hours in 737/7-8 (since 2011); 1417 hours as 737/7-8 PIC (since 2017); 103 hours 737 MAX. Had also flown other Boeing aircraft including the 737/7-800, 737, 767, 777, and 787.
p. 34/331	The Captain's most recent simulator proficiency check was conducted on October 1, 2018. Line check was performed on 30 Nov 2018. *Volpe Comment: Captain's line check was done after the emergency AD and bulletin from the Lion Air 610 accident was released.*
FO's Experience Summarized from table p. 34/331	Total 361 hours; 207 hours in 737/7-8 and MAX No other transport category flight experience mentioned.
p. 34-35/331	...the first-officer's most recent simulator event was listed as a proficiency check and occurred on December 3, 2018. His line training/check (conducted in the B737 airplane) was completed on January 31, 2019. The first-officer's ECAA license was permitted to act as first-officer in commercial air transport operations in Boeing 737-7/800 dated December 12, 2018 and Boeing 737 MAX dated December 12, 2018 and qualified to act in the capacity of first officer effective February 01, 2019. *Volpe Comment: FO's proficiency check and line check were both done after the emergency AD and bulletin from the Lion Air 610 accident was released.*

Source	Data (Quote or Summary)
p.154/331	Section 1.17.2 Ethiopian Airlines Pilot Training School The Pilot Training School currently offers accredited training programs for Commercial Pilot License with Instrument and Multi-engine Rating (CPL/IR/ME) and Multi-crew Pilot License (MPL). Ethiopian airlines pilot training follows an integrated syllabus for the ground and flight training. The theoretical Knowledge Courses comprise a total time of 920 class hours, including 80 hours for general English and 120 hours for Aviation English course. The CPL training also trains and offers regulatory body requirements, such as the ICAO English Language Proficiency requirements that necessitate the provision of structured Aviation English Training in the Pilot Training School. It also provides rating services for ICAO Level 4 English Requirements for Pilots. The training program guides students seamlessly from ab-initio training to airliner type rating, using simulation designed for multi-crew training. It also addresses the increased rates of loss of control in airline operations through Upset Prevention and Recovery Training (UPRT). In addition, train the trainees to combat the continuing dominance of multi-crew human factors in accidents through Threat and Error Management (TEM) and Crew Resource Management (CRM)

Flightcrew – Training Related to Event

Numbered items are Final Report findings.

Source	Data (Quote or Summary)
p. 234/331	The accident crew has taken the MAX difference training in a 2 hour CBT training which was recommended by the manufacturer and approved by the regulators. The CBT training recommended by the manufacturer and approved by regulators was made available to the pilots through the Airline's Logipad application on designated computer devices to each pilot. The Logipad application has the additional function of the training process and evaluation. (Learning Management System) *Volpe Note: An instructor at the airline (who trained the Ethiopian Airlines 302 PF), described the training as 6 or even 8 hours long (p. 215/331). Another instructor said it was 2 hours long, but also mentions being on a laptop for 6 hours (p. 216/331). Both said there was no simulator component of the differences training.*

Source	Data (Quote or Summary)
Volpe Summary	The operator (Ethiopian Airlines) received the emergency airworthiness directive (AD) and Bulletin issued after the Lion Air accident a few months earlier. The AD explained that erroneous AOA input can cause multiple alerts and effects and how to respond (i.e., to cut out the stabilizer trim). The AD was incorporated into the Aircraft Flight Manual (AFM) revision of November 2018 (p. 39/331) and it was released to pilots through an internal system (Logipad). The system recorded that the pilots had uploaded the AD and Bulletin (p. 218/331). The documents were also sent to each flightcrew by email (p. 187/331). The elements covered during proficiency training for the accident crew are listed on p. 186/331 for the captain (Table 24) and for the First Officer on p. 187/331 (Table 25). Both pilots were trained on stick shaker activation, IAS Disagree, and other situations that occurred during the accident flight. Additional supporting quotes given below.
p. 39/331	Airworthiness Directives (AD) One of the entries in the AD compliance report was AD-2018-23-51, Titled "To Address this potential resulting nose down trim". 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 flightcrew to have difficulty controlling the Airplane, and lead to excessive nose-down attitude, significant altitude loss, and possible impact with terrain. The compliance report indicates that compliance was through AFM revision on 11.08.2018.
p. 183/331	The ADs, Bulletins and MOMs were released through the logipad system which the pilots are required to upload as a standard procedure before going for flight. The company has got a checking system who did and who didn't. Pilots are required to update their digital updated charts and performance data by their LOGIPAD and this was done at least every 7 days. *Note: Similar description of Logipad on p. 234/331, but does not mention distribution of MOMs.*
p. 218/331	From the Department data both accident pilots took briefing about the AD and Boeing's BULLETIN
p. 187/331	Flight operations revise the seasonal recurrent training/check syllabus to include RUNAWAY STABILIZER Non-normal procedure practice and ensured that all crew members have received the AD and OMB by uploading them on Logipad. Furthermore, the documents were also sent to each B737 flightcrew by email.

