NASA/TM—2014–218382

Factors Affecting the Use of Emergency and Abnormal Checklists: Implications for Current and NextGen Operations

Barbara K. Burian
NASA Ames Research Center

July 2014

NASA STI Program…in Profile

Since it's founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TM—2014–218382

Factors Affecting the Use of Emergency and Abnormal Checklists: Implications for Current and NextGen Operations

Barbara K. Burian
NASA Ames Research Center

National Aeronautics and Space Administration
Ames Research Center, Moffett Field, California

July 2014

Acknowledgments

This work was sponsored by FAA AFS-280, Aircraft Training Systems and Voluntary Safety Programs Branch and funded thorugh FAA ANG-C1, Human Factors Division.

A number of subject matter experts generously gave their time and expertise to answer many questions that arose during the course of this study. Many also reviewed earlier drafts of this report and provided many useful suggestions. With deep gratitude, I would like to thank them: Ben Berman, Mary Connors, Will Dismukes, Mark Champion, Noah Flood, Darrin Harris, Dan Herschler, Robert Kircher, Janeen Kochan, Mark Maskiell, Roger Pfannenstiel, Shawn Pruchnicki, Chris Reed, Susan Schmidt, SkyWest Aircraft Operations Department, Ron Thomas, Jon Tovani, Brian Townsend, David Vorgias, Joel Wade, Brian Will, and four others who wish to remain anonymous. Deep appreciation is also extended to the airlines who participated in this study: American, Delta, JetBlue, PSA, SkyWest, United, and a North American air carrier that wishes to remain anonymous.

Available from:

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

This report is also available in electronic form at http://www.sti.nasa.gov
or http://ntrs.nasa.gov/

Table of Contents

List of Figures

List of Tables

Acronyms

AAPID	Aviation Accidents Prevention and Investigation Department
ACARS	aircraft communications addressing and reporting system
AOC	air operations center
ASAP	as soon as possible
ASRS	Aviation Safety Reporting System
ATA	American Trans Air
ATC	air traffic control
ATSB	Air Transport Safety Bureau
CDU	computer display unit
CL	checklist
CPDLC	Controller Pilot Data Link Communication
DSP	Display Select Panel
ECAM	Electronic Centralized Aircraft Monitoring system
ECL	electronic checklist
ECLS	electronic checklist system
EFB	electronic flight bag
EGT	exhaust gas temperature
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FMC	flight management computer
GPS	global positioning system
IAI	immediate action item
ICAO	International Civil Aviation Organization
MEL	minimum equipment list
MFD	multi-function display
MI	memory item
NAS	national airspace system
NASA	National Aeronautic and Space Administration
NextGen	Next Generation Air Transportation System
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
PBN	performance based navigation
PFD	primary flight display
QAI	Quick Action Index
QRC	quick reference card/checklist
QRM	Quick Reference Handbook
RNAV	area navigation

RNP	required navigation performance
SME	subject matter expert
TOC	table of contents
TSB	Transportation Safety Board of Canada
TWA	Trans World Airline
UK-CAA	United Kingdom Civil Aviation Authority

Definitions of Terms

Abnormal: "…a nonroutine operation in which certain procedures or actions must be taken to maintain an acceptable level of systems integrity or airworthiness" (Federal Aviation Administration [FAA], 2007a, 3-3128). Crew attention and response to the situation or condition is required but the level of severity does not reach the threshold of an "emergency" and typically an abnormal situation is not time critical. Left unaddressed however, some abnormal situations may become emergencies.

Abnormal checklist: See Emergency/Abnormal/Non-normal Checklist.

Acute stress: Stress or strain which is short-lived in duration. Acute stressors often occur suddenly, are unexpected, and are sometimes unusual.

Alerted: A condition that is sensed through the aircraft system of sensors and then presented or displayed on the flight deck through one or more methods including visual, aural, and tactile means. An alerted checklist is one that corresponds to the alerted condition and, in the case of integrated electronic checklists, is automatically displayed or queued for accomplishment by the pilots.

Annunciated: See Alerted.

Branching Item: An item in a checklist that, when evaluated, directs the user to move to and/or past other item(s) within a checklist or to jump out of the checklist to other checklists, information or materials. The two most common branching items are Conditional Items and Decision Items.

Checklist (CL): "A formal list used to identify, schedule, compare, or verify a group of elements or actions. Although a checklist may be published in a manual, it is usually intended to be used by itself, so that reference to a manual is made unnecessary. Checklists are usually formatted and presented on paper; however, they may be formatted on electronic or mechanical devices, or presented in an audio format. A checklist may or may not represent an abbreviated procedure. The items listed on a checklist may be unrelated and may not represent a procedure, such as most "normal" checklists. Abnormal and emergency checklists, however, do represent procedures. NOTE: Checklists and procedures are often confused. Operators have sometimes titled procedures "expanded checklists" or titled checklists "abbreviated procedures." A procedure is a set of actions or decisions prescribed to achieve a specified objective. A checklist is a physical aid used to overcome the limitations of human memory." (FAA, 2007a, 3-3128).

Checklist navigation: Movement from one item to the next in a checklist and jumping past items that are not appropriate to accomplish for the specific situation and/or jumping to other checklists or information in other locations or materials (e.g., performance tables). This navigation can be facilitated through the use of various design features in checklists, certain types of programming within electronic checklists, and through feedback from aircraft sensors to integrated electronic checklist systems.

Checklist title: The name given to a checklist. With regard to an emergency or abnormal condition for which a text alert is displayed, the predominant standard within the industry is that the Checklist Title should match the text alert exactly, to facilitate confirmation that the correct checklist has been accessed for accomplishment.

Chronic stress: Stress or strain which is long-lived or exists over a long period of duration.

Chunking: Grouping information as an aid to remembering it. Chunking, as a memory aid, works best when the things to be remembered share something in common, such as related meanings, or can be remembered as a single meaningful unit (e.g., area code 706 rather than 7 – 0 – 6). In terms of motor response, such as the completion of several actions from memory (see Memory Items), the actions can be recalled as a chunked and sequenced flow. Remembering or being able to perform the sequence correctly may be impaired if the sequence is interrupted or disrupted in some way.

Closed loop item: An item in an integrated electronic checklist system that pertains to an aircraft control or system state that can be sensed by the aircraft through its system of sensors. The status of the control or system state will be reflected in the way in which the closed loop item is presented on the checklist. For example, if the item indicates that a button should be pressed and the sensors sense that the button has been pressed then the checklist display will indicate that the item has been accomplished.

Cognitive processing: The mental management, manipulation, making sense of, and use of sensory stimuli, data, and information.

Concurrent task management: A strategy adopted to manage the completion of more than one task that must be completed at the same time. One strategy is to prioritize one task over another and complete one first in its entirety before shifting to complete the other. A more common strategy with tasks comprised of many steps or ongoing actions (such as monitoring) is to interleave the steps or actions from these tasks. Thus, a few steps from one task are accomplished, then a few actions related to second task are completed, then a few more steps from the first task, and so on.

Condition statement: A brief statement in a checklist which describes an emergency or abnormal condition, aircraft state, or a desired or needed action. If included in a checklist, it is typically presented just after a Checklist Title and is used by pilots to help ensure that the checklist that has been accessed is the one desired or needing to be accomplished. Condition Statements are different from and should not to be confused with Conditional Items.

Conditional item: A situation, condition, desire, or state, specified in a checklist item, that is to be evaluated as being true or not true at the time the item is reached during accomplishment of a checklist. The item is written as the first half of a logical proposition, beginning with the word "if" (If the alert message remains displayed…), followed by actions to be performed or pertinent information to be read (i.e., subordinate items) if the logical proposition is true. Generally, the word "then" which initiates the second half of a logical proposition, is not used. Conditional Items address different aspects that may or may not exist in an emergency or abnormal situation, and have the effect of moving the pilot to only those actions and information in the checklist and other materials which are pertinent to the specific circumstances encountered. See also, Decision Item.

Decision making: The process of making choices or reaching conclusions.

Decision item: A situation, condition, desire, or state that is to be evaluated as being true or not true at the time the item is reached during accomplishment of a checklist. The item is written either as a statement or as a question (The alert message remains displayed. Does the alert message remain displayed?). Decision items are followed by actions to be performed or pertinent information to be read (i.e., subordinate items) if the Decision Item is true. Decision Items address different aspects that may or may not exist in an emergency or abnormal situation, and have the effect of moving the pilot to only those actions and information in the checklist and other materials which are pertinent to the specific circumstances encountered. See also, Conditional Item.

Deferred item: An item included in an emergency or abnormal checklist that is to be accomplished generally at a later time or phase of flight, such as approach or landing.

Distress: This term is defined by the International Civil Aviation Organization (ICAO) and used by many ICAO member states, though not commonly within the United States of America (USA) with regard to an aircraft emergency or abnormal situation. It typically connotes an emergency situation. According to the United Kingdom Civil Aviation Authority's (UK-CAA) Radiotelephony Manual (Safety Regulation Group, 2013) it is "a condition of being threatened by serious and/or imminent danger and of requiring immediate assistance" by air traffic controllers (Chapter 8, page 1). When initiating a radio call to air traffic controllers (ATC) to alert them to a Distress condition, the pilot is to start the call with the international radiotelephony prefix: Mayday, Mayday, Mayday.

Electronic Centralized Monitoring System (ECAM): The system on Airbus aircraft that monitors the status of aircraft system, displays information about system status and functioning, and presents text alerts and integrated electronic checklist items for flight crew information and use. On the A320, the ECAM includes no normal checklists, only those for responding to alerted emergency or abnormal conditions and the items presented are referred to as "ECAM actions." Often, other information or actions related to these alerted checklists must also be referenced in printed quick reference handbooks.

Electronic Checklist (ECL): The integrated electronic checklist system used on some types of Boeing aircraft (e.g., B777, B787). The ECL includes normal checklists and checklists for emergency and abnormal (i.e., non-normal) conditions, both alerted and un-alerted (i.e., annunciated and unannunciated).

Electronic Checklist System (ECLS): Normal and/or emergency and abnormal checklists presented electronically. An electronic checklist system includes not only the checklist content but also the display device, interface for interacting with the display, and the programming which drives the display and functioning of the system. There are two main categories of electronic checklist systems currently in use: stand-alone electronic checklists and integrated electronic checklists.

Emergency: "…a nonroutine operation in which certain procedures or actions must be taken to protect the crew and the passengers, or the aircraft, from a serious hazard or potential hazard" (FAA, 2007a, 3-3128). Many emergencies, though not all, are time critical and quick or immediate crew attention and response is required to avert serious harm or jeopardizing aircraft airworthiness.

Emergency/abnormal/non-normal checklist: A checklist used to guide response to "a non-routine operation in which certain procedures or actions must be taken to maintain an acceptable level of systems integrity or airworthiness." (FAA, 2007a, 3-3128).

Exclusive conditional/decision item sets: Complementary Conditional Items or Decision Items that address all variations of a possible condition and are to be evaluated against each other. Example 1: a) If on the ground….. b) If in the air….. Example 2: a) Flaps are stuck at 25 to 30 degrees. b) Flaps are stuck at 15 to less than 25 degrees. c) Flaps are stuck at 0 to less than 15 degrees.

Get-in, stay-in: The philosophy of checklist design and use in which all items and information that might be needed for the remainder of a flight are incorporated into or co-located with (i.e., directly follow) a checklist needed for response to and management of an emergency or abnormal situation. Generally this design philosophy is only used when the emergency/abnormal situation is expected to have repercussions for the remainder of the flight through approach and landing, such as a hydraulics failure.

Immediate action items: “An action that must be taken in response to a nonroutine event so quickly that reference to a checklist is not practical because of a potential loss of aircraft control, incapacitation of a crewmember, damage to or loss of an aircraft component or system—which would make continued safe flight improbable.” (FAA, 2007a, 3-3128). Items consistent with this definition are also sometime called Memory Items. Some air carriers use the term “Immediate Action Items” to refer not to those that must be performed by memory but to important actions or information that must be performed without delay but time exists for referencing these items in printed form if it can be done quickly. In this use, Immediate Action Items are critical, but slightly less critical, than Memory Items.

Inhibited (alert/checklist item): An alert or checklist which is not displayed or presented for some reason. For example, some alerts are not presented (i.e., are inhibited) during critical phases of flight, such as take-off or landing, so as not to distract the pilots from more essential tasks. The display of an integrated electronic checklist may be inhibited for the same reason or because the condition it pertains to only exists as a result of another condition, whose checklist is not inhibited.

Integrated electronic checklist system: A system in which checklists are presented electronically and are connected to and receive feedback from the aircraft through a system of sensors. Checklist items that are so linked (i.e., sensed) receive information about aircraft system states will be automatically indicated as having been accomplished when the sensed state matches that specified in the checklist item. However, not all checklists and items within an Integrated Electronic Checklist System may be linked to the aircraft sensors, (see Un-alerted Checklists and Open Loop Items for more information). See also, Stand-alone Electronic Checklist Systems.

Irregular: The term “irregular” is used by some in the industry in place of the term “abnormal.”

Long-term memory: The cognitive system or systems which underlie the ability to store information in mind over long periods of time.

Memory items: Actions or information that must be performed or recalled from memory because a critical situation exists in which insufficient time is available for reference to a printed checklist. See also, Immediate Action Items.

Minimum Equipment List (MEL): A list prepared for each model of each aircraft type and approved by regulators which allows for the operation of an aircraft with particular equipment inoperative under specified conditions.

Multitasking: See Concurrent Task Management.

Non-normal: According to FAA Order 8900.1, Change 0, Flight Standards Information Management System (FAA, 2007a), a “non-normal” event is the same as an “abnormal” event, namely “a nonroutine operation in which certain procedures or actions must be taken to maintain an acceptable level of systems integrity or airworthiness” (3-3128). Thus, within FAA documents “non-normal” and “abnormal” events are equivalent and are distinguished from emergencies in terms of level of severity and the speed with which flight crew intervention may be required to address the situation.

Some manufacturers (e.g., Boeing) and air carriers however, use the term “non-normal” to mean either an abnormal *or* an emergency situation. As they use this term, both emergency *and* abnormal situations fall under the single category of “non-normal.” This is more all-encompassing than the way in which the term is defined and used by the FAA, in which “non-normal” is equivalent to “abnormal” but *does not* include “emergency” situations.

Because the meaning and use of the term “non-normal” differs within the aviation industry, it will not be used routinely in this document.

Non-normal checklist: See Emergency/Abnormal/Non-normal Checklist.

Normal: Normal operations are those which are routine, occur during every flight, and in which aircraft systems are functioning in their usual manner, i.e., no malfunctions exist. Readers must keep in mind that many normal operating tasks, such as landing an aircraft, will still need to be completed during emergency or abnormal situations.

Normal checklist: “When normal is used to describe a procedure or checklist, it refers to a routine operation (without malfunctions).” “A normal checklist is comprised of all of the phase checklists used sequentially in routine flight operations.” “A phase checklist is the normal checklist used to establish and/or verify aircraft configuration during a specific phase of flight. An example of a phase checklist is an “After Takeoff checklist.” (FAA, 2007a, 3-3128).

Off-nominal: Any type of operation which diverges from the idealized norm. Thus, an off-nominal event could be as serious as an abnormal or emergency situation or as benign as an event that is not desired but common within day to day operations, such as the performance of a go-around. Because of the imprecision with which the term off-nominal is used within the aviation industry, it will not be used in this document.

Open loop item: An item in an integrated electronic checklist that cannot be sensed by the aircraft. By definition, all items in a stand-alone electronic checklist are also open loop since none of the items receive feedback from aircraft sensors.

Opt-out gates: Items, typically formatted as Conditional/Decision Items in emergency checklists, that are traditionally used to prompt pilots to shift attention to something more time critical, such as landing/ditching in the case of a dual engine failure or smoke removal in the case of dense smoke associated with an in-flight fire. Opt-out gates are intended to help the pilots avoid tunneling of attention and assist them maintain awareness of and manage the overall emergency situation.

Paper checklist: A formal list used to identify, schedule, compare, or verify a group of elements or actions, and/or information relevant for operations that is printed on paper, cardstock, or lightweight plastic.

Procedure: “A logical progression of actions and/or decisions in a fixed sequence that is prescribed by an operator to achieve a specified objective. In short, a procedure is step-by-step guidance on how to do something.” (FAA, 2007a, 3-3128).

Progression: See Checklist Navigation.

Quick Reference Card/Checklist (QRC): A printed copy of all Memory Items/Immediate Action Items for every checklist in a quick reference handbook that has them. QRC information is usually printed on a separate card or on the cover of the quick reference handbook. Regardless of location, a QRC presents items which must be performed quickly in a single place that can be rapidly and easily located by pilots. It is used to support or confirm the swift and correct accomplishment of the items presented. If additional items remain to be accomplished (i.e., reference items), the QRC typically refers to pilot to the checklist in the QRH where they can be found.

Quick Reference Handbook (QRH): A manual kept on the flightdeck or in a cockpit which contains a compilation of paper checklists that are to be accomplished when specific emergency or abnormal conditions or events occur. Sometimes this document is referred to as a Quick Reference Manual.

Quick Reference Manual (QRM): See Quick Reference Handbook.

Recall items: Another term for Memory Items, i.e., actions or information that must be performed or remembered so quickly that time does not exist for reference to printed checklists or procedures. Some manufacturers include an item on normal checklists used before take-off and landing that involves checking the alert display for any unresolved alerts that may affect that phase of flight, often by pressing a button on the flight deck labeled “Recall”. This action is typically referred to as a “recall step” as the item is often written something like “Alerts…….RECALL” Because of possible confusion between these items and those which must be performed from memory during an emergency or abnormal situation, the term Recall Items, will not be used in this document.

Reference items: Items in an emergency or abnormal checklist that are to be read from a printed checklist as they are being accomplished, i.e., performed in a “read-and-do” fashion.

Stand-alone electronic checklist system: A checklist system whereby checklists are presented electronically, often as part of an electronic flight bag, but are not connected to and hence, do not receive any feedback about the aircraft state or status through aircraft sensors. The accomplishment of checklist items must be indicated manually by the pilots through the checklist system. See also, Integrated Electronic Checklist System.

Stress: A normal biological response to threat resulting in mental, emotional, and/or physical strain. Often the strain is caused by external stimuli which challenge a person’s perceived ability to adequately cope or respond. Stress is generally thought of in a negative light but it can also be viewed positively, such as in situations that present opportunities for heightened performance (e.g., athletic competition).

Subordinate items: Items that directly follow a Conditional/Decision Item and are only meant to be accomplished if the Conditional/Decision Item they follow is true. Subordinate items are typically indented from the left-most margin of the Conditional/Decision Item with which they are related to set them apart from other items in the checklist.

Time pressure: A stress or strain felt in response to a reduction in the amount of time available in which to perform a task.

Un-alerted: A condition or integrated electronic checklist that is not or cannot be sensed through the aircraft system of sensors.

Unannunciated: See Un-alerted.

Urgency: This term is defined by ICAO and used by many ICAO member states, though not commonly in the USA, with regard to aircraft emergency or abnormal situations. According to the UK-CAA Radiotelephony Manual (Safety Regulation Group, 2013) it is “A condition concerning the safety of an aircraft or other vehicle, or of some person on board or within sight, but does not require immediate assistance” by air traffic controllers (Chapter 8, page 1). When initiating a radio call to ATC to alert them to an Urgency condition, the pilot is to start the call with the international radiotelephony prefix: Pan Pan, Pan Pan, Pan Pan.

Working memory: A memory system that underpins our ability to actively process—hold, manipulate, analyze, and use—information mentally in real time. The capacity of working memory is finite and rehearsal (i.e., repeating the information to be remembered, over and over) is often required to keep information held in working memory. When working memory capacity is exceeded, some information drops out or cannot be processed. Working memory is required for considering different pieces of information to form an understanding of a situation, for planning and decision making, and for performing mental calculations, among other things.

Workload: The number and/or types of tasks required to be performed within a given period of time. The concept of workload also generally encompasses the kinds of demands presented by the various tasks and the levels of difficulty to perform them.

Factors Affecting the Use of Emergency and Abnormal Checklists: Implications for Current and NextGen Operations

Barbara K. Burian[1]

Executive Summary

Purpose of Line of Research: This study was conducted as a first step toward development of a holistic approach to non-normal situation response within the context of normal operations, and to consider how flight crew responses and procedures might change within the NextGen environment. Little guidance currently exists across the industry for the distribution of workload, prioritization of tasks, appropriate task shedding, and coordination of response to emergency and abnormal situations across crew members, automation, air traffic control (ATC), and AOCs.

Purpose of Current Study: The purpose of the current study was two-fold:

1. Identify current practices associated with emergency and abnormal checklist design and content that are known to be particularly challenging for checklist developers and affect checklist usability, particularly:
    - – those aspects that affect pilots' ability to identify and access the correct checklist
    - – those aspects that enable pilots to properly "navigate" or move through the checklist and related materials (e.g., performance tables), so that only the correct items for the specific situation are accomplished
2. Identify and analyze checklists for use in aspects of NextGen operations that have already been implemented, i.e., Data Comm (in oceanic operations) and required navigation performance (RNP), and checklists for possible use in the event of a global positioning system (GPS) spoofing attack.

Approach: In this study, a table-top analysis of multiple design, construction, content, functionality, and use factors associated with emergency and abnormal checklists currently used in commercial aviation was conducted. Several North American air carriers participated in this study and provided hard and/or electronic copies of Quick Reference Handbooks (QRHs) and checklists and allowed access to simulators so that integrated electronic checklist systems (ECLSs) could be studied. Subject matter experts (SMEs) from the air carrier participants also answered numerous questions. Checklists/QRHs/ ECLSs across five different aircraft types were analyzed:

- • Airbus A320 (A320),
- • Boeing 737 Next Generation (B737NG),
- • Boeing 777 (B777),
- • Canadair Regional Jet 700 (CRJ700), and
- • Embraer 190 Regional Jet (EMB190).

---

[1] NASA Ames Research Center, Moffett Field, California.

Two separate air carriers provided materials for each aircraft type, except the A320 for which three carriers provided checklists/QRHs/access to the A320 ECLS (i.e. Electronic Centralized Aircraft Monitoring System, ECAM). Therefore, a total of 11 sets of checklists/QRHs and two different ECLSs—the B777 Electronic Checklist (ECL) and the A320 ECAM—were analyzed. Baseline checklists or QRHs developed by the aircraft manufacturers (i.e., original, prior to modification by air carriers) were not included in this study.