Source	Data (Quote or Summary)
p. 183/331	During initial and proficiency training, crew used to take the stick shaker activation, IAS Disagree, Stabilizer Runaway, use of trim wheel, reaction to multiple non-normal, task prioritize and CRM training. In the proficiency check the crew has taken training using a simulator and found satisfactory. These trainings were incorporated in FCTM, AMP, QRH, and FOTPM. *Volpe Comment: AMP and FOTPM are not defined acronyms in the final EAIB report.*
p. 160-161/331	1.17.6 Approach to Stall or Stall Recovery … Do all recoveries from approach to stall as if an actual stall has occurred. Immediately do the following at the first indication of stall (buffet or stick shaker). If the Airplane is stalled, the recommended steps are to hold the control column firmly, disengage the autopilot and auto throttle, then smoothly apply nose down elevator to reduce the angle of attack until buffet or stick shaker stops Note: Do not use flight director commands during the recovery. Table 23: Stall Recovery Procedure. (Lists details of actions to be performed by the Pilot Flying and Pilot Monitoring.)
BEA Comments p. 2-3/5	The BEA notes that in the months preceding the accident flight, the flightcrew had performed recurrent training on events which actually occurred during the accident flight: Stick shaker activation, IAS DISAGREE, Runaway stabilizer, use of Trim wheel, reaction to multiple non normal, task prioritization.
NTSB Comments 1/13/2023 p. 5-6/7	The NTSB acknowledges that information about the flap position required for MCAS to activate did not appear in Boeing's FCOM bulletin and the Federal Aviation Administration's airworthiness directive in response to the Lion Air flight 610 accident. However, Boeing provided that information in a multi-operator message (MOM-MOM-18-0664-01B), which was sent to all "737NG/MAX Customers, Regional Directors, Regional Managers and Boeing Field Service Bases" on November 10, 2018 (after the Lion Air accident but before the Ethiopian Airlines accident). Although the EAIB appended Boeing's multi-operator message to the final report, the EAIB failed to mention that the flaps information appeared in that document; thus, this finding is misleading. *Volpe Comment: The finding referenced as "misleading" is #78.*

Source	Data (Quote or Summary)
p. 237/331	ASSESSMENT OF THE BULLETIN FROM THE CONTENT The statement in the back ground of the bulletin gives unclear information: **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. The above highlighted phrase in the background information "calls attention to an AOA failure condition that can occur during manual flight only". Actually, an AOA failure can occur in either manual or autopilot flight. It is the activation of MCAS which is dependent on the status of autopilot engagement, not only the failure of AOA.
p. 226/331	FCTM indicates "Excessive airloads on the stabilizer may require effort by both pilots to correct the mis trim. In extreme cases it may be necessary to aerodynamically relieve the airloads to allow manual trimming. Accelerate or decelerate towards the in-trim speed while attempting to trim manually". Forces needed to turn the trim wheel with such a mistrim and high speed are much higher than those expected to be encountered during training or in operation and likely would have required either a two-handed effort by one pilot, or a two-pilot effort.
NTSB Comments on EAIB Draft report 5/12/2022 p. 6/9	…even though the FCOM did not include the effect of airspeed on the manual trim wheel forces, that information is specifically noted in the manufacturer's flightcrew training manual. For example, the manual states "if manual stabilizer trim is necessary, ensure both stabilizer trim cutout switches are in CUTOUT prior to extending the manual trim wheel handles. Excessive air loads on the stabilizer may require effort by both pilots to correct the mistrim. In extreme cases it may be necessary to aerodynamically relieve the air loads to allow manual trimming. Accelerate or decelerate towards the in-trim speed while attempting to trim manually." … The report misses an opportunity to evaluate the effectiveness of air carrier training related to the relationship between airspeed and manual trim control forces and make safety recommendations, as appropriate, to improve industry training.

Flight Deck Alerts During the Event

Numbered items are Final Report findings.

Source	Data (Quote or Summary)
p. 247/331	(9) Immediately after lift-off, the left stick shaker activated and remained active until the near end of the recording. It was followed by a Master Caution with the associated Anti-Ice message on the MCP;
p. 50/331	Master Caution and annunciator panel
Volpe Summary	Master Caution and right system (FO side) annunciator illuminated. The indications were AOA Vane and Anti-Ice Protection. The Left Alpha Vane indicator light on the overhead panel illuminated.
p. 21/331	As a result of the erroneous left AOA value, the left stick shaker activated and the red and black stripe band exceeded the displayed LH airspeed. The left stick shaker remained active until near the end of the recording.
p. 21/331	Right and left altitude and airspeed indications started diverging (the computations of LH values were affected by erroneous LH AOA values). From that time: - LH displayed altitude values were lower than the actual pressure altitude values displayed on the RH side. - LH displayed airspeed values were lower than the actual airspeed values displayed on the RH side. - The left pitch bar and the left Pitch Limit Indicator (PLI) rapidly moved downward (left pitch bar to -10°, the PLI to around 0°) *Volpe Comment: There is no mention of the two pilots noticing the discrepancy between the LH and RH displays.*
p. 22/331	- The Pitch F/D bars disappeared ("Bias Out of View" – BOV) on both RH and LH Primary Flight Displays (PFD), as the threshold for the comparator between LH and RH F/D pitch display below 400ft RA was reached. - On the LH PFD, invalid operational speeds, corrupted by the erroneous left AOA value, were displayed (LH stick shaker speed and LH minimum operation speed being greater than the LH computed airspeed). The current LH airspeed was inside the barber pole of the speed tape (black and red stripes underlying a dangerously too low speed or dangerously too high speed).
p. 150/331	Figure 86 shows activations of GPWS alerts. At 5:40:03, the GPWS alert 'DON'T SINK' sounded twice. During all these alerts, the 'PULL UP' message should have been displayed on both PFD.

Source	Data (Quote or Summary)
p. 28/331	At 5:41:21 the RH speed exceeded 340 Kt and the overspeed warning sounded. The captain said "the speed", the F/O replied: "Captain! Speed" The overspeed warning remained active until the end of the recording as RH airspeed remained above VMO. The RH speed values stabilized between 360Kt and 375Kt and on the LH PFD, the LH computed airspeed oscillated between 335 and 350Kt.
p. 226/331	The speed exceeded VMO 340Kt (varying between 360 and 375Kt). The over speed warning triggered. The captain said « THE SPEED » at the start of the airspeed clacker (05:41:21.) to which the F/O responded 'SPEED' at 05:41:29. *Volpe Comment: The EAIB goes on to describe the large amount of physical effort the pilots used to try to control the aircraft. However, the pilots should have reduced throttle to reduce control forces in response to the stick shaker, and they did not.*
p. 249/331	33. The right hand speed exceeded 340Kt and overspeed warning sounded. It remained active until the end of the recording. The RH speed values varied between 360Kt and 375Kt (RH values). The LH computed airspeed oscillated between 335Kt and 350Kt.
p. 247/331	10. IAS, ALT DISAGREE alerts were not recorded in the FDR, but the time of appearance has been computed, as per computation, the IAS disagree alert should normally have triggered at 5 h 38 min 49 s, and stopped at 5 h 43 min 28 s; and no recording of the pilot's conversation about the alerts appearing on the PFD.
p. 152/331	These alerts [IAS disagree and ALT disagree] were not recorded in the FDR. Their time of appearance has been computed, as per computation, the IAS disagree alert should normally have triggered… [various times provided]
p. 247/331	12. While the loss of valid FMC command did not trigger any alert or mode reversion, the underlying cause (erroneous AOA) should have triggered the IAS DISAGREE and ALT DISAGREE alerts, but from the manufacturer's computations, conditions were met for the IAS DISAGREE and ALT DISAGREE alerts to appear on both PFD's;
NTSB Comments on EAIB Draft report 5/12/2022 p. 5/9	Although the FDR was not programmed to record the presence or absence of the IAS DISAGREE and ALT DISAGREE messages, all conditions were met for the alerts to be presented to the crew. […] As explained in detail in the report, a software discrepancy caused the AOA DISAGREE message not to appear, but the software discrepancy was unrelated to, and had no effect on, the display of the IAS DISAGREE and ALT DISAGREE messages

Source	Data (Quote or Summary)
p. 145/331	Summary of AOA impact on F/D pitch command Once the LH AOA values diverged from the RH AOA values, the LH pitch F/D bar provided command that were not consistent with the true state of the Airplane and the engaged modes. LH F/D pitch bar was BOV (biased out of view) 6 times. Each time, airborne systems detected an important inconsistency: - The first instance was due to a divergence between RH and LH pitch F/D commands, when the Airplane was below 400 ft. - The remaining instances were due to the Airplane not deserving the minimum climb rate during level change mode. During manual flight, while the crew was pulling on the column and successful in making the Airplane climb, the pitch F/D bar would appear; however, once the Airplane starts to descend then the pitch F/D bar would be removed thus causing the disappearing and reappearing behavior of the pitch F/D bar. - Each time the LH pitch F/D bar automatically reappeared, without any crew action. The underlying cause of the anomalous LH pitch F/D behavior was confirmed to be erroneous LH AOA sensor values. Erroneous AOA results in display of the IAS DISAGREE and ALT DISAGREE alerts. The appropriate NNC for these alerts is the Airspeed Unreliable NNC, which, as a memory item, requires that the crew turn off both flight directors. *Volpe Comment: The stall training also requires flightcrew to turn off the flight director (p. 160/331). It is not clear whether the flightcrew were aware of the IAS and ALT DISAGREE conditions, but they must have been aware of the stick shaker.*
p. 26/331	…FMC did not send any valid command to A/T. The A/T stayed in the Arm Mode. The loss of valid FMC command did not trigger an explicit alert but did result in the FMA continuing to display “ARM” instead of changing to “N1” as would normally be expected.
p. 127-8/331	LH ADIRU provided the recorded LH computed airspeed values. These recorded values never showed any invalidity pattern during the whole flight of the event. LH ADIRU provided output data without any invalidity information. As a consequence, - SPD flag never appeared on the PFD - ALT flag never appeared on the PFD

Flightcrew Responses to Alerts

The final report analysis section (Section 2, starting p. 219-239) is where EAIB considers crew actions.