Summary of Major Findings

Overall QRH/ECLS Structure and Content

- All of the QRHs analyzed include other content in addition to emergency and abnormal checklists however, what content and how much varies greatly.
- Two of the three A320 QRHs analyzed contain approximately 10 ECAM exception or bypass checklists which are to be completed instead of those checklists that are presented as part of the ECAM, only four of which are in common to both QRHs.
- Only one QRH analyzed divides checklists into the two major categories of emergency checklists and abnormal checklists. It is suggested that this distinction, which used to be the standard within the industry, may be less important than the distinction between alerted and un-alerted checklists with regard to accessing desired checklists quickly, especially with the increased use of Quick Reference Cards/Checklists (QRC; see below)
- Two QRHs have no divider pages and do not group their checklists by aircraft system. One QRH does have divider pages and groups the checklists by aircraft system but each section lacks a table of contents (TOC). Thus, when using these three QRHs pilots will have to refer to an index or have a QRH page memorized to locate a desired checklist.
- One QRH for the A320 does not include copies of checklists that appear only on the ECAM (i.e., there are no additional items or information for that checklist other than what is included in the ECAM). Thus, that QRH cannot be used as a stand-alone aid to checklist study or review. All other QRHs appear to include all emergency/abnormal checklists, even those included in ECLs, and can be used for those purposes in addition to their use during emergency and abnormal situations.
- Total number of checklists in the QRHs analyzed range from 162 to 383.
- Total number of un-alerted checklists in the QRHs analyzed range from 35 to 76 (13% to 36% of the checklists in the QRHs).
- **Further Research Needed:** Identify checklist/Checklist Title search preferences and search patterns employed by pilots (of all experience levels and varying amounts of time since recurrent training) when using paper QRH and stand-alone and integrated ECLS. Determine optimal QRH and ECLS design and functionality to support these various search patterns.
- **Further Research Needed:** Determine most effective methods for supporting pilots remembering that un-alerted checklists exist for particular circumstances and their location and access of desired un-alerted checklists in QRHs and all types of ECLS.
- **Further Research Needed:** Determine if there is an optimal method for grouping emergency and abnormal checklists (e.g., single level grouping with emergency and abnormal checklists integrated and not distinguished from each other as emergency or abnormal vs. two level grouping

with emergency and abnormal checklists grouped separately etc.) relative to reduction in pilot workload, memory requirements, and checklist accessibility.

- **Further Research Needed:** Determine ramifications in terms of pilot workload, memory requirements, and error with regard to the use of companion QRHs to supplement or be used instead of stand-alone and integrated ECLS checklists.
- **Further Research Needed:** Determine functionality and design requirements relative to workload and usability for the implementation of Class 1 EFB applications that replicate the functionality of an integrated ECLS.

Memory Items and QRCs

- Checklist items to be performed from memory are referred to as Memory Items or Immediate Action Items in eight of the QRHs analyzed. To reduce confusion in this report, those items to be performed from memory in these eight QRHs will be referred to as Memory Items, irrespective of how they are labeled by the air carriers.
- Three QRHs have both Memory Items and Immediate Action Items, with those of the second type (i.e., Immediate Action Items) being slightly less critical than those of the first type (i.e., Memory Items).
- The number of checklists with Memory Items across all QRHs ranges from 1 to 22.
- The total number of Memory Items (across all checklists in each QRH) ranges from 1 to 87.
- QRCs, which contain the Memory and Immediate Action Items for the checklists that have them, have been developed as companions for nine of the QRHs analyzed and appear on the QRH cover(s) and possibly first few pages (n = 5), as separate sections within the QRH (n = 2), or on separate cards (n = 2).
- Across the QRHs for the same aircraft type, there is a great deal of variation with regard to which checklists have Memory Items and how many there are.
- Seventy-nine percent (79%) of the 239 Memory Items coded in this study were formatted as challenge-response Action Items and 8% were formatted as sentence form Action Items.
- Twenty-four (24) of the 190 challenge-response Action Items require that both crew members confirm that the correct lever, handle, or switch has been identified before the action is taken.
- Twelve percent (12%) of the Memory Items are not Action Items. They are Conditional Items (e.g., If condition XYZ exists…), Delaying or Timer Items (which indicate the specific time when an action is to be performed, e.g., At top of descent…., After 30 seconds…), Critical Notes or other Notes (e.g., !This action cannot be reversed…, NOTE: Important information you should know…) or even Explanatory Text that describes how an action is to be completed. Additionally, some of the Conditional Items are compound requiring the pilot to recall that two conditions must be evaluated before the subsequent action should be taken (e.g., If XX exists and YY happens, then…, If AA exists or BB exists, then…).
- Thus, the recall and performance of Memory Items is not always just the simple recollection and performance of a few straight forward actions. It can also involve communicating and coordinating actions across crew members, timing the accomplishment of actions appropriately, and judgment and decision making.

- **Further Research Needed:** Determine optimal location QRC information relative to speed and accuracy of item accomplishment, crew communication and coordination, and overall situation response.
- **Further Research Needed:** Identify air carrier stated policies with regard to QRC access and use and compare with actual practice by pilots. Determine optimal method of QRC use and method accomplishment (i.e., Do-Confirm: accomplish from memory and confirm by reference to QRC vs. Read-Do: accomplish by reference to QRC).
- **Further Research Needed:** Evaluate use of three levels of item types (Memory-Immediate Action-Reference) as compared to two levels if item types (Memory-Reference) with regard to speed and accuracy of item accomplishment, crew communication and coordination, and overall situation response.
- **Further Research Needed:** To reduce human error and pilot mental workload, determine items that are essential to be performed by memory in response to various emergency and abnormal situations vs. those that can be performed through reference to a printed QRC or ECLS.
- **Further Research Needed:** Identify error rates relative to different types of items performed by memory: Action Items, Action Items requiring crew confirmation prior to accomplishment, Conditional Items, Timer Items, etc. Based on results, suggest air carriers make changes regarding which items are classified as Memory Items in their checklists, if necessary.

Checklist Navigation and Jumping

- Checklist navigation involves not only linear movement through a checklist, progressing step by step as each one is accomplished and the next one is reached, but also jumping within a checklist past inapplicable items to others that are and jumping out, and sometimes back in, to and from other checklists, materials, or information.
- The use of closed loop (sensed) items on integrated ECLS and inhibiting unnecessary secondary or consequential checklists streamline the process of checklist navigation greatly.
- Several methods are used to facilitate navigation in the paper checklists analyzed. They include the use of: single Conditional/Decision Items, Exclusive Conditional/Decision Item Sets, sentence form Action Items (e.g., Go to Performance Tables on pg. XX for single engine landing distances), and various graphics, symbols, and flow lines/arrows.
- Very few participants utilized the Get-in, Stay-in approached to the design of checklists for situations that have major repercussions for a flight through landing, such as the failure of two hydraulics systems. Therefore, pilots using those checklists will be required to jump among more than one and often multiple checklists and other sources of information through completion of the flight and situation resolution.
- The ease with which checklists and QRHs can be navigated is often best evaluated through their actual use. Even so, in this study the following observations pertaining to checklist navigation were made:
    - It was sometimes difficult to follow flow lines, particularly when they continued across multiple pages, several ran in parallel to each other because of nested Conditional/Decision and subordinate items, and when they connected to both the right and left sides of items (right and left margins).

  - Exclusive conditional sets were most easy to evaluate when they were presented or identified as a set in some way, rather than when each item was presented without any indication that its complement(s) (other item(s) in the set) was presented later in the checklist.
  - In a few checklists analyzed, the pilot is sent to a second checklist that immediately sends the pilot to a third. It was not clear why the jump to the second checklist is necessary.
  - Conditional/Decision Items, despite the inclusion of special graphics or formatting, were sometimes missed when they appeared very near the "checklist continued" item/Checklist Title repetition at the top of a second or later checklist page in the QRH. Spacing between the Conditional/Decision Item and the indentation of the subordinate items contributed to the eye jumping directly to the subordinate items.
  - Some Conditional/Decision Items are compound or complex which can be more difficult for pilots to correctly evaluate when under stress.
  - All checklists, but particularly an ECLS, should have a way to "undo" an incorrect evaluation of a (open loop) Conditional/Decision Item. In other words, the subordinate items for all potential evaluations of a Conditional/Decision Item must be available or easily accessible in case an incorrect evaluation of the item has initially been made. The ECL allows this, as of course do all paper checklists, but it unclear how this is managed on the ECAM.

- **Further Research Needed:** Evaluate efficacy, workload, and error rate of checklists designed according to the Get-in, Stay-in philosophy as compared to those that require jumping to multiple checklists and materials for response to situations that have repercussions through landing.
- **Further Research Needed:** Evaluate possible negative effects if all appropriate checklists in a QRH are designed according to the Get-in, Stay-in philosophy as compared to the possible positive effects.
- **Further Research Needed:** Identify optimal ways for facilitating navigation through paper checklists, QRHs, stand-alone and integrated ECLSs that reduce human error and workload during emergency and abnormal situations.

Diagnosis and Determining the Appropriate Checklist

- Titles of checklists that pertain to text alerts appear to match the text alert word for word.
- Checklists for three different types of events that are not directly alerted in most aircraft were analyzed: uncommanded yaw or roll, pitot-static blockage, and fuel leak.
- With regard to uncommanded yaw or roll, when using several QRHs the pilots would need to be able to first diagnose the reason for the yaw or roll before being able to identify the correct checklist to complete; only two QRHs included a checklist titled Uncommanded Yaw or Roll.
- Pitot-static blockage and fuel leaks both can cause a large number of other alerts and cues to be presented, ones which may often confuse the situation and make it difficult for pilots to make sense of the underlying problem.
- Very few of the checklists associated with alerts that might be displayed in the event of a blockage of the pitot static system make reference to the un-alerted checklist for unreliable airspeed. This lack of reference may be appropriate or may be an oversight.

- There is a surprising amount of inconsistency across the air carrier participants flying the A320 and CRJ700 with regard to inclusion of a reference to a fuel leak in (related) alerted checklists. In eight of the 15 alerted checklists identified (53%) at least one carrier makes reference to considering a fuel leak whereas no such reference is made in the same checklists belonging to the other carrier(s).
- There is consistency in whether or not a possible fuel leak is referenced in the alerted checklists in the QRHs for the other aircraft types. However, in many cases no mention of the possibility of a fuel leak is made. This lack of reference may be appropriate or may be an oversight.
- One of the final indicators of a fuel leak is the failure/flameout of one or more engines. Of the QRHs analyzed, only the A320 Dual Engine Failure checklists and the EMB 190 checklists for a single engine failure address the possible failure due to fuel leak/ starvation/exhaustion.
- **Further Research Needed:** Determine efficacy and error rates in appropriate pilot response to un-alerted conditions associated with the inclusion of reference to/information about un-alerted checklists in associated alerted checklists.
- **Further Research Needed:** Determine possible appropriateness and efficacy of developing a single checklist for uncommanded yaw and roll events that includes initial corrective actions do not first require analysis of the cause of the event.

Assumptions about Amount of Time Available and Action Effectiveness

- Some of the checklists analyzed in this study appear to have been developed with the unstated assumption that a certain amount of time would be available for item accomplishment. Examples of such assumptions are:
    - Dual Engine Failure checklists that have many items devoted to methods for relighting the engines but no immediate direction to prepare for an emergency landing or ditching if adequate time for engine relight is unavailable. In other words, no opt-out gate is presented at the beginning of the checklist or elsewhere to prompt the pilots to jump to other items if landing/ditching is imminent.
    - Three Fuel Leak checklists analyzed include items directing a diversion to the nearest suitable airport in the middle or at/near the very end of the checklist.
    - Some Dual Engine Failure checklists analyzed that do not have items to perform if neither of the engines can be re-started.
- Neither of the CRJ700 QRHs analyzed included a checklist to be used in the event of an encounter with Volcanic Ash.
- **Further Research Needed:** Conduct analysis of broad range of checklists to identify unstated assumptions with regard to when the checklist is to be used (e.g., phase of flight), types of appropriate situations for which the checklist is to be used (e.g., most extreme version of condition, such as a pressurization checklist for explosive decompression but not a slow pressurization leak), and assumed efficacy of checklist actions. Make changes to checklists to counter these assumptions as necessary.
- **Further Research Needed:** Identify circumstances in which opt-out gates might be necessary or desirable in wide variety of checklists, particularly those having possible on-going repercussions or repercussions through landing. Identify optimal methods and locations for inclusion of opt-out gates in these checklists to best support pilot overall situation awareness and situation management.

Checklists for Use in NextGen Operations

- Checklists associated with some types of NextGen Operations were analyzed in this study: GPS Spoofing, RNP, and Data Comm. These three were chosen for study because they relate to aspects of NextGen that are already implemented.
- All five of the aircraft types included in this study have alerts or indications that can be used to identify a possible spoofing attack, although some are rather subtle and/or are outside the pilot's primary field of view, i.e., on a page on the flight management computer (FMC).
- In this study, checklists that might be used in the event of a possible GPS spoofing attack were identified in the QRHs for A320 and EMB190 aircraft but not in QRHs for the other three aircraft types.
- All of the QRHs analyzed include checklists associated with malfunctions of equipment necessary for navigation as well as for issues associated with RNP or RNAV RNP AR approaches if the aircraft and air carrier is authorized for those operations.
- The checklists and information relative to RNP or RNAV RNP AR approaches indicate what should be done operationally if the required navigation precision cannot be met (e.g., break off the approach) but rarely do they address fixing or attending to a malfunction associated with this failed performance.
- Data Comm is not yet used within North American airspace but seven of the QRHs analyzed do include checklists for datalink/ACARS related issues. The B777 aircraft engage in oceanic operations where Data Comm is already in use and several of the carriers use aircraft communications addressing and reporting system (ACARS) to communicate with company dispatchers.
- Other than those checklists involving a re-set of the datalink/ACARS associated computer, there are no items in these checklists for the pilots to perform if datalink/ACARS fails.

Implications for NextGen Operations

- Although three NextGen specific checklists were analyzed, in truth almost all of the checklists included in ECLSs, QRHs and those analyzed in this study have relevance for NextGen operations. No matter how well planned and designed, emergency and abnormal situations will continue to occur during NextGen. The content of checklists for these situations may or may not need to change, but procedures must be in place for emergency aircraft, and the aircraft in the surrounding airspace, to allow the emergency aircraft to quickly descend and/or turn without conflict when an emergency descent or diversion is necessary. Likewise, procedures will need to be in place so that tightly scripted arrivals at an airport can accommodate a diverting aircraft or an aircraft that has an emergency upon landing.
- Greater attention needs to be paid to the development of checklists and procedures to respond to the identification of and response to the misuse or outside interference of onboard technologies associated with NextGen operations, such as GPS spoofing. Alerts associated with these outside attacks must also be triggered in a timely manner that reflects NextGen operational requirements.
- The lack of actions to rectify failure of equipment necessary for standard NextGen operations means that pilots must revert to other types of operations or actions. This may not have significant repercussions in the overall national airspace system (NAS) during current operations where some

of the NextGen operations are not widely used or implemented yet. However, it could have significant repercussions once NextGen operations are more fully in place.

- For example, under NextGen Data Comm failures will be dealt with by reverting to voice communications. This may be an acceptable fall back arrangement if the failure exists for a single aircraft. If the failure exists on the ground side however, affecting all aircraft in a particular sector, or multiple aircraft due to environmental conditions, it might quickly become untenable, especially given the closely spaced operations envisioned under NextGen.

Concluding Comments

By necessity, this study was focused fairly narrowly on just a few issues and checklists, primarily associated with two of the checklist design factors often causing the greatest challenges for checklist designers and pilot users, i) identifying and accessing the correct checklist and ii) navigation through the checklist and other materials needed, and checklists for use in NextGen Operations. Prioritization of checklists/response in multiple failure conditions is another highly challenging area for designers and pilots but was beyond the scope of the present study.

It is not uncommon for air carriers and manufacturers to make adjustments, changes, and additions to emergency and abnormal checklists. It is because of their critical role in helping to guide pilot response to demanding situations that developers work to make the most effective checklists possible. Well-crafted emergency and abnormal checklists of any mode of presentation—integrated ECLS, stand-alone ECLS, paper—can be very difficult to develop and each mode brings its own design challenges. Furthermore, NextGen will require the development of new checklists and procedures for response to malfunctions of new and existing technologies and may require changes to existing checklists relative to NextGen operational requirements and expectations.

One of the strengths of the analyses conducted in this study is the comparison of approaches taken by developers of ECLSs, QRHs, and checklists within the same and across different types of aircraft. This study provides useful information, illustrations, and points of comparison while maintaining confidentiality and protecting proprietary information. Through this study participants and other checklist developers may gain a greater appreciation of some of the strengths of the designs of their checklists, identify possible areas for change, and learn from approaches taken by others.

Factors Affecting the Use of Emergency and Abnormal Checklists: Implications for Current and NextGen Operations

Barbara K. Burian[2]

1.0 Introduction

Everyday throughout the world pilots encounter and manage emergency and abnormal situations on board aircraft. Even with advances in technology and increased reliability of aircraft systems, such situations will continue in the future and new types of events associated with NextGen operations are also anticipated (Kochan, Tomko, & Burian, 2014). Burian (2014) identified three major factors affecting pilot response to these situations: the operational demands presented by the situations and various contextual factors that mediate those demands, human performance capabilities and limitations under acute stress, and the design and content of emergency and abnormal checklists (see Figure1).

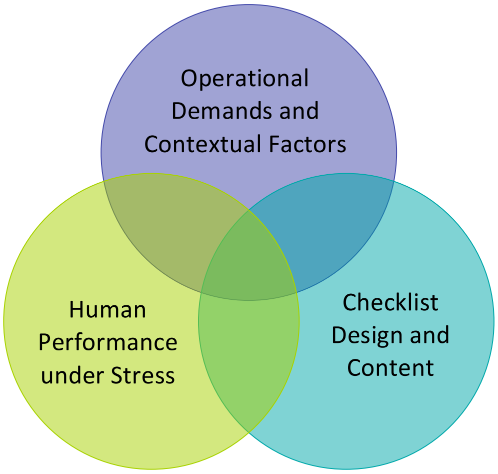


Figure 1. Primary factors affecting pilot response to emergency and abnormal situations.

The operational demands these situations pose vary according to the specifics of each event. Is the situation ambiguous or clear-cut? Is it potentially life-threatening or relatively benign? Is the event time-critical or is plenty of time available for response and corrective action? A wide variety of contextual factors (e.g., weather, visibility, automation and technology available, pilot training and experience, etc.) can increase or decrease the number and effects of the various demands (Burian, 2010, 2014).

---

[2] NASA Ames Research Center, Moffett Field, California.

Human performance capabilities and limitations under conditions of acute stress and increased workload—particularly decrements to cognitive processing, decision making, and working memory—are often overlooked or under-appreciated components affecting flight crew response to emergency and abnormal situations (Dismukes, Goldsmith, & Martinez-Papponi, 2013; Stokes & Kite, 1994). Pilots are supported in their response to most emergency and abnormal events through the use of checklists which are specifically developed to help structure and organize their actions, provide necessary information, facilitate decision making, and conclude the events successfully (Burian, Barshi, & Dismukes, 2005).

Despite the positive outcomes of the vast majority of emergency and abnormal situations, there is no lack of incident and accident reports relating shortcomings in the design and/or content of some of these checklists or problems the pilots encounter when using them. In some, thankfully rare, situations, it almost appears that pilots achieve a successful outcome *despite* the checklist they used rather than because of it.

> "…Over a year ago, a new format for the XXX [type of aircraft] emergency/abnormal checklist was enacted. The company realized that the old format was too cumbersome…It was hoped that the new format would make operations more efficient and safer…Unfortunately, the opposite has occurred. Instructors have had to point out that the new QRH [Quick Reference Handbook] checklists have numerous flaws and a confusing format…Procedures are based on yes/no decision statements that are not phrased as questions. These ambiguous decision statements can lead to confusion as to where to go for the next step. Page numbering is confusing and complex…The end result is that it is very difficult for a crewmember to find and execute the proper checklist in a timely manner in an emergency environment. Emergency and abnormal procedural steps and notes are all printed in the same font. It is easy to skip a vital procedure. The Two Engine Inoperative checklist is loaded with numerous non-critical notes and tables that should be placed at the end of the checklist. This misplaced information destroys the continuity of the checklist. As a result, crewmembers easily get lost in the middle of the checklist and miss vital steps…The YYY [engine type] high EGT procedure does not agree with the limitation section of the airplane flight manual…These are only a few of the flaws with the QRH checklists." (Aviation Safety Reporting System (ASRS) Report, Accession Number 540156; ASRS, 2001).

Checklist use in emergency and abnormal situations can range widely from no checklist consulted at all (e.g., American Trans Air [ATA] 406; National Transportation Safety Board [NTSB], 1998a) to situations in which diversion or landing was delayed so that multiple emergency and abnormal checklists could be completed (e.g., Qantas 32; Air Transport Safety Bureau [ATSB], 2013). There are some events in which corrective action must be immediately applied and, in general, no checklist is constructed to guide pilots in the performance of these actions (e.g., response to a blown tire prior to V1 during takeoff, response to an upset attitude during cruise, etc.). In cases such as these it is expected that correct pilot action will be taken as a result of pilot expertise and knowledge; time is not available to reference a printed procedure that outlines the steps to take (Burian & Boorman, 2005).

There are other situations in which time criticality and workload limits the degree to which checklists can be consulted in an emergency. For example, the crew of Aloha flight 243, which experienced an explosive decompression involving the loss of an 18 foot section of its fuselage, estimated that they completed all or parts of 17 different emergency checklists entirely from memory in the 13 minutes it took them to descend from flight level (FL) 240 to land (NTSB, 1989; Mimi Tompkins, personal communication, April 30, 2001).

Aside from these types of situations, the availability, accessibility, and the usability of emergency and abnormal checklists can be instrumental in how the events are handled (see for example Valujet 558 (NTSB, 1996), FedEx 1406 (Burian, 2004; NTSB, 1998b), and Swissair 111 (Transportation Safety Board of Canada [TSB], 2003)). The development and design of emergency and abnormal checklists is quite challenging and it is extremely unlikely that a single checklist could be designed to perfectly match the requirements of every situation in which it might be needed (Burian, et al., 2005). Nonetheless, developers rightly seek ways improve the usability of emergency and abnormal checklists to better support pilots in these often dire situations.