General

Source	Data (Quote or Summary)
p. 231/331	The stick shaker here represented a major disruption in managing the situation and the rapid onset of multiple inconsistent cues and abnormalities since take-off impacted the crew's ability to perceive the situation. The crew was in an unprecedented situation. Records at the airline level show that the crew had received training in accordance with Boeing guideline in the FCTM. In the event flight the pilot's attention was consumed with multiple alerts and managing the flight path at the same time. The effect of airspeed indication giving the pilot two different warnings, i.e. dangerously low airspeed indicated by stick shaker, minimum manoeuvring band above current airspeed versus high airspeed indicated by the numbers in the speed tape could have confused the crew. *Volpe Comment: These are speculations by the EAIB.* *Volpe Comment: There was no flightcrew conversation related to actions to take in response to stick shaker (p. 247/331).*
BEA Comments p. 1-2/5	Stick shaker activation requires application of the Approach to Stall or Stall recovery procedure, which is a memory item. As described in the FCOM/QRH, the first steps in the Approach to Stall or Stall Recovery procedure are to hold the control column firmly, disengage the autopilot and authrottle and then smoothly apply a nose down input. Only the nose down input was performed by the flightcrew.
BEA Comments p. 2/5	As the flightcrew failed to apply the Approach to Stall or Stall Recovery Maneuver and the Airspeed Unreliable Non-Normal Checklist, the autothrottle remained engaged. Due to the AOA vane separation, the autothrottle failed to transition to N1 mode and remained in ARM with takeoff thrust. The expected crew reaction was to take manual control of the thrust. This was not done, most probably because the lack of transition of the autothrottle from ARM to N1 was not identified by the crew.
BEA Comments p. 3/5	As no thrust reduction was performed by the flightcrew, airspeed increased which, in combination with insufficient trim, caused an increase of the forces on both the control column and the manual trim wheel.

Source	Data (Quote or Summary)
NTSB Comments on EAIB Draft report 5/12/2022 p. 5/9	The EAIB draft report incorrectly states (in several locations) that the MCAS made control of the airplane “impossible” but neglects to state that, if the crew had manually reduced thrust and appropriately used the manual electric trim, the airplane would have remained controllable despite uncommanded MCAS input. The flightcrew’s failure to reduce thrust manually and the excessive airspeed that resulted played a significant role in the accident sequence of events. … Because the autothrottle remained engaged and responsive to the erroneous AOA inputs, the autothrottle did not transition to N1 mode and remained in the ARM mode with takeoff thrust. The expected crew response is to manually control thrust in this situation; however, the lack of manual control and the absence of flightcrew conversation regarding the thrust settings indicate that the crew did not notice the autothrottle’s failure to transition to N1, even when the aural overspeed warning triggered as the airplane accelerated beyond about 340 knots
p. 132/331	During the whole flight of the event, A/T stayed engaged and no A/T warning triggered. At the beginning of the flight, the A/T was in ARM mode.
p. 22-30/331 Volpe Summary	Captain ordered four attempts to engage the autopilot. The autopilot successfully re-engaged at about 1000’ for 32 seconds, otherwise did not engage. *Volpe Comment: Reason for autopilot disconnects were unclear to crew. They made repeated attempts to engage autopilot. It is not clear why the crew persisted in trying to engage the autopilot.*
p. 26/331	The F/O then twice suggested “stab trim cut out?” The Captain replied “yes yes do it”. The stab trim cut-out switches were most likely put in the cut-out position at about 5 h 40 min 38 s
p. 138/331	Note: the investigation concluded that the F/O most likely moved the stab trim switches into the CUTOUT position at 5 h 40 min 38 s.
p. 26-29/331 Volpe Summary	FO moved stabilizer trim switches to the cutout. Captain requested FO to try moving the trim manually. FO communicated to captain that manual trim was not working. Captain told FO to try. The FO was unable to change trim manually while stabilizer trim cutout was reported to be active.