To get a better understanding of current practices and approaches to factors of checklist design known in the past to have caused pilots difficulty, an analysis of these factors in specific checklists was undertaken. These factors can be found squarely in the blue circle in Figure 1 above (i.e., pertain to checklist design and content). However, what often makes them problematic is the interaction of suboptimal approaches to checklist design or content with the operational demands of emergencies and abnormal situations and human performance limitations under stress, i.e., the center of Figure 1 where the three circles overlap (Burian, et al., 2005). Also included in this study was a review of emergency or abnormal checklists associated with NextGen operations and applications (e.g., Data Comm failures).

1.1 Checklist Design Factors

Fourteen inter-related factors associated with the design and content of paper and electronic checklists used for response to emergency and abnormal situations in aviation have been identified by Burian (2004, 2006) and are presented in Table 1.[3]

Two of the most challenging aspects of emergency and abnormal checklist design pertain to accessing the correct checklist for the situation and then properly navigating or moving through the checklist and related materials (e.g., performance tables) so that only the correct items for the specific situation are accomplished. Obviously, alerts and cues can be instrumental in assisting with the first, i.e., diagnosing the condition and identifying the proper checklists to be accomplished (Berman, et al., 2014). However, the structure, organization, and functionality or use of Quick Reference Handbooks (QRHs) and Electronic Checklist Systems (ECLSs) and even checklists themselves can assist pilots in accessing the correct checklist or confirming that the correct checklist has been located.[4]

---

[3] All of these factors are discussed in detail in Burian (2014).

[4] The prioritization of multiple checklists, so the most essential are accomplished first, is also critical when multiple checklists are needed in an abnormal or emergency situation. However, the issue of checklist prioritization is beyond the scope of this report.

Table 1. Paper and Electronic Checklist Design and Content Factors

Design and Content Factor	*Examples/Explanation*
Physical Properties, Interface, Integration, Functioning, and Intended Use	Size, weight, materials (type of paper, plastic, covers, bindings, etc.), tabs and divider pages, integration with displays & alerts, buttons and soft keys, mice, trackballs, touchpads, checklist selection, process for item accomplishment, etc.
Typography, Symbology, Color, Graphics and Display Characteristics	Font, font size, boldface, underlining, italics, symbols, flashing text, text & paper/display colors, numbering items, flow charting symbology, etc.
Layout, Format, and Display	Visual look, arrangement, influenced by philosophy of response/use
Organization, Access, and Prioritization	Indexes, menus, tables of content, drop-down lists, sections and subsections, types and ordering of content within QRH. ECLS, use of “prime real estate pages” (e.g., QRH covers)
Purpose	Fix, troubleshoot, stabilize/safe, disable/isolate
Objective (of checklist item)	Direct action, inform, assess, facilitate decision making, etc.
Length & Workload	Physical length, timing length, workload, who completes step
Nomenclature, Abbreviations & Numerical Information	Terms, labels, abbreviations, numerical information
Language, Grammar, and Wording	English?, verb tense, reading difficulty, clarity, orientation/perspective, level of directiveness
Level of Detail	Amount of information provided particularly with regard to how to perform an action or why
Comprehensive & Correct	All necessary steps are included, actions are appropriate for the situation, full range of situations accommodated not just worst case scenario
Engineering Coherence	Order/timing of steps makes “sense” to the aircraft (i.e., they work from an engineering perspective)
Logical Coherence	Order of actions make sense to the pilot and make “sense” from an operational perspective
Progression & Jumping (aka Checklist Navigation)	Movement within and between checklists/manuals and other materials (e.g., performance tables)

Many emergency and abnormal checklists contain different sets of items to be accomplished if certain conditions exist. For example, separate sets of items may be included in a single checklist for use when the aircraft is in or is not in icing conditions. Inclusion of both sets of these items expands the utility of the checklist and increases the likelihood that pilots will complete all appropriate actions for their situation. However, moving through the checklist to the appropriate steps and skipping past those that are not relevant can cause pilots difficulty and increases the likelihood of error.

Analyses in this study focused primarily, though not exclusively, on these two issues: i) identification and access of the appropriate checklist for specific emergency or abnormal conditions and ii) the accomplishment of the correct steps within the checklist once it has been accessed. The factors from Table 1 associated most closely with these two issues, and which therefore received primary attention during analysis, were:

- physical properties, interface, integration, functioning and intended Use
- typography, symbology, color, graphics, and display characteristics
- layout, format, and display
- organization, access, and prioritization
- length and workload
- comprehensive and correct
- progression and jumping (also known as checklist navigation)

Only specific factors known to be an issue with past checklists for emergency/abnormal situations involving one or both of the two major issues of interest were analyzed. In other words, not every factor was analyzed in each of the checklists reviewed. Furthermore, not every factor in the bullet list above was fully analyzed. For example, some symbols were analyzed because they are intended to direct pilots to the correct items within a checklist for their specific situation. However typography, which is also grouped with symbology in Table 1, was not analyzed in this study.

In addition to these factors, different types of items and elements in checklists also contribute to pilots confirming they have accessed the correct checklists and facilitate their accomplishment of the correct items within them (Burian, 2013). Therefore, this study also included an analysis of the following checklist items and elements in the selected checklists: Checklist Titles, Symptom or Cue Lists, Memory Items, Deferred Items, and Conditional/Decision Items.[5] Finally, certain aspects of overall QRH and ECLS structure, organization, and functioning/use were reviewed because of their relationship to a pilot's ability to access a desired checklist. The specific checklists and the aspects chosen for analysis in each (i.e., Checklist Design and Content Factors, and Checklist Items and Elements, as well as the overall structure, organization, and functioning/use of QRHs and two types of ECLS) are described in Section 3.0.

---

[5] Burian (2013) identified 32 different types of items and elements included in current printed emergency and abnormal checklists (paper and/or electronic). For example, the following six help pilots to confirm that the proper or desired checklist has been accessed or is being accomplished: Checklist Titles, Repetition of Checklist Titles on Subsequent Checklist Pages, Condition Statements/ Descriptions, Reproduction of Aural or Visual Alert Messages or Illuminated Lights, Symptom or Cue Lists, and Purpose/Objective of Checklist Statements. Due to time limitations, of these six only Checklist Titles (related to certain un-alerted events) and the inclusion of Symptom or Cue Lists (in checklists for a fuel leak) were evaluated in this study.

2.0 Approach

The analysis of checklists, QRHs, and ECLS can be extraordinarily lengthy and time consuming. When checklist developers are interested in completely changing the look, structure, formatting or the way that paper checklists and QRHs are used, an extensive analysis of every type of checklist design and content factor as well as all items and elements may be needed. The same type of extensive analysis may also be necessary when constructing a new electronic checklist system, regardless of whether it is a stand-alone system, such as what might be presented on an electronic flight bag (EFB), or an integrated electronic checklist system, such as the Boeing 777 ECL or that included as part of the Airbus 320 ECAM system. In these sorts of analyses, not only are the content and formatting or display evaluated, but also their usability and functionality.

However, when difficulties are identified with a single checklist, or even with a single item in a checklist, a much more narrow analysis can be undertaken. In this study, the analyses conducted fell between these two extremes but was somewhat closer to the less extensive analysis end of the continuum than the more extensive end. Subtopics associated with the two primary issues of interest were identified. The checklists for various emergency and abnormal conditions that were analyzed, relative to these subtopics, are listed below:

1. Checklist access and overall use
    - Aerodynamic stall
    - QRH and ECLS structure and functionality
        - – physical properties, interface, integration, functioning, and intended use
        - – organization, access, and prioritization
        - – layout, format and display

2. Diagnosis and determining the appropriate checklist
    - Fuel leak
    - Pitot-static blockage
    - Uncommanded yaw or roll
        - – physical properties, interface, integration, functioning, and intended use
        - – organization, access, and prioritization
        - – checklist titles
        - – symptom or cue lists

3. Situations or aspects of situations that haven’t been anticipated during checklist development
    - failure of all hydraulics systems
    - uncommanded yaw or roll
    - dual engine failure/fuel leak/volcanic ash/failure at low altitude
    - fuel leak (engine/tank)
        - – comprehensive and correct

4. Cognitive and workload demands and checklist use
    - dual engine failure
    - fuel leak
    - All hydraulics failure

- QRH and ECLS structure and functionality
    - physical properties, interface, integration, functioning, and intended use
    - typography, symbology, color, graphics, and display characteristics
    - layout, format, and display
    - organization, access, and prioritization
    - length and workload
    - progression and jumping
    - memory items (entire QRH)
    - deferred items
    - conditional/branching/memory items

5. Checklist navigation
    - Dual engine failure
    - Fuel leak
    - All hydraulics failure
    - QRH and ECLS structure and functionality
        - physical properties, interface, integration, Functioning, and intended use
        - typography, symbology, color, graphics and display characteristics
        - organization, access, and prioritization
        - length and workload
        - progression and jumping
        - conditional/branching/memory items

6. Assumptions about Amount of Time Available
    - Fuel leak
    - Dual engine failure
    - Pitot-static blockage
    - All hydraulics failure
    - layout, format, and display
    - length and workload
    - progression and jumping
    - conditional/branching/decision items

7. Checklists for Use in NextGen Operations
    - Data comm associated checklists
    - Required Navigation Performance (RNP) associated checklists
    - Checklists for GPS spoofing
        - comprehensive and correct
        - checklist titles

Study findings are presented in two different ways. In Section 3.0, analyses are presented for each checklist or area, individually. Findings related to the seven numbered subtopics above are presented and discussed in Section 4.0.

Several North American air carriers participated in this study by contributing hard and/or electronic copies of QRHs and checklists, allowing access to simulators so that ECLSs could be studied, and by providing subject matter experts (SMEs) who answered numerous questions.[6] Checklists/QRHs/ECLSs across five different aircraft types were analyzed: A320, B737NG, B777, CRJ700, and EMB190. Two different air carriers provided materials for each aircraft type, except the A320 for which three carriers provided checklists/QRHs/access to the A320 ECLS (i.e. ECAM). Therefore, a total of 11 sets of checklists/QRHs and two different ECLSs—the B777 ECL and the A320 ECAM—were analyzed.[7] Relevant checklist/QRH/ECLS differences across the carriers for each aircraft type, when they were found, are reported. Although many pilots, instructors, checklist developers and other subject matter experts (SME) have described issues associated with emergency and abnormal checklist use, both positive and negative, no observations were made of pilots actually using these checklists, QRHs, or ECLSs as a part of the current study.

To de-identify the air carriers who participated and protect their proprietary information as much as possible, checklist content is generally described rather than reproduced verbatim in this report, and for the most part, generic versions of Checklist Titles have been used. However, to facilitate the participants identifying findings which apply specifically to them, numbers or Roman numerals were randomly assigned to each QRH/ECLS provided. In the results presented in the sections below, these numbers or Roman numerals appear in parentheses and in red type (e.g., “Two QRHs (14, 19) included….”). Participants have been informed which number(s) refer to their QRH(s)/ECLS(s)/checklist(s).

Checklists and procedures are constantly being updated and revised, sometimes because new operational issues need to be addressed and other times because improvements are sought. Thus, the checklists and QRHs that were analyzed in this study, which were current at the time they were provided by the air carriers, may well be somewhat different now, a few months later. Nonetheless, the overall issues identified remain relatively pervasive throughout the industry and warrant exploration and discussion, even if the specific checklists or QRHs analyzed have changed slightly. Because it is unknown which checklists may be different now and in what ways, present verb tense will be used to describe all of the findings.

3.0 Results

3.1 Overall QRH/ECLS Structure and Content

Paper checklists to guide response to both alerted and un-alerted emergency and abnormal situations during line operations are generally collated and placed in a manual called a QRH. Other information which might be referenced in an emergency or abnormal checklist or might be needed during response to such a situation, such a performance data, is also often placed there as well. Occasionally, instead of a QRH, the checklists appear in a Flight Manual, which generally contain a

---

[6] Emergency and abnormal checklists, QRHs, and ECLSs are initially developed by aircraft manufacturers and their subcontractors (i.e., Original Equipment Manufacturers [OEMs]). Air carriers or users of these materials often then make modifications or additions to them, both in content and in layout or formatting. Therefore, the checklists, QRHs and some ECLSs for the same aircraft type might look quite different at two different carriers. Baseline or standard checklists/QRHs from OEMs were not evaluated as part of this study, only those materials used by participant air carriers during their actual line operations.

[7] Due to the difficulty in obtaining samples from air carriers for analysis, no stand-alone electronic checklists or ECLSs were analyzed as part of this study; only the Boeing ECL and Airbus ECAM, which are integrated ECLSs, were included.

much broader range of material and information than that needed during an abnormal or emergency situation (e.g., aircraft limitations, systems specifications and normal functioning, etc.).

QRHs are often developed even for aircraft that are equipped with stand-alone or integrated electronic checklists. As will be described later, in these cases the QRHs may be used as back-ups in case the ECLS fails, as supplements to the ECLS, as training or study aids, or any combination of the three. Ten hard copies of QRHs and one electronic Flight Manual (7), which included emergency and abnormal checklists in one of its chapters, were analyzed in this study.[8]

Although it is possible that some of the air carriers who participated use stand-alone electronic abnormal/emergency checklists during line operations, none were asked to share them for this study and it is unknown how many might be in use. Two participants fly the B777 and three fly the A320, each of which have integrated ECLSs (ECL and ECAM, respectively). Integrated ECLSs are connected to the aircraft systems through a network of sensors which reveal system status to the pilots and can have a direct effect on the functionality of the ECLS, such as when actions that have been accomplished are sensed as having been completed and disappear or turn a different color to indicate this. Although they are both integrated ECLS, the Airbus ECAM and the Boeing ECL each operate differently.

Airbus ECAM. As its name implies, the ECAM monitors aircraft systems and displays information about them through two primary cockpit displays, the Upper ECAM and the Lower ECAM (see Figure 2). During emergency or abnormal conditions, it displays text alerts associated with the condition and corrective actions for the crews to take (i.e., checklist steps). In Figure 2, the title of an abnormal condition (FUEL AUTO FEED FAULT) appears in amber in the lower left section of the upper ECAM display and is followed by one checklist item to be accomplished, in blue type. The alerts and checklist actions are automatically displayed and prioritized so the most critical alerts and actions, based on algorithms developed by ECAM designers, are always presented first when more than one emergency/abnormal condition exists.

As checklist items are accomplished, they disappear giving the appearance of "scrolling off" the display. Seven lines are available for the display of messages. A downward green arrow appears at the bottom of the upper ECAM display to indicate the presence of ECAM messages of a lower priority if more alerts and checklist items exist than can be displayed (i.e., more than seven lines worth of information). As displayed items are accomplished and their associated alerts cleared, they disappear allowing others to "scroll up" and be displayed for accomplishment. System synoptics are also automatically displayed, in the lower ECAM display, which show the status of the malfunctioning system and the effect the crew actions are having on it as checklist steps are accomplished. Upon the completion of the displayed checklist items and review of the system synoptic, the pilots are to call up the Status page of the ECAM which includes a list of inoperative equipment, if any, and other information which might be pertinent for the remainder of the flight, such as changes to approach procedures. Although system synoptics are displayed automatically when an alert for a specific system is displayed, the pilots can also select the synoptics to be displayed manually.

---

[8] Unless a distinction must be made between the QRHs and the electronic Flight Manual, the Flight Manual may be referred to as a QRH when presenting findings to simplify wording in this report.

Figure 2. Airbus ECAM displays.

The content of the checklists in the ECAM can be customized to some degree when the aircraft is purchased but, for the most part, cannot be changed by the air carriers once they have been delivered. Therefore, most operators develop a QRH that contains additional steps or information for the crews to reference for many ECAM checklists, in addition to checklists for conditions that are not alerted and thus not presented on the ECAM. Many air carriers, but not all, also develop some QRH checklists that are to be used *instead* of the steps presented on the ECAM when the actions on the ECAM are undesirable for some reason. These checklists are typically called ECAM exceptions or ECAM bypass checklists. In this study one A320 air carrier (III) has no such checklists, whereas the other two who contributed A320 QRHs have 10 and 11 such checklists (I and II, respectively) to be used in lieu of those appearing on the ECAM. These two QRHs have only four bypass/exception checklists in common, the rest appear in only one of the two QRHs.

Boeing ECL. On the Boeing 777, the engine indication and crew alerting system (EICAS) is related to but distinctly separate from the ECL. When an EICAS text alert is displayed, a white square (a "checklist icon") appears next to it if there is an associated checklist to be accomplished. When the pilot presses the CHKL button on the cockpit Display Select Panel (DSP) the checklist is automatically presented on one of the cockpit multi-function displays (MFD). If multiple EICAS alerts are displayed with checklists for accomplishment, when the CHKL button is pressed a list of checklists (the Non-normal Checklist Queue) is presented for the pilot to select among. Unlike the

ECAM, the ECL does not prioritize the order in which multiple checklists should be accomplished but it does group them in the Queue according to the level of severity of their associated alert messages (warning, caution, etc.), with the most recent appearing at the top within each group. The pilot interacts with the ECL through the use of a touchpad and mouse and can move back and forth through the pages of multiple page checklists. When an item has been accomplished, rather than disappearing as with the ECAM, items change color from white to green and a green check mark appears in front of the item on the display (see Figure 3).

Some system synoptic displays are also available on the B777 and are called up manually by pressing separate buttons on the DSP, much in the same way as system synoptics are manually displayed on the Airbus ECAM.

Because the B777 ECL can be modified by air carriers, new checklists can be added and changes to existing checklists can be made as needed. Thus, the checklists in B777 QRHs match exactly in content those on the ECL and are generally never referenced during actual emergency or abnormal situations; the ECL is used instead.

Both the ECAM and ECL checklists contain closed loop and open loop items. Closed loop items are those that receive sensor feedback and are affected by the accomplishment of the stated action (i.e., disappear, turn green). Open loop items are those that receive no sensor feedback; the aircraft cannot sense if the action has occurred, such as having contacted air traffic control (ATC) to declare an emergency. On the ECAM, open loop items remain displayed, regardless of their completion status, and the pilots ignore them after they have been accomplished and move to the next item on the list. On the ECL, pilots use the touch pad and mouse to check-off open loop items when they've been accomplished; doing so will also turn the item text green.

FIRE ENG R

Fire is detected in the right engine.

✓ RIGHT AUTOTHROTTLE ARM SWITCH . . . . OFF

✓ RIGHT THRUST LEVER . . . . .CLOSE

✓ RIGHT FUEL CONTROL SWITCH . . . . .CUTOFF

✓ RIGHT ENGINE FIRE SWITCH . . . . PULL

✓ If FIRE ENG R message remains displayed:

RIGHT ENGINE FIRE SWITCH . . . . ROTATE
Rotate to the stop and hold for 1 second.

Figure 3. Boeing 777 ECL.

As with open loop items, there are also emergency or abnormal conditions which are not sensed by the aircraft and hence, are un-alerted[9] (e.g., unreliable airspeed indications). In these situations, the flight crews must first be aware that an emergency/abnormal condition exists, accurately diagnose it, and then recall that a checklist exists for the condition. The ECAM only includes emergency/abnormal checklists that are alerted so checklists for un-alerted situations on the A320 are found only in companion QRHs.

On the B777 ECL, un-alerted checklists can be found by first selecting the Non-Normal Menu (at the top of the ECL display, see Figure 3) which causes a list of checklist subsections to be displayed (see Figure 4), including one for Unannunciated (un-alerted) Checklists. Selection of the Unannunciated Checklists section causes the list of all un-alerted Checklist Titles to be displayed for the pilot to select among.

3.1.1 What Was Analyzed and Why

The structure, content, and functionality of QRHs and ECLSs have a direct relationship to the ease with which pilots have in accessing the correct or desired checklist for their situation and the level of workload involved when using them. The content available through the ECAM and ECL, as well as their general functioning, has been described above. A wide range of content may be included in QRHs and is described in the Findings section below. QRH functionality is determined not only by its content but also by how the content is organized and how the QRH is intended to be used. For example, the types and locations of indexes, the grouping of similar checklists into sections or subsections, the use of divider pages and tabs, and related features all contribute to how and the ease with which the QRH is used. All of these features have been analyzed in this study. The numbers of alerted and un-alerted checklists for each aircraft type for each air carrier participant were also analyzed, as well as things air carriers do to increase the likelihood that a desired un-alerted checklist can be found (e.g., include it multiple times in an index under slightly different titles).

---

[9] Although some conditions are not specifically alerted, various other alerts may be presented on the flight deck when the conditions exist. For example, Fuel Leak is a condition that is not directly sensed and thus, is un-alerted, but an alert for FUEL IMBALANCE may be displayed when a fuel leak is present.

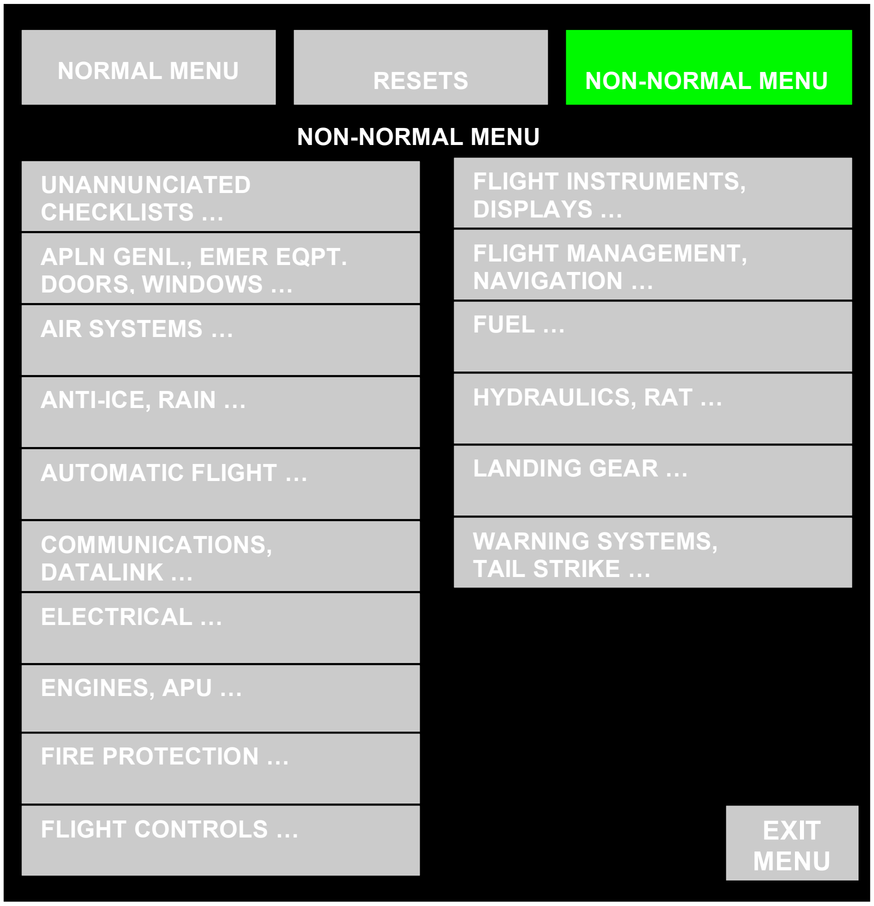


Figure 4. Boeing 777 ECL non-normal checklist menu.

3.1.2 Findings

Table 2 summarizes the types of content contained within the QRHs analyzed, including the type of information presented on the outside and inside of the QRH front and back covers, different types of indexes, the division of emergency/abnormal checklists in the QRH into sections or subsections, the inclusion of section/subsection Tables of Content, and the inclusion of performance tables or information and other material. As mentioned earlier, one air carrier (7) provided only an electronic copy of their aircraft Flight Manual (they do not produce a hard copy QRH for this aircraft type) so various physical characteristics common with QRHs (such as a cover) do not exist. Some of the other types of content contained within in the QRHs analyzed, not specified in Table 2, include such things as resetting aircraft computers (1, 3, 5, 8, 9), icing holdover times (3, 5, 8), and braking action (2, 9, 10), among many others.

Table 2. QRH Content

Content	*Number of QRHs*	*Participants*
QRH name/aircraft type/air carrier name on cover	10	1, 2, 3, 4, 5, 6, 8, 9, 10, 11[a]
QAI on cover	3	1, 4, 6
QRC on cover	6	2, 3, 5, 8, 9, 10
Evacuation checklist on cover	9	1, 2, 3, 4, 5, 6, 8, 9, 10
QRH/checklist general Information	3	1, 4, 6
List of effective pages/revision record	11	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
Index(es) for alerted conditions	4	1, 2, 5, 9
Index for un-alerted conditions	2	1, 5
Alphabetical index for all conditions	10	1, 2, 3, 4, 6, 7, 8, 9, 10, 11
Use of tabs and divider pages	8	1, 3, 4, 5 ,6, 8, 10, 11
Normal checklists	2	4, 6
Emergency/abnormal/non-normal checklists	11	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
Separation of checklists into two major sections: emergency and abnormal	1	11
Separation of emergency and abnormal checklists into aircraft system subsections	9	1, 3, 4, 5 ,6, 7, 8, 10, 11
Each checklist subsection has a table of contents	8	1, 3, 4, 6, 7, 8, 10, 11
Emergency/abnormal/non-normal maneuvers	2	4, 6
Performance tables and information	5	2, 3, 8, 9, 10
Other Information or material	7	1, 2, 3, 5, 8, 9, 10

[a] The manual title ("Quick Reference Handbook") and aircraft type series are printed on the front cover however the cover of the QRH that was analyzed does not include the airline name and the specific aircraft type has been hand written on the cover using a black marker.

QRH Covers. As can be seen in Table 2, most participants choose to include information which the crews might need to locate quickly on the covers of their QRHs, such as Evacuation Checklists, and Memory and/or Immediate Action Items (i.e., Quick Reference Card (QRC) information). All participants' hard QRHs that do not include QRC information (1, 4, 6) include a Quick Action Index (QAI) instead, except for one (11). To the degree that the participants are representative of the industry within the US, it appears that most carriers see the value in using QRH covers as a means to help their pilots easily or quickly access checklists or checklist items which may be time critical.

ECLS Checklist Access. As described above, the ECAM automatically selects, prioritizes, and displays alerted checklists for pilots to accomplish. In the case of a single alert, the ECL automatically selects the checklist associated with the alert, if one exists, and displays it when prompted by the pilot. If multiple alerts are displayed on the B777 EICAS, pilots decide the prioritization of the checklists that have been presented on a list and select them one at a time for display and accomplishment.

Un-alerted checklists on A320 aircraft can only be accessed through printed QRH (or a stand-alone ECLS, if one exists). So too, ECAM bypass or exception checklists should be accessed solely through the QRH. Un-alerted (unannunciated) checklists on the ECL can be accessed manually through the ECL Non-Normal Menu and section menus as described earlier.

ECL Menus, QRH Indexes, and Checklist Titles. The Non-Normal Menu and Section menus on the B777 ECL serve the same function as QRH Indexes: they include a listing of Checklist Titles, which are organized according to a specific scheme, to aid pilots in locating a desired checklist. There are a wide variety of index or menu organization schemes. A *Lights Index*, which is not included in any of the QRHs analyzed in this study, presents a reproduction of cockpit lights, typically from the overhead systems panels, along with the page number in the QRH where checklists to be accomplished can be found if those lights are illuminated. *Alert Indexes* present a listing of the text alerts, typically in alphabetical order, which might be displayed in the cockpit on the ECAM, EICAS, or other type of crew alerting system along with the page numbers where their associated checklists can be found. All levels of alerts might be combined in a single index, or different indexes might be constructed for the different levels of alerts (Warnings, Cautions, Advisory, Status, etc.); none of the QRHs analyzed included multiple alert indexes. *Un-alerted Indexes* include only un-alerted Checklists Titles with their page numbers. *Master Indexes*, which may or may not be labeled as such, included the titles and page numbers for all checklists included in the QRH or ECL, both alerted and un-alerted. Table 3 presents the types of indexes found in the QRHs analyzed and in the ECL Non-normal Checklist menu structure.

The Immediate Actions Indexes and the ECAM Exceptions/Bypass Indexes, identified in Table 3, are located on the outside of the back QRH covers. All the primary indexes for locating emergency and abnormal checklists within the QRH are located at or very near the beginning of the QRH (1, 2, 3, 4, 5, 6, 8, 9, 10) or Non-Normals Chapter in the electronic Flight Manual (7) with the exception of one (11), which is located at the very end of the QRH. All of indexes list Checklist Titles and the exact page numbers where they can be found with the exception of one (11) which only indicates the section in which each checklist is located; users must refer to the table of contents in each section to identify the page on which the desired checklist is located.

Table 3. QRH Indexes and ECL Menu Structure

Type of QRH Index	*How Organized*	
	Alphabetical	*Grouped by Aircraft System (then Alphabetical)*
Single alert index	1, 2, 5, 9	
Un-alerted Index	1, 5	2
Master Index	1, 3, 4, 6, 7, 8, 10, 11	9, ECL Menus
Immediate actions Index (QRC)	2, 9	
ECAM exceptions/bypass index	I, II	

The vast majority of alerted Checklist Titles in the QRHs appear to match exactly the alert message text as it appears on the ECAM, ECL, and/or pilot alerting system. Doing this helps pilots to confirm that the correct checklist for a particular alert has been accessed. In some QRHs (e.g., 3, 5, 8, 11) a single checklist is referenced more than once in an Index but with slightly different titles (e.g., Unreliable Airspeed, Airspeed Unreliable). This is typically the case with un-alerted checklists, but not always. Including different titles for the same checklist in Indexes increases the likelihood that pilots will be able to locate the one that is desired because they do not have to recall the exact wording of the title. This is particularly helpful when a checklist that might logically be expected to be found in one system section but is actually located in another. For example in one QRH (9), the NAV ADR Disagree checklist is listed in the Flight Controls section rather than in the Flight Instruments and Navigation section. Although titles for some checklists might appear in multiple places within an index, in none of the QRHs was the same checklist found in multiple sections/locations.

Sections, Subsections, and Tabbing. All of the QRHs are divided into various sections and subsections. Most often colored tabs, which protrude from the right edge of the QRH pages, and divider pages are used to delineate the sections and subsections (1, 3, 4, 5, 6, 8, 10, 11), but two QRHs (2, 9) included no tabs or divider pages. Of those that use divider pages for grouping the emergency and abnormal checklists, six (1, 3, 4, 5, 6, 8) use section numbers to label the tabs and two (10, 11) have both section numbers and names labeled on the tabs. Five (1, 3, 4, 6, 8) of those who use just numbered tabs also print the name and number of all checklist subsections on the divider pages. In the one (5) that does not do this the pilots must memorize which section goes with which tab number or must turn to the sections until the desired one has been located. Several QRHs also use different colored pages to set off some sections (2, 9, 10) or for temporary revisions/information (3, 4, 11); white paper is used for pages that contained emergency/abnormal checklists across all of the QRHs analyzed except for one (10), which uses gray paper.

It used to be quite common to divide QRH checklists into two major categories: ones which were time critical (emergency) and others which were important but less time critical (abnormal). Only one of the QRHs analyzed (11) used these two high level groupings of checklists. Those in the Emergency section were further grouped by aircraft system or issue (e.g., Powerplant, Smoke/Fire/Fumes, etc.) using divider pages with red, labeled tabs. Those in the Abnormal section were similarly grouped but the divider pages had amber colored tabs. None of the other QRHs analyzed or the ECL use Emergency/ Abnormal super categories; all checklists for these types of events are not distinguished as emergency or abnormal and are usually grouped just by aircraft system (1, 3, 4, 5, 6, 7, 8, 10). Two QRHs (2, 9) do not group checklists by system though many for a particular system can be found relatively near each other in the QRH. Although companion QRHs for the A320 ECAM and Boeing ECL in this study do not use emergency or abnormal delineations, the colors of the alerts and Checklist Titles, when presented on the ECAM/EICAS/ECL displays do appear in either red or amber type to indicate the level of alert severity (warning or caution, respectively). The ECAM, EICAS, and other alerting systems also have other levels of alerts such as Advisory and Status messages. Some QRHs analyzed include sections with information, and sometimes actions to accomplish, relative to Advisory (11) and Status (5, 11) messages.

All of the QRHs that group the checklists by aircraft system (1, 3, 4, 6, 7, 8, 10, 11) also include Tables of Content (TOC) for each of these sections except for one (5). In the eight that do include section TOCs, pilots can access the desired checklist in one of three ways: use an Index, turn to the desired section and use the TOC, or recall the exact page number of a checklist and turn directly to it. When section TOCs are not used or checklists are not grouped into sections (2, 5, 9) pilots must either refer to an Index or recall the exact page number for a checklist.

ECAM and Companion QRHs. The three air carriers who provided A320 QRHs take somewhat different approaches as to the content they include and when the QRH is to be consulted relative to the accomplishment of additional items beyond those in the ECAM. It was already reported that only two of them have ECAM exception/bypass checklists. This is because the other carrier (III) was able to elicit Airbus's help in making some modifications to checklists in the ECAM so none need to be completely bypassed in favor of different versions in the QRH.

Two of the QRHs (I, III) include copies of all ECAM checklists in the QRH even if there are no additional QRH items to complete. However, the QRH from the third A320 air carrier (II) does not include a copy of those ECAM checklists that have no additional QRH information or items (255 checklists appear on the ECAM only). This suggests that the developers intend for their QRH to be used solely for response to emergency abnormal situations and not also as a stand-alone document for training or study.

When an alerted condition is displayed on the ECAM, pilots flying at one of the carriers (I) are instructed to complete any Memory Items and then consult the list of ECAM exception/bypass checklists on the QRH cover. If the alert does not pertain to one of those checklists they are instructed to complete the ECAM procedures in their entirety and then refer to the QRH for any follow-on items or information. At another air carrier (III) pilots are to do much the same with the exception of considering the possibility of ECAM exception/bypass checklists since none exist for them.

At the third carrier (II) however, reference to completing ECAM actions appear in a variety of locations in different QRH checklists. Sometimes there is a statement at the beginning of the checklist that indicates that the ECAM items should be completed first, before the QRH items. Other times, reference to completing ECAM items appears in the middle or at the end of the QRH checklist. Just from reviewing the printed QRH, it is difficult to know how and when their pilots are instructed to refer to the QRH relative to the accomplishment of ECAM actions.

Number of Emergency/Abnormal Checklists. The number of emergency and abnormal checklists in each QRH/electronic Flight Manual analyzed for this study were tallied and appear in Table 4. QRHs from four participant air carriers (1, 4, 6, 7) have a specific section which contains many, if not all, of the un-alerted checklists. Many of the un-alerted checklists in the QRHs analyzed pertain to the functioning of aircraft engines and the avionics/autoflight systems.

Table 4. Number of Emergency and Abnormal Checklists

QRH	*Total Number of Checklists*	*Number of Un-Alerted Checklists*	*Percentage of Un-Alerted Checklists*	*Section with the Most Un-Alerted Checklists*
1	348	45	13	Miscellaneous
2	261	52	20	Engines
3	383[a]	69[a]	18	Additional procedures
4	259	35	14	Miscellaneous
5	263	66	25	Avionics
6	164	59	36	Miscellaneous
7	275	39	14	Unannunciated
8	378[a]	68[a]	18	Additional procedures
9	379[b]	57	15[b]	Autoflight, avionics
10	162	58	36	Engines
11	270	76	28	Tie: Engines and avionics

[a] Twenty of these checklists appear in an Additional Procedures section, not technically emergency or abnormal conditions.

[b] Total QRH checklists = 124, checklists on ECAM only = 255. Fifty-seven un-alerted checklists in the QRH is 15% of the total number of checklists but is 46% of the checklists in the QRH.

The percentage of un-alerted checklists relative to the total number of emergency and abnormal checklists ranges from 13% (1) to 36% (6, 10) with a median of 18%. QRHs for less technologically advanced aircraft (B737NG, CRJ700) tended to include greater percentages of un-alerted checklists than those for aircraft that are more technologically advanced (A320, B777), but large differences in the number of alerted checklists were found even across the QRHs for more technologically advanced aircraft.

3.2 Memory Items

Memory Items (sometimes referred to as Recall Items or Immediate Action Items) are generally thought of as actions that are so time critical that they must be performed right away, without reference to printed checklists. A common example of a Memory Item is the direction for pilots to don oxygen masks and goggles when an in-flight fire exists. Checklists that include Memory Items often, but not always, also include additional items (sometimes referred to as Reference Items) that *are* to be read from a printed checklist as they are being accomplished.

Some air carriers label Memory Items as Immediate Action Items. However, others include Immediate Action Items as a middle category between Memory Items and Reference Items, i.e., items that are somewhat less time critical than Memory Items and may or may not be expected to be completed from memory. Thus, the term "Immediate Action Item" does not have a consistent meaning within the industry. Table 5 presents the three categories of items and the various ways they are labeled and how they are to be performed across the industry, based on analyses in this and earlier studies (e.g., Burian & Geven, 2005).

Table 5. Memory, Immediate Action, and Reference Item Labels and Performance

Item Category	*Item Label*			*How Item is to be Performed*		
	Memory Item	*Immediate Action Item*	*Reference Item*	*From Memory*	*By Reference to Printed QRC*	*By Reference to Printed Checklist*
Memory Items	Yes	Sometimes	No	Usually	Sometimes	No
Immediate Action Items	Not Usually	Yes	No	Sometimes	Sometimes	Not Usually
Reference Items	No	No	Yes	No	No	Yes

Both Memory Items and Immediate Action Items were analyzed in this study regardless of how they were actually labeled by the air carriers (see the shaded boxes in Table 5). If only two categories of items are used by an air carrier, those in the first (to be performed from memory) are referred to as Memory Items in this report, even if the air carrier labels them as Immediate Action Items (hence, two categories: Memory Items and Reference Items). This is done to clearly distinguish these items from those in the second category of items to be performed quickly (Immediate Action Items) by those air carriers who use all three categories (Memory, Immediate Action, Reference).

As has been noted by several researchers, (Burian, 2014; Dismukes et al., 2013; Stokes & Kite, 1994), human memory can be negatively affected by acute stress, such as exists in many types of emergency and abnormal situations. Therefore, checklist developers must balance the need for pilots to respond quickly with an appreciation that pilots may perform actions unreliably when relying solely upon their memories to guide what they should do, how they should do it, and when (Au, 2005). In general, the greater the number of items to be performed from memory, the greater the cognitive load for pilots.

To reduce this load but still support the quick response by pilots to some, time critical situations, Quick Reference Cards or Checklists (QRCs) were developed and began to be used by some air carriers during flight operations in the mid-to-late 1990's (Hamman, 1997). A QRC is a printed copy of all Memory Items (and also Immediate Action Items, if they exist) for every checklist in a QRH that has them. QRC information is usually printed on a separate card (similar to the kind used for Normal Checklists) or on the cover of the QRH. Sometimes there are more items than can be comfortably fit on the outside and inside of QRH covers so the first few pages of the QRH, in addition to the covers, are also sometimes used for presenting QRC information. Less commonly, a separate section within the QRH may be used for presenting QRC information. Regardless of location, the intent of the developers is to present items which must be performed quickly (Memory/ Immediate Action) in a single place which can be quickly and easily located by pilots to support or confirm their swift and correct accomplishment.

Often, pilots are to access the QRC information, find the section pertaining to their situation (i.e., the items associated with their desired checklist) and perform the actions printed on it by referencing

QRC. Thus, Memory Items may not necessarily be completed by memory anymore (see Table 5). When three categories of items are used though, Memory Items are still typically performed from memory and Immediate Action Items are typically performed by reference to the QRC. Upon completion of QRC items (be they Memory and/or Immediate Action Items), pilots are directed to the remaining Reference Items for those checklists, if any, located inside the QRH. Some air carriers have adopted use of the QRC but their pilots are still expected to accomplish all of the items on it, including the middle category, Immediate Action Items, from memory.

Some air carriers use a Quick Action Index (QAI) which is visible though the clear, plastic, front cover of the QRH. It does not include the reproduction of Memory or Immediate Action Items as a QRC does, but instead lists the names and page numbers of checklists within the QRH which contain such items, as well as any other checklists that developers believe might need to be quickly accessed by pilots.

3.2.1 What Was Analyzed and Why

Several aspects related to Memory Items, Immediate Action Items, QRCs and QAIs were tabulated and analyzed for this study including the number of checklists with Memory and Immediate Action Items in each QRH analyzed and the number and type of Memory Items in each checklist. The availability of QRCs was also noted. While the study was in progress, QRCs were developed as companions for two different aircraft QRHs that were being analyzed. Therefore, an analysis of the effect adoption of the QRC had on the number of Memory Items in the two QRHs was also conducted. All analyses in this area were conducted to yield information relative to pilot workload, particularly cognitive workload, when using these materials in response to emergency and abnormal situations.

3.2.2 Findings

Table 6 presents the number of Memory and Immediate Action Items in each of the QRHs analyzed, the number of checklists included in a QAI, if one was used, and where QRC information is presented, if one is available. It starts with indicating whether the QRH analyzed has two categories of items (Memory and Reference) or three (Memory, Immediate Action, and Reference).

Table 6. Number of Memory Items, Immediate Action Items, and Use of QAIs

	Air Carrier Participant QRH Number[1]										
	1[1]	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***
Number of item categories (2 or 3)	2	3	2	2	3	2	2	2	3	2	2
Number of checklists with MIs[2]	4	7	5	9	5	14[b]	5	6	1	7	22
Total number of MIs across all checklists[3]	6	9	27	33	13	70[b]	8	10	1	20	87
Number of checklists with IAIs[4]	—	19	—	—	6	—	—	—	7	—	—
Total number of IAIs across all checklists	—	120	—	—	48	—	—	—	62	—	—
Number of checklists with both MIs and IAIs	—	19	—	—	4	—	—	—	1	—	—
Number of checklist titles on a QAI	20	—	—	15	—	20[c]	—	—	—	—	—
Location of QRC[5]	—	V	V	D	S	D	—	V	V	V	S

[1] Dash (—) = not applicable.

[2] MIs = Memory Items (includes items labeled as "Immediate Action" which are to be performed from memory when no other Memory Items exist).

[3] The total number of Memory Items does not include any Immediate Action Items, even if the air carrier instructs its pilots to complete both Memory Items and Immediate Action Items from memory. (Whether or not this was true could not be determined for all air carriers during this study.)

[4] IAIs – Immediate Action Items.

[5] V = QRC printed on QRH Cover, D = QRC printed on a separate Card/Sheet, S = QRC located in section within the QRH.

[a] Air carrier has a "QRC" but it is a contingency guide for Oceanic Operations – does not pertain to Memory or Immediate Action Items.

[b] After revising checklists as part of the development of a QRC, the total number of checklists with memory items dropped to 5 and the total number of memory items across these checklists now totals 30.

[c] Two of the Checklist Titles on the QAI refer to the same checklist, however.

Table 7 presents the checklists in QRHs with Memory Items (MIs), and the number in each grouped by type of aircraft. As can be seen in this table, significant differences can exist across different air carriers who fly the same type of aircraft in the number of memory items and the number and kinds of checklists that include them. To facilitate comparison within and across aircraft types, the Checklist Titles in Table 7 reflect the condition for which the checklist is to be used and may not match the exact titles used by the individual air carriers.

Table 7. Checklists with Memory Items by Aircraft Type

Aircraft Type	*Checklist Title*	*Number of Memory Items for Air Carriers*[1]		
		A	*B*	*B*/C*[2]
A320	Airspeed Unreliable	11	1	
	Cabin Altitude	2	1	
	Captain’s PFD, ND and Upper ECAM Display Blank			1
	Emergency Descent	2	1	
	Loss of Braking	10	3	
	Smoke, Fire, or Fumes/Avionics Smoke	2		
B737NG	Aborted Engine Start		1	
	Airspeed Unreliable		4	
	APU Fire	2	2	2
	Cabin Altitude Warning	3	10	9
	Dual Engine Failure	4	8	8
	Emergency Descent		9	
	Engine Fire/Severe Damage/Separation		9	9
	Engine Limit/Surge/Stall		2	2
	Engine Overheat		5	
	Flight Deck Door - Deny Entry	1		
	Intermittent Takeoff Configuration Warning Horn		7	
	Landing Configuration Horn Sounds		1	
	Overspeed		1	
	Runaway Stabilizer		10	
	Smoke, Fire, or Fumes	2		
	Takeoff Configuration Horn Sounds		1	
	Uncommanded Rudder, Yaw, or Roll	7		
B777	Aborted Engine Start		1	1
	Airspeed Unreliable		6	6
	Cabin Altitude Warning	2	7	7
	Dual Engine Failure	2	2	2
	Engine Autostart Failure		1	1
	Engine Fire		8	8
	Engine Limit/Surge/Stall		2	2
	Engine Severe Damage/Separation		4	4
	Flight Deck Door - Deny Entry	1		
	Stabilizer Runaway or Failure		2	2
	Smoke, Fire, or Fumes	2		

(continued on next page)

Table 7. Checklists with Memory Items by Aircraft Type (continued)

Aircraft Type	*Checklist Title*	*Number of Memory Items for Air Carriers*[1]		
		A	*B*	*B*/C*[2]
CRJ700	AC Power Lost		1	
	Aileron System Jammed		4	
	APU Fire		3	
	Brake Overheat		2	
	Cabin Altitude Warning/Emergency Descent	3	6	
	Configuration Warning		1	
	Ditching or Forced Landing Imminent		4	
	Dual Engine Failure	2	8	
	Elevator System Jammed		4	
	Engine Fire/Severe Damage on Ground		7	
	Engine Fire/Severe Damage in Flight		9	
	Engine Overspeed		1	
	Evacuation		12[a]	
	Hydraulics (1 or 2) High Temperature		3	
	Loss of Braking on Ground	4	3	
	Main Landing Gear Bay Overheat		2	
	Rejected Takeoff		4	
	Reverser Deployed		1	
	Rudder System Jammed		2	
	Smoke or Fumes	2		
	Stabilizer Trim Runaway	2	2	
	Stall Recovery		5	
EMB190	Aborted Engine Start		2	
	Cabin Altitude	2	2	
	Jammed Control Column - Pitch	2	1	
	Jammed Control Wheel - Roll	2	1	
	Nosewheel Steering Runaway	1	1	
	Pitch/Roll/Yaw Trim Runaway	1	2	
	Smoke or Fumes	2		

[1] Air Carrier Participants have been randomly assigned a Letter (A, B, C) for the purposes of this table. It was felt that the random numbering system used elsewhere in this document would not sufficiently protect air carrier identity and proprietary information in this table.