Source	Data (Quote or Summary)
p. 228/331	During the radio communications with the ATC, the F/O's action on the control column was released which increased forces on the Captain's control column. The Captain then requested the F/O to check the Master Caution. Then, they both announced "left alpha vane". The FDR data at that time is consistent with the crew pressing the Master Caution recall button to review the existing faults. This might indicate the captain probably wanted to reassess the faults and get to the root cause of the problem which started when they first had a master caution light right after lift-off. *Volpe Comment: EAIB is speculating about the crew's thinking.*
p. 226/331	The possibility of both pilots applying force on the manual trim wheel in order to overcome the huge force that was required to turn the manual trim wheel was over ruled as it was found to be inconvenient as well as impractical due to the fact that the captain was holding the control column with a huge amount of force that required a two handed input to prevent the aircraft from diving. At different times during the event flight the captain was heard requesting assistance from his FO to pull with him as well.
p. 230/331	The flightcrew's attention was consumed by the repetitive nose down commands from MCAS, terrain alert and the desire to climb to a safe altitude. The sudden and unexpected change in the situation right after takeoff, and the distraction due to high noise level (stick shaker, and associated aural warnings) in the cockpit coupled with the uncontrollability of to control the airplane affected the effectiveness of their CRM.
NTSB Comments on EAIB Draft report 5/12/2022 p. 5/9	Given that the conditions were met for the IAS DISAGREE and ALT DISAGREE messages to be annunciated to the crewmembers, their lack of conversation or action in response to the annunciations should be explored in the context of the flight deck environment, workload, crew experience, and training.
BEA Comments p. 2/5	The crew never referred either to IAS DISAGREE or ALT DISAGREE messages, which supports the conclusion that the IAS DISAGREE and ALT DISAGREE messages were most probably not seen by the crew throughout the flight. The captain's resources, already affected by the multiple and confusing alerts, were further distracted by his insistence on engaging the autopilot instead of flying manually the aircraft. This may have further prevented him from identifying the IAS DISAGREE and ALT DISAGREE messages, and from applying the associated procedures.

Source	Data (Quote or Summary)
NTSB Comments on EAIB Draft report 5/12/2022 p. 5-6/9	Appropriately countering uncommanded nose-down inputs with manual electric trim nose-up inputs, as was expected per crew procedure described in the FCOM bulletin and the emergency AD, would have resulted in control column forces remaining in a controllable regime during the flight, including when the stabilizer trim cutout switches were in the CUTOUT position.

Procedures and Checklists

Source	Data (Quote or Summary)
BEA Comments p. 2/5	The BEA disagrees with the part of the proposed scenario (paragraph 2.1 of the report) which states that the crew was "waiting for a safe altitude to execute non normal procedures". This is not supported by any crew exchange on the CVR.
p. 228/331	The crew did not mention or attempt to use any checklist.
Volpe Summary	The EAIB inferred that the crew's failed attempt to use the manual trim wheel was done "as per the runaway stabilizer-non normal checklist." The NTSB disagrees with EAIB, see comments below.

Source	Data (Quote or Summary)
NTSB Comments on EAIB Draft report 5/12/2022 p. 6/9	2.4 The EAIB report inaccurately states that the crew performed actions “per the procedure.” Evidence shows that the crew did not appropriately perform non-normal procedures after receiving annunciations relating to unreliable airspeed, stall warning, and runaway stabilizer. The crew also did not respond as expected to the overspeed warning by disconnecting the autothrottle and reducing power. Emergency AD 2018-23-51 and FCOM Bulletin ETH-12 instruct flightcrews to conduct the runaway stabilizer checklist, which requires them to “control airplane pitch manually with control column and main electric trim,” • If the crew had conducted the procedure in the emergency AD and the FCOM bulletin, the crew would have used manual electric trim to reduce control forces. However, FDR data show minimal crew use of manual electric trim. • If the crewmembers had performed the memory items for the airspeed unreliable and/or runaway stabilizer checklists, they would have disengaged the autothrottle. A manual reduction of thrust would have further assisted in reducing control forces. However, FDR data show that the autothrottle remained engaged and that thrust remained at full power. • All these actions were expected per procedure and were to be conducted before moving the stabilizer trim cutout switches to the CUTOUT position Even after moving the stabilizer trim cutout switches to the CUTOUT position, the crew decided to return the switches to the NORMAL position, contrary to the FCOM bulletin and the emergency AD which direct crews to ensure that the switches “stay in the CUTOUT position for the remainder of the flight.”
p. 247/331	(17) Although, the use of auto flight system in most non-normal scenarios would help reduce crew workload and give more time for the crew to analyse the situation, it was not consistent with the procedure to use it with an ongoing stick shaker. It was identified from the CVR that the flightcrew did not discuss any issue related to the stick shaker;
BEA Comments p. 3/5	The flightcrew’s failure to apply the Approach to Stall or Stall Recovery Maneuver or the Airspeed Unreliable Non-Normal Check-list allowed the autothrottles to remain in ARM mode, with TOGA thrust.
BEA Comments p. 3/5	The Captain’s attempts to engage AP was in contradiction with the Approach to Stall or Stall Recovery maneuver check list, which was expected to be applied in reaction to the stick shaker activation.
BEA Comments p. 3/5	The IAS DISAGREE and ALT DISAGREE alerts were very probably not seen by the crew who thus did not apply the Airspeed Unreliable Non-Normal Check-list.