[2] Three Air Carriers provided QRHs for the A320, hence the need for a third column (C). Additionally, while the study was on-going, QRCs were developed as companions for a B737NG QRH and a B777 QRH which were being analyzed. Changes to the number of checklists with Memory Items for the B737NG can be seen in column B* (original Memory Item Counts for this QRH can be found in Column B). The number of Memory Items for the B777 in column B did not change as a result of the adoption of the QRC (see column B*).

[a] This checklist has a total of 12 memory items but 7 are to be performed by the Captain and 5 by the First Officer

The numbers of Memory Items do not tell the whole picture of the cognitive workload demands they present. For example, in a few of the checklists in Table 7 with relatively high numbers of Memory Items, upon their completion the user is directed to jump to and accomplish a different checklist which also has a high number of memory items. Thus, in some cases the pilots may be expected to be able to recall as many as 17 different items without reference to a printed checklist or QRC.

Something else that adds to the cognitive workload of Memory Items is not just their number, but their complexity. Many pilots (and checklist developers) think of Memory Items as only being those steps which require them to perform some action from memory (i.e., challenge-response or sentence form Action Items), such as:

Engine Fire Handle……………………………Pull
Contact ATC and declare an emergency.

Indeed, most of the 239 Memory Items[10] coded in this study were challenge-response Action Items (n = 190; 79%) or sentence form Action Items (n = 20; 8%). However, 24 (13%) of the 190 challenge-response Action Items require that both crew members confirm that the correct lever, handle, or switch has been identified before the action is taken:

Engine Fire Handle………Confirm………..Pull

Confirmation ensures that the correct aircraft system control (e.g., left or right) has been located prior to an important action being taken with it, such as when fuel is cutoff to the left engine which is on fire; in this example it is essential that fuel *not* be cutoff to the right engine, which is not on fire. However, confirmation requires coordination between crew members which may be difficult to remember or obtain during moments of surprise that can accompany the sudden initiation of a critical event (Casner, Geven, & Williams, 2012; Kochan, Breiter, & Jentsch, 2004; Thackray & Touchstone, 1983), which is precisely when Memory and Immediate Action Items are to be accomplished.

Furthermore, 12% of the 239 Memory Items coded are item types different than Action Items, such as Conditional Items (e.g., If condition XYZ exists…), Delaying or Timer Items (which indicate the specific time when an action is to be performed, e.g., At top of descent…., After 30 seconds…), Critical Notes or other Notes (e.g., !This action cannot be reversed…, NOTE: Important information you should know…) or even Explanatory Text that describes how an action is to be completed. Additionally some of the Conditional Items[11] are compound requiring the pilot to recall that two conditions must be evaluated before the subsequent action should be taken (e.g., If XX exists and YY happens, then…, If AA exists or BB exists, then…).

Although all these non-Action Items are considered Memory Items, pilots and checklist developers often forget to think of them as such and do not appreciate the extra cognitive load they place on pilots during a particularly stressful time. Thus, the recall and performance of Memory Items is not always just the simple recollection and performance of a few straight forward actions. It can also

---

[10] There were a total of 284 memory items across all 11 QRHs analyzed in this study prior to one air carrier reducing the number in one of their QRHs when they developed a QRC. The resulting total number of Memory Items (239) will be used throughout the remainder of this report. In one QRH (3) it was found that two checklists not included in the list of checklists with Memory Items, do in fact have memory items and their numbers are included in the tables above.

[11] Conditional/Decision Items are discussed in more detail in section 3.7 Dual Engine Failure.

involve communicating and coordinating actions across crew members, timing the accomplishment of actions appropriately, and judgment and decision making.

3.3 Aerodynamic Stall

3.3.1 What Was Analyzed and Why

It is generally agreed within the industry that accurate diagnosis of and recovery from an incipient or full aerodynamic stall must occur more quickly than accessing and following printed procedures allow. When rapid and correct diagnosis and reaction do not occur, tragedy can result (e.g., Colgan Air 3407 [NTSB, 2010a], Air France 447, [Bureau d'Enquêtes et d'Analyses (BEA), 2012]). Therefore, it was not expected that checklists for response to an aerodynamic stall would be found in QRHs or ECLSs. Analyses were conducted to see if that was the case and if such checklists did in fact exist, the content of the checklists were examined.

It was also not expected that information pertaining to false stall warnings would be included, again because such a diagnosis needs to be made very quickly so that recovery actions are *not* commenced (see Trans World Airline [TWA] 843 [NTSB, 1993]). Analyses were also conducted to see if this prediction held true.

Analyses of these types of information contribute to an understanding of the philosophy developers have with regard to overall QRH and ECLS use. Are they only for providing actions and information required for emergency and abnormal situation response? Are they also to be used as a part of training or to remind crews how to perform atypical maneuvers or actions just before they need to do so? Identification and analysis of information provided relative to aerodynamic stall—true or false—along with that of other information, such as the content included in QRHs and ECLSs, help to answer these questions.

3.3.2 Findings

One of the QRHs analyzed (11) does include a checklist for aerodynamic stall recovery and another (3) includes a checklist for a low energy state. The first is located in the Flight Controls subsection of its Immediate Action section and the second is located in its Autoflight section. The checklist for stall recovery (11) includes five items for actual recovery from a stall (e.g., lower the nose of the aircraft to reduce angle of attack) but they are to be performed from memory rather than items that are to be completed one at a time in reference to the checklist. The remaining checklist items are primarily Notes with information that has primary relevance during the stall recovery sequence (e.g., avoid the use of sudden control inputs during recovery). Thus, although it is formatted as a checklist and located in the QRH with other checklists of its type, it is likely that it is primarily included for use as a training aid rather than a set of steps to guide actual response to a stall. The checklist for response to a low energy state (3) has a single item directing the pilots to advance the thrust levers. Therefore, this checklist doesn't really address recovery from an aerodynamic stall though it might have applicability for one that is incipient but not yet advanced enough to trigger a stall warning.

Two QRHs (4, 6) provide information about stall recovery procedures and issues to consider during recovery in their Maneuvers sections and even list the actions that should be taken by the pilot flying (PF) and pilot monitoring (PM) during recovery. Two others (7, 10) provide such information in other documents, such as in a Flight Manual. It is highly likely that this information in any of these locations, including in the QRH, is primarily intended to be used for training purposes.

There is no information about how to detect or respond to a false stall warning (e.g., aural alert, stick shaker, stick pusher, etc.) included in any of the checklists or information pertaining to recovery from aerodynamic stall or low energy state. However, three QRHs (2, 5, 8) include checklists specific to response to false stall warnings, such as the false activation of a stick shaker. Additionally, in at least one checklist involving air data reference (ADR) in two A320 QRHs (I, III), pilots are cautioned that a false stall warning might be activated in some circumstances. Interestingly, in one of the same checklists in the third A320 QRH analyzed (II), no mention is made of the possibility of a false stall warning and pilots are even told to comply with any stall warnings that might occur. It is possible that equipage differences across the three air carriers, or some other difference, accounts for these differing directions regarding response to stall warnings in these checklists.

3.4 Uncommanded Yaw or Roll

3.4.1 What Was Analyzed and Why

The uncommanded yaw or roll of an aircraft is often, though not always, an event which is un-alerted. In those cases pilots are often left with the task of determining the cause of the uncommanded yaw or roll in order to determine the appropriate checklist to accomplish if one titled "Uncommanded Yaw or Roll" does not exist. In this study, an analysis was conducted of the types of alerts that might be displayed and checklists that might be appropriate to use in different types of uncommanded yaw or roll situations. This was fairly difficult to do because an uncommanded yaw or roll might cause some alerts to be presented (the situation of interest here) whereas some alerted situations might cause an uncommanded yaw or roll to occur—a "which comes first, the chicken or the egg" type question.

3.4.2 Findings

There was not complete agreement among the aircraft type specific SMEs consulted during this study but Table 8 gives a flavor of the variety of checklists included in the QRHs analyzed, that might be associated with an uncommanded yaw or roll event.

Table 8. Some Checklists Associated with Uncommanded Yaw or Roll Events

Checklist Title[1,2]	*QRHs*
Uncommanded Yaw and/or Roll	5, 10
Jammed or Restricted Flight Controls/FLIGHT CONTROLS	2, 4, 6, 7, 8, 10
Aileron Jam	5, 11
Rudder Jam	3, 5, 8, 9, 11
Stabilizer/Elevator Jam	1, 9
(some sort of) Trim Runaway	2, 8, 10, 11
Flight Control Computer Fault	1, 3, 9
Flight Control Spoiler Fault	1, 3, 9, IV
Spoiler Fault	1, 3, 9
Standby Rudder	6, 10, IV

[1] A more generic version of some Checklist Titles has been used to help maintain air carrier anonymity.

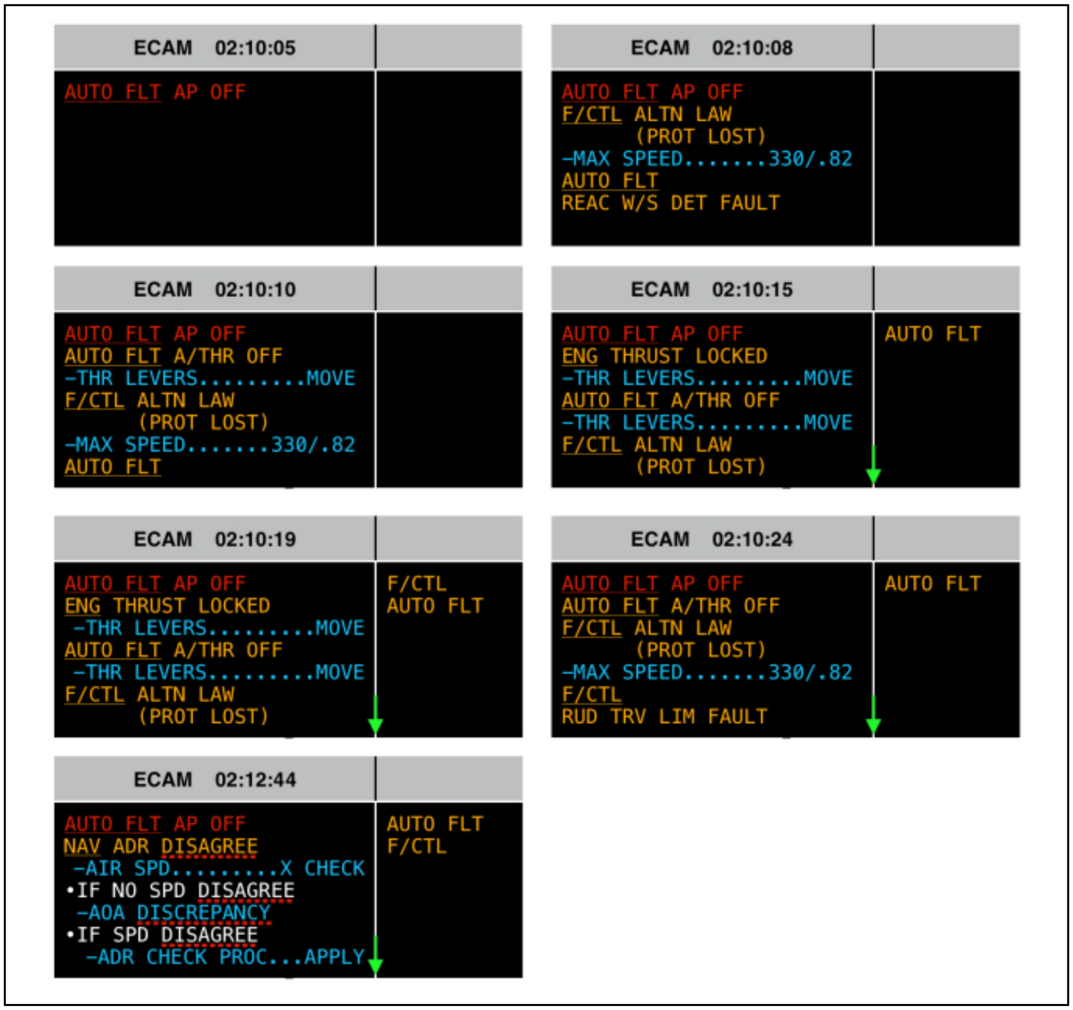
[2] All capital letters = alerted Checklists Titles; capital and lower case letters = un-alerted Checklist Titles.

Some of the differences seen in Table 8, particularly with alerted Checklist Titles, pertain to aircraft type differences and it is possible that some of the conditions associated with them might actually result in an uncommanded yaw or roll rather than just be used in response to such an event that has already occurred. Nonetheless, all of the QRHs include at least one checklist for some type of jammed flight control system although several (1, 3, 5, 9, 11) do not have checklists to be used for all the different types of flight control systems that might become jammed. However, one (5) of these does have a dedicated checklist titled Uncommanded Yaw and/or Roll as does only one other QRH (10) analyzed. Thus, with the exception of these two QRHs (5, 10), pilots must first be able to correctly diagnose the cause of the uncommanded yaw or roll event before being able to access the most appropriate checklist to accomplish.

Only four of the QRHs (2, 8, 10, 11) for use on three different aircraft types, include checklists for some type of trim runaway event. It is unknown if the other QRHs lack checklists for some type of runaway trim because the developers/OEMs do not believe those events would occur on those types of aircraft or if trim runaway is a possible event that has not been considered by the checklist developers/ OEMs.

3.5 Pitot-Static Blockage

Some of the most difficult emergency/abnormal situations for flight crews to diagnose involve blockage in the pitot-static system. The text alerts presented to pilots can be rather opaque and may do more to confuse the pilots than help them understand exactly what is going on or why (Berman, et al., 2014). For examples of this see Figures 5 and 6 in which the ECAM and EICAS alert messages displayed to the crews of Air France flight 447 (an A330) and Birgenair flight 301 (a B757), respectively, have been recreated. On both flights, the pitot tubes were blocked: with ice crystals for Air France 447 (BEA, 2012) and probably with mud/insect debris for Birgenair 301 (Walters & Sumwalt, 2000).



```
ECAM   02:10:05
AUTO FLT AP OFF
```

```
ECAM   02:10:08
AUTO FLT AP OFF
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
AUTO FLT
REAC W/S DET FAULT
```

```
ECAM   02:10:10
AUTO FLT AP OFF
AUTO FLT A/THR OFF
-THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
AUTO FLT
```

```
ECAM   02:10:15
AUTO FLT AP OFF
ENG THRUST LOCKED
-THR LEVERS.........MOVE
AUTO FLT A/THR OFF
-THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
                              AUTO FLT
```

```
ECAM   02:10:19
AUTO FLT AP OFF
ENG THRUST LOCKED
 -THR LEVERS.........MOVE
AUTO FLT A/THR OFF
 -THR LEVERS.........MOVE
F/CTL ALTN LAW
      (PROT LOST)
                              F/CTL
                              AUTO FLT
```

```
ECAM   02:10:24
AUTO FLT AP OFF
AUTO FLT A/THR OFF
F/CTL ALTN LAW
      (PROT LOST)
-MAX SPEED.......330/.82
F/CTL
RUD TRV LIM FAULT
                              AUTO FLT
```

```
ECAM   02:12:44
AUTO FLT AP OFF
NAV ADR DISAGREE
 -AIR SPD.........X CHECK
•IF NO SPD DISAGREE
 -AOA DISCREPANCY
•IF SPD DISAGREE
  -ADR CHECK PROC...APPLY
                              AUTO FLT
                              F/CTL
```

Figure 5. Air France 447 ECAM displays if no messages had been erased (BEA, 2012, pg. 97).

Note that only in the last probable ECAM display for AF 447 in Figure 5, over 2 minutes into an event that lasted less than 4 minutes, would there have been any mention of airspeed discrepancy issues. However, Figure 5 depicts the *likely* ECAM displays that would have been presented to the AF447 crew if no messages had been erased (i.e., accomplished or cleared) as determined by the investigators of the accident. Exactly what ECAM alerts and actions were and were not displayed to the crew is largely unknown.

RUDDER RATIO
MACH/SPD TRIM

Figure 6. Initial EICAS advisory messages, Birgenair 301 (Walters & Sumwalt, 2000).

Neither of the ECIAS messages displayed to the crew of Birgenair 301 early in their emergency point to unreliable airspeed (see Figure 6). Furthermore, in addition to alert messages that may not facilitate direct interpretation of the condition, blockages in the pitot-static system can also result in a wide range of other, sometimes contradictory, alerts, cues, and information on the flight deck that can complicate accurate diagnosis, e.g., concurrent stall and overspeed warnings, disconnection of autopilots and autothrust systems, loss of flight directors and/or primary flight displays (PFDs), and changes in flight control laws and levels of flight envelope protection. When some of these alerts, cues, or information come and go—seemingly at random—as many did for the crew of Air France 447 (see Figure 7), diagnosis is even further complicated.

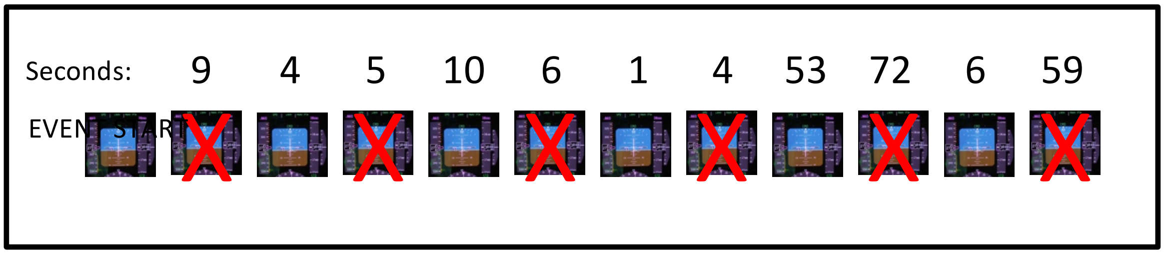


Figure 7. Partial sequence and amount of time crossbars on Air France 447 left and right PFDs appeared and disappeared (BEA, 2012). This figure does not depict the crossbars as they actually appear on the A330 PFD.

3.5.1 What Was Analyzed and Why

The primary issues of interest here pertain to how to help pilots correctly diagnose their situation (untrustworthy airspeed indications due to pitot-static blockage) and determine which checklist(s) is/are the most appropriate to accomplish in response. The types of alerts that might be displayed in the event of blockage in the pitot-static system and the checklists available for response were reviewed. Special attention was given to text alert names and the titles given to the checklists regarding the degree to which they might facilitate an accurate diagnosis of the situation. An analysis was also conducted of the relationship between un-alerted and alerted checklists for blocked pitot-static system events.

3.5.2 Findings

There are three main types of conditions related to pitot-static blockage that are alerted and have associated checklists in most of the QRHs studied: i) failure of the components responsible for air data interpretation, ii) disagreement among the redundant or parallel components responsible for air data interpretation, and iii) disagreement among indicated airspeeds on the flight deck (see Table 9). The text alert names and Checklist Titles given to these situations vary widely across the five aircraft types in this study, because of different names given to the same or similar types of equipment by the OEMs (e.g., ADS, ADR, ADIRU), true differences in aircraft sensors and/or pitot-static systems, and/or an emphasis on something by one OEM, but not others (see Tables 9 and 10). Some differences also exist because content in one checklist (e.g., EFIS COMP MON) includes similar content that is spread across more than one checklist in other aircraft QRHs.

Table 9. Pitot-Static Blockage Related Conditions Commonly Alerted

Condition	*QRHs*	*Sample Checklist Titles*
Failure of Component Responsible for Air Data	1, 2, 3, 4, 7, 8, 9, 11	NAV ADR FAULT ADS FAIL Air Data Computer Failure[1]
Air Data Disagreement	1, 3, 4, 5, 7, 9, 11	NAV AIR DATA SYS NAV ADR DISAGREE EFIS COMP MON
Indicated Airspeed Disagreement	1, 3, 5, 6, 9, 10, 11	NAV IAS DISCREPANCY IAS DISAGREE EFIS COMP MON

[1] This Checklist Title is not associated with a cockpit alert (i.e., it is un-alerted).

As described earlier, in addition to the alerts that appear in Tables 9 and 10, a variety of other alerts may sound or be displayed that are secondary actions or conditions to the pitot-static blockage such as loss of thrust asymmetry compensation, autopilot disconnected, autothrust lock, flight control law changes, and the like. Although some of these indications may be useful (e.g., autothrust lock, flight control law changes, autopilot disconnected) by themselves, they do not facilitate diagnosis of the overall condition. Others that reflect conditions that are tangentially related to the primary problem with the pitot-static system (e.g., thrust asymmetry compensation) are likely to complicate a pilot's ability to formulate a correct understanding of the problem.

Table 10. Other Alert Messages and Checklists Associated with Pitot-Static Blockage

Aircraft Type	*Alert Messages/Checklists*[1]
A320	ADR Check Procedure Double Probe Heat Fail OVERSPEED Unreliable Airspeed
B737NG	Airspeed Unreliable ALT DISAGREE AOA DISAGREE
B777	Airspeed Unreliable AIRSPEED LOW GND PROX SYS HEAT PITOT L + C + R HEAT PITOT L (C) (R) OVERSPEED SGL SOURCE AIR DATA SGL SOURCE DISPLAYS WINDSHEAR SYS
CRJ700	ADC Failure Pressurization Manual Control Inertial Reference System Failure
EMB190	ADS HTR FAIL ADS PROBE FAIL Unreliable Airspeed

[1] Some Checklists were not found in both/all QRHs analyzed for that type of aircraft

Un-alerted Airspeed Unreliable Checklists. Most QRHs analyzed (1, 2, 3, 4, 6, 7, 8, 9, 10) also include an un-alerted checklist for use when the airspeed is determined to be unreliable (see Table 10).[12] Two sets of analyses were conducted related to this checklist. The first issue of interest was a determination of what situation warranted the accomplishment of the checklist. For the most part, the developers of these checklists or knowledgeable SMEs would need to be consulted to determine this. However, five of the checklists analyzed contain Condition Statements and two also include Objective Statements (i.e., what accomplishment of the checklist is designed to achieve). These statements reveal the information sought and can be seen in Table 11.

---

[12] Typically the title for this checklist is some version of "Airspeed Unreliable" or "Unreliable Airspeed." Both will be used in this section so as not to favor the title of one OEM over another. In none of the QRHs analyzed were both versions of the title included in the Indexes. Thus, pilots must know the exact title used in their QRH in order to locate the title, and hence the checklist, quickly.

Table 11. Airspeed Unreliable Checklist Condition and Objective Statements

Line	*Numbers of QRHs*	*Condition Statement*	*Objective Statement*
A	2	The airspeed or Mach displays are suspected to be unreliable. (Items which may indicate unreliable airspeed are listed at the end of this checklist.)	
B	1	Unreliable airspeed indications caused by pitot/static probe obstruction or radome damage.	
C	2	The pitch attitude is not consistent with the phase of flight, altitude, thrust and weight, or noise or low frequency buffeting is experienced.	To establish the normal pitch attitude and thrust setting for phase of flight.

In Table 11, the Condition Statement in line A indicates that the checklist would be appropriate to be accomplished when it is possible that the airspeed or Mach displays are unreliable. The parenthetical sentence implies, but does not stipulate, that pilots should consult the list at the end of the checklist to confirm this diagnosis prior to accomplishing the checklist.

The Condition Statement in line B is more definitive: a known unreliable airspeed condition exists. Furthermore, it either a) informs the crew as to why the condition exists or b) confirms that if a known obstruction of the pitot-static probe or damage to the radome exists resulting in untrustworthy airspeed indications, this is the appropriate checklist to accomplish.

The Condition Statement in line C however, makes no mention of unreliable airspeed indications, although the checklist is titled such. It appears here that an attempt was made to go beyond restating the title in the Condition and Objective Statements and instead describe cues or indications in the cockpit which might exist. Although neither stated nor implied, it is incumbent upon the pilots to interpret these cues against the airspeed indications and thus, determine if the displayed airspeed indications are unreliable. It is unknown if pilots find these Condition and Objective Statements useful or if pilots are thrown off by their lack of reference to airspeed, unreliable or otherwise.

The second set of analyses related to un-alerted, unreliable airspeed checklists involved the relationship between them and checklists that are alerted. Alerts are compelling and pilots naturally attempt to accomplish the checklists associated with them. However, recall that there are a variety of alerts which might be displayed or indicated during blocked pitot-static system events; some are highly pertinent but others may be spurious or secondary to the primary problem. How and when might it also, or instead, be appropriate to accomplish the un-alerted airspeed unreliable checklist? The analyses conducted cannot fully answer the question but can identify when the designers of these checklists considered it and provided guidance to pilots relative to it. Table 12 includes a list of alerted checklists, by aircraft type, and indicates if reference to that QRH's un-alerted unreliable airspeed is made in it. Only four of the aircraft types in this study are included; neither of the QRHs analyzed for the CRJ700 includes an un-alerted checklist for unreliable airspeed displays.

Table 12. Alerted Checklists and Un-Alerted Unreliable Airspeed Checklists

Aircraft Type	*Alerted Checklist Title*[1]	*Reference to Unreliable Checklist*	*Description*
A320	NAV ADR DISAGREE[2]	No/Yes	Yes: Immediately sends pilot to the un-alerted checklist if the airspeeds disagree No: Not applicable
	NAV ADR FAULT	No	
	NAV IAS DISCREPANCY	No	
	OVERSPEED	No	
B737NG	ALT DISAGREE	No	
	AOA DISAGREE	No	But does indicate that airspeed, altimeter, IAS DISAGREE alert and ALT DISAGREE alerts may occur
	IAS DISAGREE	Yes	Immediately sends pilot to the un-alerted checklist
B777	NAV AIR DATA SYS[3]	No/Yes	In one QRH, implies that the pilot can consult un-alerted checklist to obtain pitch and thrust settings but no direction to complete un-alerted checklist
	AIRSPEED LOW	No	
	GND PROX SYS	No	
	HEAT PITOT L + C + R	No	Includes information that air data will be unreliable in icing conditions but no reference to Airspeed Unreliable Checklist
	HEAT PITOT (L) (C) (R)	No	
	OVERSPEED	No	
	SGL SOURCE AIR DATA	No	
	SGL SOURCE DISPLAYS	No	
	WINDSHEAR SYS	No	
EMB190	ADS FAIL	No	
	ADS HTR FAIL	No	
	ADS PROBE FAIL	No	

[1] The alerted titles appear in at least one, but not necessarily all, of the QRHs of each aircraft type.

[2] One of the three A320 QRHs analyzed includes a NAV ADR DISAGREE checklist that does make reference to the un-alerted Unreliable Speed Indication/ADR Check checklist.

[3] This checklist in the other B777 manual analyzed refers the pilot to the Performance Section of the Flight Manual for pitch and thrust settings instead of the Airspeed Unreliable checklist. Again, no direction is given to the pilot to complete the Airspeed Unreliable checklist.

Note that very few of the alerted checklists in Table 12 make any type of reference to the un-alerted, airspeed unreliable checklist, and when such a reference is made, it most often consists of a direction to the pilots to jump to that checklist and accomplish it. It is possible that the lack of reference to the un-alerted checklist in most of the alerted checklists is appropriate (if, for example, it would be incorrect for pilots to accomplish it when the alerted condition exists). However, if that is the case, it is advisable for checklist designers to explicitly state that in the alerted checklists so pilots don't also complete the un-alerted checklist in error. None of the alerted checklists specifically stated that the un-alerted checklist for airspeed unreliable should not be accomplished.

One of the A320 QRHs analyzed also contains an un-alerted checklist for use in the event of a double failure of pitot or alpha probe heaters (see Table 10). This checklist sends the pilot to the ADR DISAGREE checklist which, in turn, immediately instructs the pilot to jump to and accomplish the un-alerted checklist for unreliable airspeed if the airspeeds do disagree.

3.6 Fuel Leak

On August 24, 2001, Air Transat flight 236, an A330 aircraft, experienced a fuel leak in the right engine on a flight from Toronto, Canada to Lisbon, Portugal. The flight diverted to Lajes Airport in the Azores, Portugal and completed a successful all-engines out, visual approach and landing at 06:45 UTC (Aviation Accidents Prevention and Investigation Department [AAPID], 2004).

Following a standard position report made at 05:03 UTC, the crew completed a review of the aircraft systems and noted that oil indications for the right engine (amount, temperature, pressure) deviated greatly from those for the left engine but were still within normal operating parameters. The crew was still involved in trying to resolve the mystery of these aberrant indications when 30 minutes later an ECAM advisory message displayed indicating a fuel imbalance (AAPID, 2004)

The crew brought up the FUEL system synoptic display on the ECAM, noted an imbalance between the left (high) and right (low) inner wing fuel tanks and initiated the imbalance procedure from memory, i.e., without consulting the FUEL IMBALANCE procedure, which is un-alerted. The FUEL IMBALANCE checklist begins with a Caution Statement that if a fuel leak is suspected, the procedure should not be completed. According to investigators, the crew might have had no reason to suspect a fuel leak (even if they had consulted the FUEL IMBALANCE checklist) since the anomalous oil indications appear, on the face of it, to be unrelated to the fuel system, and the crew suspected the oil indications displayed were incorrect (AAPID, 2004). Just 12 minutes later (05:45 UTC) the crew was alerted that they would have insufficient fuel to reach their planned destination and initiated a diversion to Lajes, Portugal. Without success they continued to troubleshoot the origin of the problem and although they mentioned the possibility of a fuel leak, at no time did they consult or accomplish steps from the un-alerted FUEL LEAK checklist in their QRH (AAPID, 2004).

The crew had no time to complete ECAM actions associated with ENG 2 FUEL FILTER CLOG, FUEL R WING TK LO LVL[13], FUEL L + R WING TK LO LVL[14], and other related alerts because they were focused on the diversion and still trying to determine the exact location of the leak or if they in fact even had a leak. "The crew stated that they continued to believe that the low quantity indications were caused by some type of computer error, and continued with this belief up to and beyond the flameout of the right engine." (p. 58; AAPID, 2004).

During their investigation into this accident, the AAPID identified at least 25 other in-flight fuel leak events that had occurred in the previous 10 years, some which that had been fairly minor but several that were quite serious, such as resulting in an engine fire or diversion and emergency landing (AAPID, 2004). Sensors and automation on board aircraft are not able to directly sense a fuel leak and as this accident illustrates, it can be very difficult to identify a fuel leak and accurately diagnose its source. Furthermore, an in-flight fuel leak may be an event that is seldom, if ever, covered during training (AAPID, 2004).

3.6.1 What Was Analyzed and Why

As with pitot-static obstructions, when a fuel leak exists, a variety of other alerts may be presented which may or may not lead the pilots to consider the actual underlying problem, such as in the Air Transat 236 accident just described. It is therefore essential that the checklists associated with these alerts address the possibility of a fuel leak, if appropriate, and that the content of un-alerted Fuel Leak checklists be carefully considered so as to provide the pilots the best support possible in situation diagnosis and response during these high workload and very stressful situations. Checklists that would likely get alerted in a variety of fuel leak situations were analyzed as well as the content of un-alerted Fuel Leak Checklists. Special attention was given to whether the checklist could be used for fuel tank leaks and fuel leaks in the engines, the provision of cues that might indicate a fuel leak and the presence of information or steps to confirm or diagnose the location of the leak, as well as the possible incorporation of items from other checklists that might be needed later during flight, such as from normal approach and landing checklists or checklists for an emergency landing or ditching.

3.6.2 Findings

<u>Alerts and Alerted Checklists</u>. Since a fuel leak is not sensed and directly alerted on any of the aircraft types included in this study, analyses began with a focus on the types of alerts that might be displayed when a fuel leak of any type exists and whether the checklists associated with those alerts make any reference to a possible fuel leak (see Table 13).

---

[13] Although this procedure in the QRH contained a Caution Statement that it should not be accomplished if a fuel leak is suspected, at the time of the accident this Caution did not appear in the actions displayed on the ECAM (AAPID, 2004).

[14] At the time of this accident, both the FUEL R WING TK LO LVL and FUEL L+R WING TK LO LVL procedures called for the wing tank crossfeed to be turned on (AAPID, 2004).

Table 13. Reference to Fuel Leak/Fuel Leak Checklist in Other Alerted Checklists

Aircraft Type	*Alert/Alerted Checklist Title*	*Reference to Fuel Leak/Un-alerted Fuel Leak Checklist*[1,2]		
		A	*B*	*C*
A320	FUEL L(R) WING TK LO LVL	Yes	Yes	Yes
	FUEL L + R WING TK LO LVL	No	Yes	No[3]
	FUEL CTR TK PUMP 1(2) LO PR	Yes	No	No
	FUEL CTR TK PUMPS LO PR	No	No	No
	FUEL L(R) TK PUMP 1 + 2 LO PR	Yes	No	Yes
	FUEL IMBALANCE	Yes	Yes	—
B737NG	Fuel IMBAL light illuminates/IMBAL	Yes	Yes	
	Fuel LOW light illuminates/LOW	Yes	Yes	
	FUEL PUMP LOW PRESSURE	No	No	
B777	FUEL DISAGREE	Yes	Yes	
	FUEL IMBALANCE	Yes	Yes	
	FUEL LOW CENTER	No	No	
	FUEL PRESS ENG L, R	No	No	
	FUEL PRESS ENG L + R	No	—	
	FUEL PUMP CENTER, L, R	No	No	
	FUEL PUMP L AFT, FWD	No	No	
	FUEL PUMP R AFT, FWD	No	No	
	FUEL QTY LOW	Yes	Yes	
CRJ700	FUEL IMBALANCE	Yes	Yes	
	FUEL CH 1/2 msg[4]	No[3]	No[3]	
	L (R) FUEL LO PRESS	No	Yes	
	LO FUEL	No[3]	No[3]	
	MAIN EJECTOR L (R)[5]	No	Yes	
	SCAV EJECTOR L (R)[5, 6]	No	No	
	L (R) MAIN EJECTOR and L (R) SCAV EJECTOR[5]	Yes	Yes	
	L (R) XFER SOV	No	Yes	
	Abnormal Increase of Center Tank Fuel Quantity[7]	No	Yes	
EMB190	FUEL IMBALANCE	Yes	Yes	
	FUEL 1 (2) LO LEVEL	Yes	Yes	
	ENG 1 (2) FUEL LO PRESS	Yes	Yes	

[1] Air Carrier Participants have been randomly assigned a Letter (A, B, C) for the purposes of this table.

[2] Dash (—) = this alerted checklist does not exist in this QRH

[3] Although there is no reference to a fuel leak in this checklist, it does instruct pilots to land as soon as possible. Thus, by the time this alert is displayed, it may be that the checklist designers were more concerned about diversion and completion of an emergency landing than trying to identify a possible leak with an attempt to rectify it.

[4] SMEs disagreed with regard to whether this alert would be displayed in a fuel leak situation.

[5] A SME who was consulted stated that these alerts would be displayed relatively late in a fuel leak situation, just before engines began to flameout. Thus, reference to fuel leak checklists to attempt rectification may be of little help at this stage.

[6] No mention of fuel leak but the checklist does instruct pilots to monitor for abnormal fuel depletion.

[7] Un-alerted checklist.

There is a surprising amount of inconsistency across the air carrier participants flying the A320 and CRJ700 with regard to inclusion of a reference to a fuel leak in the alerted checklists listed in Table 13. In eight of the 15 checklists (53%) at least one carrier makes reference to considering a fuel leak whereas no such reference is made in the same checklists belonging to the other carrier(s)[15] (see the rows that are shaded). This suggests that relative to these alerts either one air carrier (or possibly two) is being overly cautious or incorrect in suggesting a fuel leak consideration, or that the other air carrier(s) is not providing important information for their crews to think about.

For the ten alerted checklists in Table 13 across four aircraft types, in which there is complete agreement and no reference to fuel leak is made, it is possible that i) none is warranted, ii) by the time the alert is displayed rectification of a fuel leak is of little use and greater attention should be paid to other activities such as ditching or landing, or iii) such a reference is warranted but isn't included by checklist designers for some reason, possibly including simple oversight. Only systems experts with the checklist developers can determine which of these is true for each of these checklists.

A variety of other types of alerts, cues, and information might also be presented or be available to the flight crew in a fuel leak situation. These include messages displayed in a variety of different places on the flight management computer display unit (FMC CDU), illuminated lights, fuel gauges, and fuel system schematic displays, among others. Some of the most common of these additional sources of information for crews to evaluate across the five aircraft types can be found in Table 14. Many of the alerted and un-alerted checklists associated with a possible fuel leak make reference to these additional sources of information. However, several do not and some of those which do, don't provide very much guidance to the pilots about how to integrate this information with other alerts and cues to formulate an accurate diagnosis of their situation.

One of the final indicators of a fuel leak, of course, is the failure/flameout of one or more engines. Of the QRHs analyzed, only the A320 Dual Engine Failure checklists and the EMB 190 checklists for a single engine failure address the possible failure due to fuel leak/starvation/exhaustion (see Table 15). The fact that engine failure due to fuel leak/exhaustion is not addressed in any of the other engine failure checklists analyzed appears to be a significant oversight. In checklists for dual engine failure this lack is particularly critical because the actions for pilots to take in these situations differs significantly if there is or is not any fuel remaining. This will be discussed in more detail in section 3.7 Dual Engine Failure (Fuel Remaining), below.

---

[15] In one case (A320: Fuel Imbalance), one carrier did not include the checklist in its QRH.

Table 14. Other Common Flight Deck Alerts or Cues Associated with Fuel Leaks

Alert or Cue	*Location*
USING RSV FUEL	FMC CDU
INSUFFICIENT FUEL	FMC CDU/scratchpad
CHECK FMC FUEL QUANTITIY	FMC CDU
Destination EFOB turns amber	FMC F.PLN or FUEL PRED page
DEST EFOB BELOW MIN	MCDU scratchpad
Fuel IMBAL light illuminates	Fuel Gauges/Fuel Quantity Indications, forward panel/display
Fuel LOW light illuminates	Fuel Gauges/Fuel Quantity Indications, forward panel/display
FUEL PUMP LOW PRESSURE light illuminates	Overhead panel
Unexpected total fuel quantity difference between the EICAS indicated fuel quantity and the FMS predicted FUEL	EICAS and FMC FUEL MGT page
Large difference between EICAS fuel indication and PERF INIT 3/3	EICAS and FMC PERF page
Engine failure(s)/ENG FAIL/ENG FLAMEOUT	Variety of locations and indicators throughout the cockpit

Table 15. Reference to Fuel Leak in Engine Failure Checklists

Aircraft Type/QRH	*Single Engine Failure Checklist(s)*	*Dual Engine Failure Checklist(s)*
A320	No	Yes
B737NG	No	No
B777	No	No
CRJ700	No	No
EMB190	Yes	No

Un-alerted Fuel Leak Checklists. All of the QRHs analyzed include an un-alerted Fuel Leak checklist. In some cases the checklists include a list of cues or indications for crews to use to help them determine if they have a leak. Most of these checklists also include actions to take or information to evaluate to confirm evidence of a leak and/or determine its source; only the Fuel Leak checklists in the CRJ700 QRHs include neither of these things (see Table 16).

The Fuel Leak checklists in all three A320 QRHs, one B777 QRH and one CRJ700 QRH address fuel leaks in two possible locations: engine or fuel tank. All of the other six Fuel Leak checklists were written to address a leak in only one of those two possible locations. The Fuel Leak checklists in both B737QRHs indicated that it is only for use in the event of an engine fuel leak as a tank leak was considered to be highly unlikely. No reference to other possible fuel leak locations is made in the remaining four (2, 4, 5, 8) Fuel Leak checklists.

Table 16. Un-Alerted Fuel Leak Checklists

Aircraft Type/QRH	*A320*	*B737NG*	*B777*	*CRJ700*	*EMB190*
For Leak in Tanks, Engine, or Both	Both	Engine[1]	Engine/ Both[2]	Tank/ Both[3]	Tank
Includes Items re: Diversion Might Be Needed/ Land ASAP and Where in CL	Yes, varies[4]	Yes, possible diversion, near start of CL	Yes, land at nearest suitable airport, in middle of CL	Yes, land at nearest suitable airport, start of CL [5]	Yes, land at nearest suitable airport, varies[6]
Provides Cues that Might Indicate a Fuel Leak	Yes	Yes	Yes	No	Yes
If Cues provided, Where are they Located in the Checklist (CL)	Very beginning of CL	End of CL in Supplemental Section	End of CL in Supplemental Section	—	Very beginning of CL
Information Given to Confirm or Diagnose a Fuel Leak	Yes	Yes	Yes	No[7]	Yes, though not very detailed
If Confirm/Diagnosis Items Included, Where are They Located in the CL	Throughout CL (Dx location of leak)	First page, relatively early in CL	First page, relatively early in CL	—	First page, very early in CL
Incorporates All Normal Approach/ Landing Checklist Items[8]	No	No	Yes, but in one QRH only	Yes, but in one QRH only	No
Incorporates Items for Emergency Landing[8]	No	No	No	No	No
Incorporates Items for Ditching[8]	No	No	No	No	No

[1] Specifies that it does not address the "unlikely possibility of a tank leak."

[2] The Fuel Leak checklist in one B777 QRH is for an engine leak only; the other one analyzed is for both engine and tank fuel leaks.

[3] The Fuel Leak checklist in one CRJ700 QRH is for a tank leak only; the other one analyzed is for both engine and tank fuel leaks.

[4] Two A320 QRHs: Land ASAP when leak confirmed, at start of CL after list of fuel leak detection methods; Third A320 QRH: Divert to nearest suitable landing, near very end of CL but jump to this item relatively quickly if fuel leak is in the engine or pylon.

[5] Both CRJ700 QRHs analyzed direct pilots to land at the nearest suitable airport at the very beginning of the checklist (one also states that a diversion may be required). Additionally, both direct the pilots that a landing

should not be delayed in an attempt to determine the leak location and to expedite the landing if a LO FUEL message is displayed.

[6] This item appears as the very first in one EMB190 QRH Fuel Leak checklist and as the last item on the Fuel Leak checklist in the other EMB190 QRH.

[7] Although one CRJ700 QRH checklist suggests that the leak source may be identified by looking through windows in the cabin.

[8] Fuel Leak checklist includes/incorporates or co-locates all pertinent items from these other checklists.

All of the Fuel Leak checklists make some reference to the fact that a diversion might be necessary and/or include some sort of direction about landing soon, although where in the checklist this information is provided varies greatly (see Table 16). Only the checklists for the CRJ700 also include guidance to the pilots that a landing should not be delayed in an attempt to locate the source of the fuel leak and to even expedite it if a LO FUEL message is displayed. The provision of such explicit guidance can be quite helpful for pilots to maintain a "big picture" view of their situation and make decisions about workload management and task shedding appropriately, something that can be difficult to do in highly stressful situations such as these (Burian, 2014; Dismukes, et al., 2013).

Checklist Navigation and Jumping. Sometimes checklist developers integrate or co-locate information from other checklists or materials with checklists for situations that might have on-going implications for the remainder of the flight, such as fuel leak, engine failure, hydraulics failure, and in-flight smoke, fire, or fumes. Information that is incorporated or co-located typically includes such things as approach and landing checklist items, emergency landing/ditching checklists, and/or evacuation checklists. When incorporated into an emergency/abnormal checklist, they are sometimes referred to as deferred items, meaning ones that are to be completed during later phases of flight after the rest of the items have been accomplished.[16]

The design philosophy behind doing this integration/co-location is called "Get-in, Stay-in" and, as the name implies, eliminates the jumping among multiple checklists and materials that might be required to see a flight to its end. This greatly reduces pilot workload, eliminates the possible error of jumping to the wrong checklist or material, and also allows for some information from these other checklists to be customized to the needs of the specific situation.