Source	Data (Quote or Summary)
BEA Comments p. 3/5	The flightcrew didn't fully apply the Runaway Stabilizer NNC when the MCAS triggered. Only step 5 of this NNC was applied (moving the stabilizer trim switches to CUTOUT).
NTSB Comments on EAIB Draft report 5/12/2022 p. 5/9	Upon either the activation of the stickshaker or the annunciation of the IAS DISAGREE message, the expected crew response is to turn off the autothrottle.

Flightcrew Task Management

Communications with ATC

Source	Data (Quote or Summary)
p. 22-29/331 Mix of quotes and Volpe Summary	At 05:39:12, the F/O contacted ATC radar, calling out a "SHALA 2A departure, crossing 8.400 ft". *Volpe Comment: The stick shaker activated 28 sec before FO initiated this routine call to ATC.* After RADAR identification, FO read back the clearance to the ATC. Captain told the FO to advise ATC that they were "unable and request to maintain runway heading". Captain repeated request to FO to: "Request to maintain runway heading; We are having flight control problems". At 5:40, the F/O advised ATC that they are unable to maintain SHALA 1A and the captain reminded him to request runway heading. This request was approved by ATC. Captain told FO: "advise ATC they would like one four thousand, we have a flight control problem." The FO complied. The request was approved by ATC. *Volpe Comment: This appears to be the first time the FO mentioned the flight control problem to ATC.* At 5:42:15, the F/O requested "Radar Ethiopian three zero two request vector to return to home » Following ATC instruction to turn to 260°, a new target heading of 262 ° was set. The aircraft heading at that time was 102°. *Volpe Comment: Flightcrew did not declare an emergency (PAN-PAN or MAYDAY) at any point. ATC did not query the flightcrew about their condition.*

Timeline

Numbered items are Final Report findings.

Source	Data (Quote or Summary)
p. 17/331 Volpe Summary	The airplane lifted off the ground at 0538 UTC, which is 8:38 am local time, in daytime VFR conditions.
p. 30/331 Volpe Summary	Flight ended 23 seconds after 4th automatic nose down trim. Total flight time from rotation to end was 5 minutes 10 seconds

Source	Data (Quote or Summary)
p. 246/331	Power (7) During takeoff roll, the engines stabilized at about 94% N1. From this point for most of the flight, the N1 Reference remained about 94%.
p. 20/331	Phase1: From takeoff to Autopilot engagement (from 5h 36 min 12 s until 5h 39 min 23 s)
p. 21/331 Volpe Summary	Approximately 10 to 15 seconds after takeoff (rotation) the stick shaker activated and the FO announced Master caution, Anti-Ice.
p. 248/331	26. As the flaps reached the up position with the autopilot OFF and because of the erroneous left AOA value, the FCC activated the 1st automatic nose down trim (MCAS) for 9 seconds;
p. 23/331	At 05:39:23, at about 1,000 feet Radio Altitude, the crew attempted a third auto-pilot engagement. CMD A (LH autopilot) engaged in HDG/VNAV modes.
p. 23/331	Phase 2: Under Autopilot engagement (from 5h 39 min 23 s until 5h 39 min 56s)
p. 24/331	At 05:39:56, A/P disconnected automatically after remaining engaged for 32 seconds as the following logic conditions were reached…
p. 25/331	Phase 3: From A/P disconnect to stabilizer trim cutout (from 5h 39 min 56s until 5h 40 min 38s)
p. 18/331	At 5:40:22, the second automatic nose-down trim activated. Following nose-down trim activation GPWS DON'T SINK sounded for 3 seconds and "PULL UP" also displayed on PFD for 3 seconds.
p. 27/331	Phase 4: flight while the stab trim cutout switches were in the cutout position (from 5h 40 min 38 s until 5h 43 min 11 s)
p. 225/331	Five seconds after the end of the Captain's electric trim-up inputs, a third automatic nose-down trim was triggered. There was no corresponding motion of the stabilizer since the stab trim cut-out switches were in cut-out position.
p. 28/331	At 5:42:47, the captain said« Ok, what was it? Master Caution? The F/O says «Master caution? » The captain asked the F/O to verify. The FDR data at this time is consistent with the crew pressing the MASTER CAUTION recall button to review the existing faults. The F/O answered "Master Caution Anti Ice". The Captain said "Left Alpha Vane". The F/O acknowledged "Left Alpha Vane".

Source	Data (Quote or Summary)
p. 30/331	Phase 5: Stab trim cut out switches back in normal position (point K) until the end of the flight (from 5h 43 min 11 s until 5h 43 min 44 s)
p. 250/331	(43) Five seconds after the trim-up inputs, the fourth MCAS triggered;
p. 30/331	At 05:43:21, approximately five seconds after the last main manual electric trim up input, a automatic trim nose-down (4th MCAS) triggered for about 5s.

Operations

Source	Data (Quote or Summary)
p. 21-29/331 Volpe Summary	Autopilot Captain attempted to engage (ordered command) autopilot four times. Autopilot only activated on third try, for 32 seconds. Stab Trim Cutout After second automatic nose down trim, Captain asked FO to activate the electric nose up trim along with him. Crew discussed the use of the stabilizer trim cutout. Stabilizer trim cutout was activated a few seconds later. (The EAIB concludes that the FO took the action per the Captain's command, see quote from p. 138/331.) After about 2 ½ minutes the Captain said "Put them up". A click similar the Stabilizer trim cut-out switches being put back on was heard on the CVR. Manual Trim and Backpressure Control column forces averaged 94 lbs. and oscillated between 80 and 110 lbs. during flight when stabilizer trim cutout switches were in the cutout position. Captain twice asked FO to pull up with him ("Pull with me"). Both pilots applied force on the control column. Captain asked the FO if the trim was functional. The FO replied that the trim was not working and (Captain) asked if he could try it manually. The FO stated that it is not working. The captain then asked FO to "keep with me" implying to help with resisting control column forces. Crew was still applying an average force of 94 lbs. Captain asked FO to recall master caution faults.
p. 97/331	CVR Transcript: At 5:40:35 the FO questioned, "Stab trim cut-out? Stab trim cut-out?"

Source	Data (Quote or Summary)
p. 138/331	According to the CVR transcript, the crew exchanged about the use of "stab trim cutout". At 05:40:37, the Captain expressed "yes, yes, do it", followed by the FO answer "Stab trim cut-out". *Note: The investigation concluded that the F/O most likely moved the stab trim switches into the CUTOUT position at 5 h 40 min 38 s.* *Note: The CVR transcript (p. 97/331) shows that this command "yes, yes, do it" was given in the pilot's native language, not in English.* At the end of the flight, (at 05:43:11), one pulse of manual electrical stabilizer trim up command was recorded (one single sample), followed 3 seconds later by a pulse of 2 samples. The stabilizer reached 2.3 units. At those times, both Stab Trim Cutout switches were in the NORMAL position. The following exchanges were provided by the CVR transcript: 05:43:09 "Put Them UP" 05:43:11 COMMAND put it on. *Note: The CVR transcript (p. 100/331) shows that a command at 05:43:10 "put it on" was given in the pilot's native language, not in English.*
NTSB Comments on EAIB Draft report 5/12/2022 p. 6/9	Even after moving the stabilizer trim cutout switches to the CUTOUT position, the crew decided to return the switches to the NORMAL position, contrary to the FCOM bulletin and the emergency AD, which direct crews to ensure that the switches "stay in the CUTOUT position for the remainder of the flight." The available evidence for this accident did not indicate why the crew performed this action. By not evaluating the human factors associated with this crew action, the report provides a limited understanding of the circumstances leading to the airplane's nose-down pitch before impact.
Starting p. 114/331 Volpe Summary	Section 1.16.1 Simulator Assessment of Control Column and Trim Wheel Force Per post-accident tests, trim was likely not movable due to high aerodynamic forces. Summary of observations starts p. 117/331. This includes the following item: 5. On the event flight during the time the flightcrew tried to use the manual trim wheel, about 40 turns of the manual trim were required to get back to the neutral position.
BEA Comments p. 3/5	The captain used several times the electric trim to try to counteract the MCAS nose down orders. However he never applied trim inputs for a sufficient duration to relieve the high control column forces. This is contrary to the observations made during the ECAB simulator sessions where the pilots felt that it was instinctive to use the electric trim to counter the nose down situation.

Source	Data (Quote or Summary)
BEA Comments p. 3/5	The reason why the captain did not apply longer electric trim inputs could not be understood.
BEA Comments p. 2-3/5	The BEA notes that in the months preceding the accident flight, the flightcrew had performed recurrent training on events which actually occurred during the accident flight: Stick shaker activation, IAS DISAGREE, Runaway stabilizer, use of Trim wheel, reaction to multiple non normal, task prioritization. However, during the accident flight, the flightcrew did not make appropriate use of the associated applicable procedures on which he had received training in the preceeding months. Insufficient support from the F/O, and more generally a deficient crew resource management by both flightcrew members, likely contributed to the crew failure to make an appropriate use of applicable procedures in the first phases of the flight.