As can be seen in Table 16, in the un-alerted Fuel Leak checklists analyzed in this study, only those in one B777 QRH and one CRJ700 include what appear to be all the appropriate items to complete from their normal approach and landing checklists. None of the Fuel Leak checklists for any of the other aircraft types do so but some (1, 4, 5) do make reference to information that has importance for approach and landing such as flap settings to use and Vref speeds. None of the un-alerted Fuel Leak checklists (for any aircraft type) include items related to conducting an emergency landing or ditching, although a few do make reference to the need to jump to and complete those checklists if necessary.

Most of the Fuel Leak checklists require multiple jumps within them as the pilots are directed to the appropriate steps to accomplish if certain conditions exist, such as if the leak is in an engine or a tank, the rate of reduction of fuel is symmetrical or asymmetrical across tanks, fuel in a tank is greater than or less than a given quantity, various alerts are or are not displayed, and range to a

---

[16] This, of course, presumes that the emergency or abnormal condition occurred prior to these later phases.

suitable landing site is or is not a concern, among others. Many, although not all, Fuel Leak checklists analyzed also reference other checklists the pilots might consider or should jump to and accomplish, such as those for shutting down an engine or completing a single engine landing. Jumping past items within a checklist and jumping outside of a checklist to other checklists or materials has been analyzed in detail relative to Dual Engine Failure checklists and is discussed below.

3.7 Dual Engine Failure (Fuel Remaining)

It goes without saying that the failure of both engines on a two engine aircraft is a highly time-critical situation, even more so when the failure occurs at a low altitude (see US Airways 1549 [NTSB, 2010b]). Therefore, dual engine failure checklists have to be particularly well designed to support the pilots not only in attending to the failure of the engines but also in managing the overall situation in the event that an emergency landing or ditching is required.

Conditional/Decision Items. As mentioned earlier, many emergency and abnormal checklists, especially those for responding to a dual engine failure, include items to be read and accomplished only if specific circumstances exist. For example, if all the usable fuel on board has been exhausted, pilots should be directed to only those items in a dual engine failure checklist for that circumstance: no fuel exists; it would be a waste of time for pilots to complete multiple steps to relight the engines if there is no fuel.

Thus, the inclusion of different branches of items in a checklist allows a certain degree of customization to help better match the actions and information to the specific circumstances surrounding each emergency or abnormal condition. However, their inclusion poses many significant challenges for checklist designers. The pilots must first be prompted to evaluate their situation and determine if the specific circumstance being addressed, in fact, exists. The prompt must be clearly stated and unambiguous so that pilots understand exactly what they are meant to be evaluating. Second, the additional items to be accomplished must be presented so they can be easily identified for accomplishment (or skipping past if the specific circumstance identified does not exist). Finally, it must be clear to the pilots if any items remain to be accomplished after those related to the specific circumstance have been accomplished or skipped. Checklist designers have employed a variety of approaches to address all three of these issues.

The first is managed by presenting the pilots with a description of the specific circumstance to be evaluated. Often this is done in the form of a Conditional Item:

If the CABIN CARGO SMOKE light is illuminated,

If in icing conditions,

Other times designers present the item as a statement which is to be evaluated as being true or false or as a question to which the answer is yes or no, thus written as a Decision Item:[17]

The CABIN CARGO SMOKE light is illuminated.

Is the aircraft in icing conditions?

---

[17] Since a variety of these approaches are used in the participants checklists, the items will be referred to as Conditional/Decision Items in this document unless a distinction between the two is being made.

Sometimes more than one thing must be exist before the subsequent actions are to be taken so the item is presented in a compound, or even compound/complex form.

> Oil temperature is between 150° C and 165° C or EGT continues to rise.
>
> If the CABIN CARGO SMOKE light is illuminated and range to a suitable landing site is a concern,
>
> If in icing conditions and the CABIN CARGO SMOKE light is illuminated or range to a suitable landing site is a concern,

And finally, sometimes complementary states are presented and the pilot is to select which of the states is correct.

> If on ground,
> If in air,
>
> In icing conditions.
> Not in icing conditions.
>
> Flaps are stuck at 25 to 30 degrees.
> Flaps are stuck at 15 to less than 25 degrees.
> Flaps are stuck at 0 to less than 15 degrees.

Conditional/Decision Items such as these are referred to as “exclusive” because they are to be evaluated against each other. And, if one is selected, the other(s) in the set is/are excluded and information and actions related to it/them must be skipped. Various graphics or approaches to formatting are sometimes used to clearly distinguish Conditional/Decision Items that are part of an exclusive set. Some of the approaches identified in this study will be described in the Findings section below.

Evaluation of these various Conditional/Decision Items by the pilots flying on aircraft with integrated ECLS (e.g., B777, A320) is only required if the circumstances described in the item cannot be sensed by the aircraft (i.e., open loop). Otherwise, the items and information associated with the Conditional/Decision Item (i.e., subordinate items) will automatically be selected for presentation in the checklist since the circumstance has been sensed to exist.

Subordinate items are typically indented from the left margin under the Conditional/Decision Items to which they pertain. A few different methods are used to facilitate pilots navigating through the checklists to only those subordinate items that are pertinent; the methods to do this used by the checklist developers who designed the checklists under analysis in this study will also be discussed in the Findings section below.

3.7.1 What Was Analyzed and Why

Two of the QRHs analyzed (1, 3) include separate checklists for dual engine failure situations where fuel is or is not remaining. Only those checklists in these QRHs that are to be used if fuel is remaining were analyzed for this section. Because needed responses to dual engine failures that occur at high altitudes (i.e., cruise) differ greatly from those that occur close to the ground, assumptions made by the designers about the amount of time available for response, as indicated by direction to different sections of the checklists based upon amount of time remaining, were analyzed. Workload associated with the checklist design and potential for errors were assessed through i) the degree to which designers chose to follow the Get-in, Stay-in philosophy by the incorporation of items from normal approach and landing checklists or from checklists for ditching or emergency landing, and ii) analysis of Conditional/Decision Items, checklist navigation and jumping, both within the checklist and outside to other checklists or information,

As analyses were being conducted, some interesting observations were made about the content in some of the Dual Engine Failure and related checklists (e.g., Volcanic Ash) and are also reported below.

3.7.2 Findings

None of the 11 Dual Engine Failure checklists analyzed include a Conditional/Decision Item or other guidance that direct the pilot to a later portion of the checklist for items to accomplish if time is short and the aircraft is close to the ground (i.e., an "opt-out gate"[18]). Thus, they appear to have been written with the assumption that the engine failure has occurred with sufficient altitude to attempt one, possibly several, relights. Two checklists (4, 7) are very short, however, and four (2, 3, 5, 8) do include some sort of direction to land as soon as possible or at the nearest suitable airport somewhere in the checklist, although not always near the beginning. After some initial items, one of these checklists (5) also directs the pilots to accomplish as much of the checklist as possible before abandoning it to accomplish checklists for approach and landing. This is the only Dual Engine Failure checklist analyzed that mentions anything about these phases of flight prior to the end of the checklist.

Several do include reference to ditching or an emergency landing at the end of the checklist, but only five (1, 2, 3, 8, 9) incorporate or co-locate some, though sometimes not all, normal approach/landing or Emergency Landing checklist items; only two (3, 9) incorporate or co-locate items from the Ditching checklist. None of the Dual Engine Failure checklists incorporate items from or co-locate the Evacuation checklist but one (3) does include an item instructing that an evacuation should be initiated.

Thus, fewer than half of the Dual Engine Failure checklists analyzed are consistent to any degree with the Get-in, Stay-in philosophy of checklist design and use. This philosophy may not be well known or its advantages, in terms of pilot workload and error reduction, may be underappreciated by checklist designers. It is also possible that some who are familiar with the philosophy, may choose not to apply it believing that it makes individual checklists too long, the QRH too big or unwieldy, or because of limitations in the design of integrated ECLSs.

It is concerning that none of the Dual Engine Failure checklists analyzed has an opt-out gate near the beginning of the checklist (or has a separate checklist) to move pilots directly to landing or ditching items if the dual engine failure occurs close to the ground. In some of these checklists this may be because no reference is made at all, or items included, with regard to emergency landing or ditching;

---

[18] Opt-out gates are items, typically formatted as Conditional/Decision Items, that are commonly used to prompt pilots to shift attention from the current task to focus on something more time critical such as landing/ditching in the case of a dual engine failure or smoke evacuation in the case of dense smoke associated with an in-flight fire.

in others it may because the checklist is written with the assumption that at least one engine has been successfully re-started.

Conditional/Decision Items, Checklist Navigation and Jumping. Because jumping to different sections within a checklist and in and out of a checklist to other checklists or information (e.g., performance tables) can increase pilot workload and potential for error, the internal and external jumps included in the 11 Dual Engine Failure checklists were analyzed. This was actually fairly difficult to do. First, all of the internal and external jumps included in each checklist were counted; these are the first numbers that appear in the Internal Jumps and External Jumps columns in Table 17. These numbers, however, do not represent the actual number of jumps that a pilot might have to perform when accomplishing the checklist as some would be bypassed (i.e., jumped over) under various circumstances.

So, the greatest number of jumps that would be required when using the checklist, without repetition of any method to relight the engines that had already been tried once, were counted and are presented as the second set of numbers within the same two columns in Table 17. In most cases, these jumps reflected the "minimum worst case dual engine failure scenario," defined as one in which adequate time is available so that all of the different methods presented to relight engines can be attempted just once and none of the attempts are successful. As discussed later in this section, some checklists do not include items to accomplish if neither engine can be re-lit (i.e., the assumption is that, at a minimum, the relight of at least one engine is successful). Also, some do not include any or more than one method for engine relight for the pilots to attempt, most likely because of engine design and/or automated relight features.

All counts were made using the paper checklists in the QRHs provided by the participants; the maximum number of jumps required in real operations might be fewer if any of the Conditional/Decision Items in the A320 ECAM and B777 ECL are sensed as inappropriate for accomplishment and are automatically not presented.

Table 17. Dual Engine Failure Checklists: Navigation and Jumping

QRH/ Checklist	*Jumping*					*Special Formatting of Exclusive Sets*[2,3]	*Flow Lines to Facilitate Navigation*[2]
	Internal Jumps[1]	*External Jumps*[1]	*Conditional Item(s)*	*Decision item(s)*	*Directed Jump(s)*		
1	1 - 1	4[a] - 3[a]	yes	no	no	no	no
2	5 - 3	12[b] - 4[b]	yes	no	yes	yes	no
3	3 - 1	2[a] - 2[a]	yes	no	yes	no	no
4	0 - 0	1[c] - 1[c]	no	no	no	—	—
5	6 - 4	5[c] - 2[c]	yes	no	yes	yes	no
6	6 - 5	2[c] - 2[c]	yes	yes	yes	yes	no
7	0 - 0	2[d] - 2[d]	no	no	yes	—	—
8	6 - 4	2[a] - 1[a]	yes	yes	yes	**	yes
9	4 - 4	2 - 1	yes	no	no	yes	no
10	6 - 6	2[c] - 2[c]	yes	yes	yes	yes	no
11	6 - 6	4 - 1	yes	yes	yes	**	yes

[1] Total number of (internal or external) jumps - Most number of (internal or external) jumps the pilot would have to perform for if neither engine relights, with no multiple attempts to relight using the same method.

[2] Dash (—) = not applicable

[3] ** Use of modified flow chart formatting with arrows for Decision Items has the effect of presenting the Items as Exclusive pairs although both possibilities are not written, just one condition with arrows for YES or NO, the condition is true or exists.

[a] Includes one jump out and then one jump back into the Dual Engine Failure checklist

[b] Includes jumping from immediate action items at the front of the QRH to the rest of the Dual Engine Failure checklist and then jumps at the end of the checklist out, then back in, and then back out again.

[c] Includes jumping from immediate action items at the front of the QRH/QRC to the rest of the Dual Engine Failure Checklist.

[d] Direction to refer to performance table located in explanatory information prior to actual checklist items

Analyses revealed the use of three different types of items that facilitate or guide navigation within or jumps to/from the Dual Engine Failure checklists: Conditional Items, Decision Items, and statements that simply direct that a jump be made, without an evaluation if such a jump is necessary (see Table 17). Only two checklists (4, 7), which were both relatively short, did not utilize any Conditional Items; they also did not include any jumping internal to the checklist. However, the four (6, 8, 10, 11) that used Decision Items, used them predominantly and had very few items formatted as Conditionals (i.e., If….). Of the four that used Decision Items, one (8) worded the items in the form of a question whereas the other three worded them as sentences. Statements which directed that a jump be made, without evaluation, were typically used to direct the pilot to the checklist in the QRH following the completion of memory or immediate action items on a QRC and/or to direct the pilot to another checklist whose need was unequivocal, such as a single engine landing checklist following the successful relight of only one engine.

As discussed earlier, the inclusion of Conditional/Decision Items allows for the customization of actions to most closely match those required in the specific situation that has occurred. Their benefit is offset, however, in that their inclusion lengthens a checklist and can hamper the ability of a pilot to navigate to only those items that are correct to be accomplished without error. This can be mitigated through the use of well-designed checklists and clearly worded items in all checklist modalities and the use of closed loop (i.e. sensed) Conditional Items in integrated ECLSs such as the Airbus ECAM and the Boeing ECL.

There are three different design features used for single Conditional/Decision Items (i.e. not part of an exclusive set) in the paper Dual Engine Failure checklists analyzed in this study.[19] The first is presenting the item in *no way different* from that used for presenting other items in the checklist. The second is to highlight the item in some way to draw attention to the fact that it requires an evaluation or decision. Often the use of bolding text, capitalizing text, and/or the placement of some type of symbol or bullet in front of the Conditional/Decision Item is used.

IF THE AP TRIM message is displayed,

☒ If the AP TRIM message is displayed,

The third presentation method observed is the use of a modified flow chart symbology and/or flow lines (8, 11). This is used with Decision Items only. The item is presented as a statement or as a question with lines and arrows extending from the statement to direct the user to different groups of items in the checklist (i.e., branches in the checklist) depending upon the veracity of the statement or answer to the question (i.e., “Yes” or “No,” see Figure 8). Arrows used to help guide the pilot to (and past) different groups of items appear in a variety of places in the checklists that use them, including on the right side of checklist items.

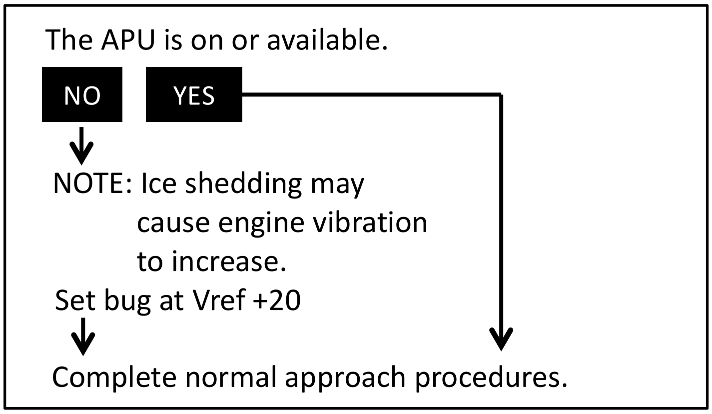


Figure 8. Sample decision item with flow lines.

When multiple arrows must run parallel to each other, such as when a Decision Item and its subordinate items are nested as subordinate to another Decision Item, different line characteristics are sometimes used to help distinguish the lines from each other. In Figure 9, there are two sets of nested Decision Items with subordinate items and differently weighted lines are used to distinguish among the arrows.

---

[19] The design features depicted in this document do not exactly match those used in the actual checklists reviewed and are provided as illustrations of the design concepts only. This is done to help protect proprietary information.

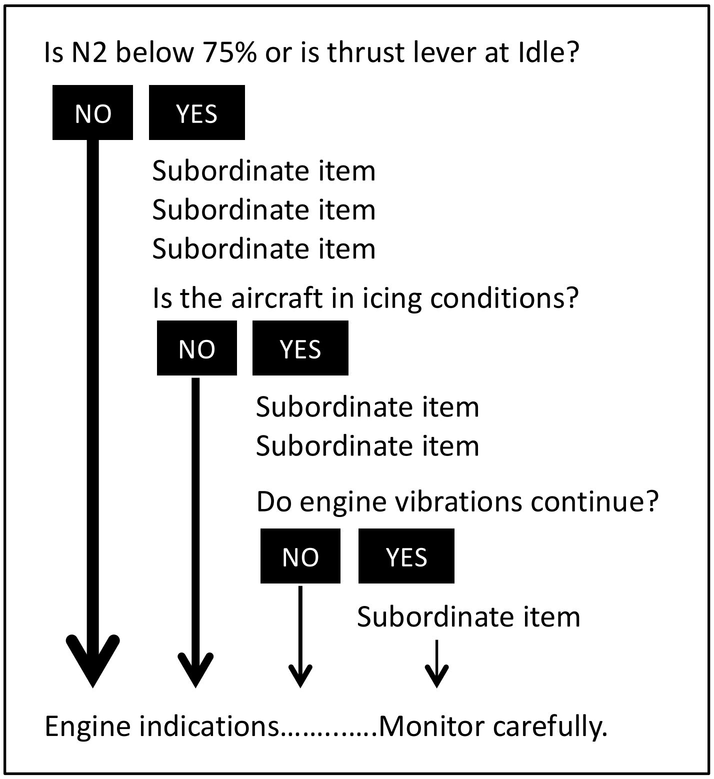


Figure 9. Sample nested decision items and flow lines.

The use of modified flow chart symbology when displaying individual Decision Items, such as in Figures 8 and 9, has the effect of turning them into half of a two item exclusive set, even though the complementary item is not explicitly stated. For example, "Is the aircraft in icing conditions? Yes/No" is little different from "The aircraft is in icing conditions. The aircraft is not in icing conditions."

When Conditional/Decision Items are explicitly written as complementary and part of an exclusive set they are sometime formatted in different ways. In the Dual Engine Failure checklists analyzed, three different methods for presenting exclusive Conditional/ Decision Items were identified. One method (1, 3) is to simply present each item in the exclusive set one at a time with each followed by its appropriate subordinate items. Thus, they appear to be just individual Conditional/Decision Items, each to be evaluated separately on their own. It is only after one arrives at the complementary item(s) that it becomes apparent that it and the earlier item are part of an exclusive set.

Pilots are often better able to evaluate which Conditional/Decision item(s) in an exclusive set is appropriate for their situation when the items are presented as a group and pilots are directed to evaluate all of them together and pick between/among them. Two formatting methods for doing this were observed in the Dual Engine Failure checklists analyzed. One is to list the exclusive conditionals and instruct the pilot to "Pick one." After choosing the item among the exclusive set that reflects their circumstances, pilots are then directed to the step numbers within the checklist to accomplish relative to that item.

The other method found for identifying Conditional/Decision items that are part of an exclusive set involves the use of symbols or lines/arrows and sometimes words, such as those illustrated in Figure 10.

Other Content Issues. Engine failures typically occur for one of four reasons (sometimes in combination): something is wrong with the engine (e.g., structural failure), something is wrong with the fuel, something is wrong with the air, or something is wrong with the spark/ignition. In terms of fuel, the most common issues are fuel contamination (see British Airways 38, Air Accidents Investigation Branch [AAIB], 2010) or fuel exhaustion/starvation, sometimes due to a fuel leak. As mentioned in the Fuel Leak section earlier and repeated in Table 18, only the Dual Engine Failure Checklists in the three A320 QRHs analyzed address fuel leak as a possible concern. All of the other checklists analyzed appear to be written with the assumption that fuel is available and accessible and no guidance is given to the pilots about what they should do or what checklist(s) they should accomplish if that is not the case.

A common problem with the "air" resulting in dual engine failures is contamination due to volcanic ash. Volcanic Ash Checklists were found in 9 of the 11 QRHs analyzed and seven of those checklists have an item at or near the end that sends the pilot to the Dual Engine Failure checklist if both engines have failed (see Table 18). The other two Volcanic Ash checklists (4, 7) incorporate items related to dual engine failure into them instead. No checklist for Volcanic Ash is included in the CRJ700 QRHs though it is possible that dealing with Volcanic Ash may be discussed in other materials not analyzed as a part of this study (e.g., training manuals).

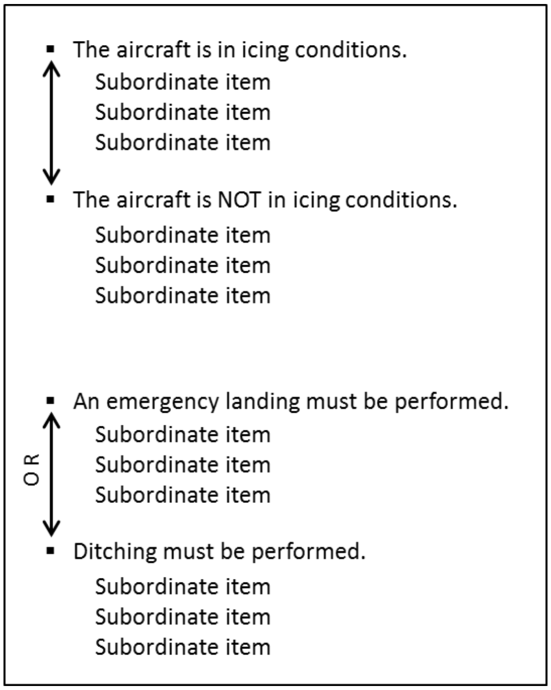


Figure 10. Sample symbology use with exclusive conditional/decision item sets.

Table 18. Some Dual Engine Failure Checklist Content Observations

Content	*QRHs/Checklists*
Checklist ends with assumption that at least one engine has been successfully re-started (i.e., does not address possible continued failure of both engines)	4, 6, 7, 10
Volcanic Ash checklist sends pilot to Dual Engine Failure Checklist, if necessary	1, 2, 3, 6, 8, 9, 10
Dual Engine Failure Checklist mentions something about Volcanic Ash	9
Dual Engine Failure Checklist mentions something about Fuel Leak	I, II, III

3.8 Failure of All Hydraulic Systems

Checklists for two conditions that could have implications for the remainder of the flight have been analyzed and discussed earlier: fuel leak and dual engine failure. In both cases, the resolution of the problem must be found relatively quickly, depending upon contextual factors such as phase of flight, or an emergency landing or ditching may be the result. In contrast, the in-flight failure of a single or even two hydraulics systems is generally not time critical, in and of itself, but will have implications for the rest of the flight through landing because of the role hydraulics can play in extending flaps, spoilers, and gear, and control of thrust reversers, nose wheel steering, and the yaw damper, among other things.