Predictability, Reliability, and Intended Function of Systems

Source	Data (Quote or Summary)
p. 26/331	At the beginning, FMC detected a significant difference between the RH and LH True Airspeed (erroneous LH ADIRU computed values due to erroneous LH AOA value). From this time, FMC did not send any valid command to A/T. The A/T stayed in the Arm Mode. The loss of valid FMC command did not trigger an explicit alert but did result in the FMA continuing to display “ARM” instead of changing to “N1” as would normally be expected. *Volpe Comment: Also cited under Flight Deck Alerts During the Event.*
p. 132/331	During the whole flight of the event, A/T stayed engaged and remained in ARM mode.
p. 134/331	Note: By design, when no valid airspeed is available, the FMC changes the TARGET N1-[1/2] to the climb value. A N1 target value of 89% is consistent with a Climb phase. *Volpe Comment: Even as MCAS was causing the nose to go down, the auto-throttle power setting remained high (default behavior).*
p. 138/331 Volpe Summary of CVR	Manual trim forces were excessive. The FO stated that “it is not working,” referring to an attempt to use manual trim. *Volpe Comment: It appears that the pilots were not aware of how difficult the manual trim would be under these circumstances.*

Source	Data (Quote or Summary)
p. 114-121/331 Volpe Summary	Trim and control column forces were investigated by committee in a simulator at airspeeds and trim settings experienced during this flight and were found to range from difficult to move to not movable by test pilots.

FAA Approval Issue

Source	Data (Quote or Summary)
p. 253/331	(74) 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 the 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 documented in the stabilizer trim and auto flight safety assessment.

Official Safety Recommendations

Source	Data (Quote or Summary)
p. 256-258/331	1. Multiple alerts, stick shaker, repetitive MCAS activations impacted the flightcrew understanding of the situation on board and didn't enable them to handle the flight efficiently; This obscured the problem and the flightcrew could not arrive at a solution during the initial or subsequent automatic AND stabilizer trim input. **Therefore, the EAIB recommends** that the Airplane manufacturer consider the effect of all possible flight deck alerts and indications on flightcrew recognition and response; and incorporate design, flightcrew procedures, and/or training requirements where needed to minimize the potential for flightcrew actions that are inconsistent with manufacturer assumptions. 2. There was CBT training for a few hours long which were supposed to cover the difference between MAX and NG but there was no information related to MCAS description in the system. **The EAIB recommend** that the manufacturer provide sufficient time and adequate training associated with a new MCAS description in the system.

Source	Data (Quote or Summary)
	3. The specific failure modes that could lead to uncommanded MCAS activation, such as an erroneous high angle from a single AOA input to the MCAS, were not simulated as part of the 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 documented in the stabilizer trim and autoflight safety assessment. **The EAIB recommends** that the Boeing to reconsider the design of the system in such a way that AOA data input from both sensors (LH&RH) are received and analyzed by FCC before sending any command to MCAS. 4. Without descriptive MCAS awareness of the function and its effect, it would be more difficult for the flightcrew to understand the complexity. Instead of focusing on the runaway stabilizer in the AD, the crew would have been aware of MCAS. **The EAIB recommends** that Boeing instead of runaway stabilizer provide MCAS description and advise how to mitigate MCAS during repetitive AND command. 5. FHA of MCAS was considered the effect of undue activation of MCAS on flight controls, but it did not consider possible effect of underlying root causes on other systems, displays and warnings. Introduction of MCAS function did not lead to revise the System Safety Analysis (SSA) for failures of AOA sensors. **The EAIB recommends** that the FAA to review all probable causes of failure which have been considered during functional hazard assessment (FHA). **The EAIB recommends** that the manufacturer put awareness for the effect of a single erroneously high AOA sensor input is received by the flight control system, the MCAS can command repeated Airplane nose-down trim of the horizontal stabilizer which leads to excessive Airplane nose-down attitude, significant altitude loss, and impact with terrain. 6. The data from the flight data recorders, as summarized in reports of the ET 302 accident and the Lion Air Flight 610 accident, indicated that if a single erroneously high AOA sensor input is received by the flight control system, MCAS can command repeated Airplane nose-down trim of the horizontal stabilizer.

Source	Data (Quote or Summary)
NTSB Comments on EAIB Draft report 5/12/2022 p. 6/9	1.4. The EAIB draft [and final] report incorrectly states that Boeing did not respond or failed to respond appropriately to Ethiopian Airlines' request for more information about the MCAS after the Lion Air accident. • Boeing provided information to all 737 MAX operators in November 2018 (after the Lion Air accident but before the Ethiopian Airlines accident) to address uncommanded MCAS inputs. This information included operations manual bulletin (OMB)/FCOM bulletin ETH-12, FAA emergency AD 2018-23-51, a multi-operator message, dedicated meetings, and email messages. • Boeing's response to Ethiopian Airlines' request for more information about the MCAS, dated December 3, 2018, provided specific guidance about the OMB and checklist prioritization. In particular, the response indicated, "As is stated in the OMB, 'If uncommanded stabilizer trim movement is experienced in conjunction with the erroneous AOA flight deck effects, the instructed course of action is to use the Stabilizer Cutout switches per the existing [runaway stabilizer] procedure.'"

NTSB Recommendations

Refer to Section 4.6 NTSB Recommendations to FAA (p. 263-264/331) for full text.

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