Most modern aircraft have three hydraulics systems with a fair amount of overlap or redundancy among them. Even so, the loss of two systems has significant ramifications for how the approach and landing of the aircraft is managed. The loss of all three systems is significantly more serious and although such an event may be considered extremely improbable (Federal Aviation Administration [FAA], 1988), it has been known to happen (see United Airlines 232; NTSB, 1990).

3.8.1 What Was Analyzed and Why

QRHs were examined to determine if the failure of all hydraulics systems was anticipated by checklist developers and a checklist for response to such a condition was included. If not, the checklist for the coincident failure of the two hydraulics systems with the greatest ramifications for the remainder of the flight, as indicated by SME judgment and/or lists of inoperative equipment often included in such checklists, was used for the remaining analyses. Those analyses included examinations of the phase(s) of flight for which the checklist could be appropriately used and the possible presence of opt-out gates to move the pilot to appropriate items if the failure occurs close to the ground. As with analyses of some of the earlier checklists discussed, level of workload associated with checklist use was also assessed through the inclusion/non-inclusion of items from other checklists which might be necessary, such as approach and landing, and alternate flap and/or gear extension (i.e., utilization of the Get-in, Stay-in philosophy of checklist design and use).

3.8.2 Findings

None of the QRHs examined include a checklist with items to complete for the loss of all three hydraulics systems, although the B737NG QRHs do include a note stating that the rudder is inoperative if the pressure in the standby hydraulics system is low and the two primary systems have been lost. For the purposes of all remaining analyses reported in this section the checklists for low hydraulics pressure in the following two systems, for each aircraft type, were used:

• A320:	G & Y
• B737NG:	A & B
• B777:	R & C
• CRJ700:	2 & 3
• EMB190:	1 & 2

None of these checklists are written for a dual system hydraulics failure that occurs on the ground, only for those in-flight. Hydraulics failures do occur from time-to-time while an aircraft is taxiing; however in these events, it may be assumed that no time exists for reference to a printed checklist and that pilots must engage in the appropriate actions, learned during training, from memory. However, a sudden event requiring immediate response may not always be the case.

> "Hydraulic caution light illuminated while taxiing to runway 3C. I began required procedures and completed the QRH checklist. The captain contacted maintenance and requested a tow back to the gate. We both were applying pressure to the brakes. I began to make an announcement to the passengers when the aircraft began to move. The captain began to shut the engine down. The aircraft began to yaw to the left. The captain applied differential power and reverse. The aircraft would not stop. When it was clear we had no brakes to stop the plane, the captain immediately shut both engines down. We rolled to a stop in the grass. A very poorly written QRH emergency checklist, I believe, should be modified and improved…The checklist is for use inflight, not on the ground." (Accession Number 437817; ASRS, 2001).

All of the checklists analyzed are relatively long, with the exception of two (2, 9), and all include information about or lists of inoperative items and most of the ramifications the failures have for the remainder of the flight. All of them appear to be written for a dual hydraulics failure that occurs during cruise or at least prior to commencement of the approach phase of flight and none have opt-out gates to facilitate jumping to relevant items if the aircraft is close to the ground and landing is imminent. Because the coincident failure of two hydraulics systems does not force an aircraft to land immediately, it is possible that checklist developers assume that regardless of the phase of flight when the failure is discovered, pilots will have, or will make, enough time to complete the checklist prior to commencing approach and landing. Hence, if the failure is discovered *during* approach or landing, the approach or landing will be aborted so the hydraulics failure checklist can be accomplished.

As can be seen in Table 19, all of the checklists include at least some items or information relevant to approach and landing and three (1, 2, 7) appear to include approach and landing checklists in their entirety.

Table 19. Content in Checklists for Low Pressure in Two Hydraulic Systems

Checklist Content	*QRH/Checklist*
Includes all appropriate approach/landing checklist items	1, 2, 7
Includes some but not all approach/landing checklist items/information	3, 4, 5, 6, 8, 9, 10, 11
Includes items for with regard to altered or alternate flap extension[1]	1, 4, 6, 7, 10
Includes at least some items or information regarding alternate/manual gear extension	1, 2, 3, 4, 5, 6, 7, 8, 10, 11
Includes information about what to do if gear do not extend or if gear only partially extends	3, 9[a]
Addresses performing a missed approach and/or diversion planning	3, 4[b], 6, 7[b], 8, 9, 10

[1] Hydraulic system does not control flap movement in some aircraft so no alternate flap extension method is needed when there is a hydraulic system failure.

[a] Checklist sends the pilot to the separate Alternate Gear Extension checklists which instructs the pilot to accomplish the Landing with Abnormal Landing Gear checklist if the gear does not extend or only partially extends.

[b] Only information provided pertains to not exceeding a particular speed during a go-around.

When some but not all approach/landing checklist items are included, often the item(s) that is/are included isn't/aren't exactly as it/they appear(s) on the normal checklist(s) but instead is information relative to those normal checklist items such as the flap settings or Vref speeds to use.

Although all checklists, except for one (9), incorporate at least some information relative to alternate or manual gear extension, only one (3) also incorporates information about what to do if the gear does not extend or only extends partially. The hydraulics failure checklist that does not incorporate any information about alternate gear extension (9) instead sends the user to separate alternate gear extension checklist which does indicate what should be done if the gear does not extend properly. Thus, only the developers of these two dual hydraulic system checklists have designed them to lead pilots to the necessary information if the gear does not extend properly using alternate/manual methods.

It is possible that the lack of information about what to do if the gear does not extend properly may be because alternate gear extension often relies upon using gravity to let them drop and the assumption is that they will always extend using this method. However some Alternate Gear Extension checklists in the QRHs analyzed make mention that the nose gear will not drop due to gravity and/or that the gear may not lock in place and some other maneuver might be required to achieve this (e.g., a sideslip maneuver). Often it was found that this and other information that is included in the Alternate Gear Extension checklists, that appears to be relevant, is not incorporated into the dual system hydraulics failure checklists that were analyzed, even though other information regarding alternate gear extension is.

Similarly, as can be seen in Table 19, only five of the dual hydraulics system failure checklists analyzed address issues associated with performing a missed approach and/or diversion planning in any detail.

3.9 Checklists for NextGen Operations

As NextGen continues to be implemented and new technologies and automation are developed to fully achieve the NextGen operational vision, new emergency or abnormal checklists for malfunctions associated with those technologies may be needed (Kochan, et al., 2014). Two aspects of NextGen that are already in use by North American carriers, though to differing degrees, pertain to 1) the utilization of Data Comm rather than voice communications over the radio with ATC, primarily in overseas operations; and 2) required navigation performance (RNP) associated with performance based navigation (PBN).

Data Comm (i.e., Controller Pilot Data Link Communication [CPDLC]) is a digital, text-based system for sending messages between ATC and pilots (Nguyen, et al., 2011). When implemented through an integrated system on board aircraft, such as Future Air Navigation System/1A (FANS/1A), flight plan changes sent by ATC can be uploaded directly into the aircraft FMC. When Data Comm is implemented through existing text messaging systems that are not integrated with the aircraft flight management system (FMS), such as aircraft communications addressing and reporting systems (ACARS), pilots must manually input the changes to flight plans sent by ATC.

As its name indicates, RNP operations require that aircraft must be capable of flying along a certain path with a specified level of precision. Furthermore, unlike area navigation (RNAV) operations, under RNP the aircraft performance must be continually monitored and the pilots must be informed if RNP parameters have been exceeded (International Civil Aviation Organization [ICAO], 2007).

3.9.1 What Was Analyzed and Why

As new technologies and types of operations are adopted, procedures for dealing with associated malfunctions may sometimes lag. Therefore, the inclusion of checklists in QRHs for malfunctions or issues associated with two aspects of NextGen operations, Data Comm and RNP, were analyzed. Although Data Comm has not been implemented yet within the US, B777 aircraft engaged in oceanic operations may be using Data Comm for communication with ATC. Additionally, many of the participant air carriers currently use ACARS as a means for pilots to communicate with company dispatchers so it would be expected that those who do would have guidance included in their QRHs for pilots about what to do if ACARS fails, even though they are not yet using ACARS for Data Comm with ATC.

Almost all North American air carriers fly RNAV routes which means that the aircraft must fly a specified course with a certain degree of accuracy 95% of the time (FAA, 2007b). Some participant air carriers, in certain aircraft types, are also authorized to fly RNP approach procedures, which typically specify an accuracy of 1.0 to 0.3 nm but can go as low as 0.1nm for some approaches. Therefore, checklists associated with RNP could be expected to be included in some of the QRHs analyzed. With regard to these RNP associated checklists, a distinction must be made between i) the failure of the aircraft to fly within the required parameters and ii) the failure of the automated RNP monitoring system or degraded navigation signals. In the first, the RNP navigation sources (e.g., Global Positioning System [GPS]) are providing valid position information to the aircraft, but the aircraft is not following the desired course with the required precision. In the second, the navigation sources are not providing adequately accurate position information to the aircraft systems or the systems for monitoring the accuracy of this position are malfunctioning. Analyses included identification of the presence of emergency/abnormal checklists for both situations.

3.9.2 Findings

Data Comm. Seven QRHs (1, 3, 4, 6, 7, 9, 10) analyzed in this study include checklists pertaining to datalink/ACARS issues.[20] Given the fact that Data Comm is not implemented within North American airspace yet, and ACARS is not used by all air carriers, this finding is not surprising. Some checklists pertain to faults in the datalink/ACARS system whereas others pertain to the loss of the datalink connection. In almost all cases, except for those checklists involving a reset of the pertinent computer, there are no actions for the pilots to perform or information provided, other than that included in the Condition Statement which describes the situation. Some aircraft manufacturers or air carriers provide a checklist to go with every text alert displayed on the EICAS/ECAM/crew alerting system, even if there are no actions to perform or notes to read, just for “crew awareness.” Thus, for most failures related to datalink/ACARS systems, there is little for the pilots to do, beyond resetting computers, other than “revert to manual,” i.e., voice communication. Reverting to voice communication has always been the planned fallback under NextGen when Data Comm is not working for some reason (fault or loss of connection), when communication has become confused, or when communication must happen quickly, such as in the case of an emergency (FAA, 2009). Therefore, given this expectation, it is probably unlikely that checklists with many actionable items to be accomplished by the pilots will be developed for future use when Data Comm is implemented within North American airspace.

RNP Operations. As one would expect, all eleven QRHs include checklists for use in the event of a failure or malfunction in equipment responsible for navigation (e.g., GPS), or when actual navigation performance (ANP) is outside of that which is required. Since this equipment is necessary for normal navigation/RNAV, not just RNP approaches, their inclusion is to be expected. Six of the QRHs (2, 4, 6, 7, 8, 10) include checklists or procedures specific to RNP or RNAV RNP AR (Authorization Required) approaches.

3.10 GPS Spoofing

GPS is used on most modern aircraft for navigation and is necessary for many planned applications under NextGen operations (FAA, 2009). The spoofing of GPS signals, and detecting when this has occurred, is therefore a significant concern in the aviation community. A GPS spoofing attack “attempts to deceive a GPS receiver by broadcasting counterfeit GPS signals, structured to resemble a set of normal GPS signals, or by rebroadcasting genuine signals captured elsewhere or at a different time.”[21] The spoofed signal may cause the GPS receiver to figure its position incorrectly (i.e., somewhere other than where it actually is) and, in Next-Gen operations using automatic dependent surveillance, could potentially be used to display aircraft that are not really there on a pilot's or controller's traffic display. There is also a concern that bogus signals could be used to overpower real GPS signals to “carry-off” or draw an aircraft away from its intended course,

---

[20] Datalink is the technological capability that allows Data Comm and ACARS communications to occur.

[21] http://en.wikipedia.org/wiki/Spoofing_attack#GPS_Spoofing

although some suggest that this concern is overblown and doing so would be far more difficult than is realized (Anderson, 2013).

3.10.1 What Was Analyzed and Why

QRHs were reviewed to determine the presence of a checklist that could be used by pilots in the event that a GPS spoofing attack occurs.

3.10.2 Findings

Although all five aircraft types included in this study have some types of alerts or indications that could be used to identify a possible GPS spoofing attack (Berman, et al,, 2014), checklists for possible use in such an event were identified in the QRHs for A320 and EMB190 aircraft only, not for the other three aircraft types. The checklists provided entail a comparison of the aircraft's GPS identified location with that figured or displayed through some other source (e.g., FMS). However, the checklists for the EMB190 appear to assume that in the event of a discrepancy, it is the GPS, not the FMS, which should be used as a source for navigation.

4.0 Cross-Cutting Analysis and Implications

4.1 Checklist Access and Overall Use

Non-normal vs. Emergency/Abnormal. In the past, checklists to guide pilot response to emergency or abnormal situations were placed in one of two categories: emergency checklists or abnormal checklists. Emergencies are, thankfully, rarer than abnormal conditions but are generally more time critical and, by using these two levels of classification, emergency checklists could be collected in a separate section in a QRH to allow faster access. As evidenced in this study, this practice has fallen out of vogue, at least among many North American air carriers, possibly in part for the following two reasons.

First a major aircraft manufacturer (Boeing) stopped using this categorization for their emergency and abnormal checklists. In the mid 1990's they started referring to all such checklists as "non-normal" even though their use of this term is not aligned with the FAA definition of "non-normal."[22] By only using one major grouping instead of two, pilots do not have to remember in which of the two major sections the checklist is located when looking for it in a QRH.[23] Additionally, an event that might be considered abnormal in one situation might be considered an emergency in another (Burian & Boorman, 2005).

Other manufacturers of aircraft included in this study appear to have adopted the use of "non-normal" as a singular checklist category (distinct from normal checklists) or possibly, participant carriers have adopted this convention for use with their non-Boeing aircraft to standardize their approach to emergency and abnormal checklists across all of their fleets.

---

[22] "Non-normal" means the same as "abnormal" as used by the FAA. As Boeing uses it, "non-normal" includes both abnormal and emergency conditions, not just abnormal.

[23] See Saudi Arabian Air flight163, August 19, 1980, for an example of an accident involving the pilots searching unsuccessfully in the wrong QRH section (Abnormal) for their desired checklist.

A second possible explanation for the use of "non-normal" instead of "emergency" and "abnormal" is that linking text alerts for conditions with the titles of checklists to be used in response to those conditions may facilitate the location of these checklists, even for time critical events. So, now the greater distinction between these checklists affecting their access may be whether or they are alerted or un-alerted, rather than whether they are for an emergency or an abnormal condition.

Alerted vs. Un-alerted. Using the same wording for alerts and the titles of their associated checklists helps to ensure that the desired checklist has been accessed, although some care must be taken as many alerts, and hence alerted checklist titles, can be rather complex and/or similar to others. When a checklist exists for an un-alerted condition, however, crews must recall that it is available and pertinent and know how to go about finding it.

Training and QRH/emergency/abnormal checklist review helps with the first—remembering that an appropriate checklist exists—but a variety of approaches used by some of the participants in this study also help to support not only the first but especially the second: knowing how to go about finding it. Three QRHs and the ECL Non-normal Checklist Menu include separate indexes or a menu in which all of the un-alerted checklist titles are listed. Approximately half of the QRHs also include some un-alerted checklists titles more than once in one or more indexes with slightly different wording (e.g., Airspeed Unreliable, Unreliable Airspeed). Thus, the pilots will not have to remember the exact wording of the title in order to find the desired checklist relatively quickly. Adding titles to an index, or even adding indexes, does not appreciably lengthen a QRH but it does help to counteract some of the human memory or cognitive processing difficulties common during stressful situations (Burian, 2014; Dismukes, et al., 2013; Staal, 2004; Stokes & Kite, 1994).

Developing mechanisms to support pilots remembering and finding un-alerted checklists becomes increasingly important as their number increases. Over one-third of the checklists in two QRHs analyzed are un-alerted and the number of un-alerted checklists found in this study range from 35 to 76, across different aircraft types. When comparing QRHs only within aircraft types, differences in the number of un-alerted checklists range between 1 and 12. Thus, air carriers operating aircraft of the same type with a similar level of advanced technology can vary, some to a relatively large degree, in the number of un-alerted checklists they provide for their pilots.

QRH/ECLS Content and Philosophy of Use. All of the QRHs analyzed included content in addition to emergency and abnormal checklists. Some of this information is needed during response to certain emergency and abnormal situations, such as single engine drift down altitudes, or during normal operations that are not ideal, such as landing distances when braking action is poor or de-icing fluid holdover times. This "one-stop shopping" approach to QRH design can be quite helpful in that it eliminates pilots having to refer to multiple manuals for needed information. However, this benefit must be weighed (literally) against the possibility of making the QRH too big and heavy to handle easily—a problem that can be addressed to some degree through the use of EFBs. The amount and types of additional content included varied widely across the QRHs; None of them were found to be difficult to handle during analysis but they generally rested on a table, not a lap or held in one hand as they would be when in use on the flight deck.

One carrier who flies the A320 has chosen not to include duplicate copies of checklists that only have ECAM actions (i.e., no additional items or information) in the companion QRH. Thus, this QRH cannot be used as a stand-alone training aid in addition to use during operations. Pilots cannot call up checklists on the ECAM just to review them, as they can with the ECL, so the only way for them to look up an A320 emergency or abnormal checklist for review is to refer to the companion QRH or, if not included there, other materials which may or may not be carried on board. All of the other QRHs evaluated can be used not only during emergency and abnormal situations but also as training aids and to review if a question arises. Those that include maneuvers or information about special operations (e.g., RNAV RNP AR approaches) can also be reviewed in-flight right before the maneuver or special operation must be performed. Obviously, what is and is not included in a QRH is a reflection of the air carrier's philosophy about the purpose of the QRH and how and when it is to be used.

QRH/ECLS Structure, Organization and Checklist Access. As should have been evident relative to several of the analyses reported in Section 3, checklist access and use is highly affected by the modality employed for checklist presentation. Integrated ECLSs have distinct advantages over their paper counterparts in that many can be automatically identified, accessed, displayed, prioritized, can indicate or easily help track item accomplishment status, facilitate movement to only the correct items to be accomplished in the specific circumstances encountered, and give real-time feedback on the status of the pertinent aircraft systems as items are being accomplished. These benefits are diminished, however, if the programming behind the integrated ECLS does not adequately support prioritization of checklists or if the ECLS cannot be modified, requiring the development of companion paper QRHs or stand-alone ECLSs that must be consulted before, during, or after the accomplishment of items in the integrated system or for un-alerted events. When such a companion QRH is necessary, a consistent approach to its use relative to the accomplishment of items displayed through the integrated ECLS (e.g., only consult the QRH when the ECLS items have all been completed) is essential to reduce the likelihood that checklist accomplishment related errors will be made during event response.

As addressed in Section 3.1, the ease with which all checklists in a QRH can be accessed is a function of its structure, organization, and the inclusion of features such as indexes, tables of content, labeled tabs, and the like. Two QRHs analyzed include no tabs or divider pages and the checklists are not grouped in any particular way, such as by aircraft system. The advantage of this approach for checklist developers is that new content can just be added at the end. Furthermore, since checklists always have the same page numbers, there is no need to revise page number references when new content is added. The disadvantage for pilots, however, is that checklists related to a particular aircraft system are located in several places throughout the QRH. If the pilots wish to compare two or more, such as when trying to confirm that a particular checklist is the one desired, they must expend greater effort to locate them.

Additionally, the grouping of checklists into smaller subsections, such as by aircraft system, and the inclusion of TOCs for these subsections, provides a third method for pilots to use when looking for a particular checklist, in addition to referencing an index or having the page number memorized. In the QRH analyzed that provides no subsection TOCs and uses numbered subsection tabs without also including information about the content in each subsection without actually turning to the subsections, the pilots must resort to using indexes alone or memorizing page numbers to find a desired checklist. Because different humans naturally prefer different search methods, and because that learned during training may easily be momentarily forgotten during times of stress, it is advantageous to offer multiple methods by which checklists can be located.

4.2 Diagnosis and Determining the Appropriate Checklist

As already discussed, integrated ECLSs automatically present or queue the appropriate checklist when pilots are notified of emergency or abnormal conditions through a text alert, and matching the names of Checklist Titles to text alerts greatly facilitates the identification of appropriate checklists in QRHs. However, when an emergency or abnormal condition is not directly alerted and the appropriate, or appropriateness, of an un-alerted checklist must be identified or determined, the task can be more difficult.

In this study, checklists for three different types of events that are not directly alerted in most aircraft were analyzed: uncommanded yaw or roll, pitot-static blockage, and fuel leak. Uncommanded yaw or roll is a little different from the other two in that the event might be a consequence of other alerted conditions, whereas pitot-static blockage or fuel leaks tend to cause other conditions to be alerted. Uncommanded yaw or roll is also typically identified though fairly obvious flight control or aircraft behavioral cues. Cues and alerts for pitot-static blockage and fuel leak can be more subtle and are distributed in several locations throughout the flight deck on a variety of displays, including pages on the FMC (Berman, et al., 2014).

In the analyses of checklists that might be completed in the event of an uncommanded yaw or roll, it was discovered that in several QRHs, the pilots would need to be able to first diagnose the reason for the yaw or roll before being able to identify the correct checklist to complete—only two, for different aircraft types, include a checklist titled Uncommanded Yaw or Roll. Much like the philosophy recently adopted by the industry to guide the design of checklists for in-flight smoke, fire, and fumes (Flight Safety Foundation [FSF], 2005), it might be of benefit to have a checklist which focuses first on general actions for recovery from uncommanded yaw or roll, followed by different sections for use depending upon the cause. It is also possible that checklist developers believe that an uncommanded yaw or roll event is one that might require immediate response, similar to recovery from a stall, so no time exists for reference to a checklist and following recovery, a separate checklist related to the cause could be consulted.

Pitot-static blockage and fuel leaks both can cause a large number of other alerts and cues to be presented, ones which may often confuse the situation and make it difficult for pilots to make sense of the underlying problem. This is the result of the logic behind the alerting systems, which in some circumstances may be desirable, and cannot be helped once the aircraft is in production. When well-designed however, checklists can help pilots immensely in making sense of alerts and cues that may seem opaque, contradictory, or unrelated to the main issue at hand. The following aspects of checklist design and content, especially for un-alerted checklists, are particularly pertinent:

- Checklist Titles
- Condition Statements
- Cue, Symptom, and Alert Lists or Descriptions
- Referencing Un-alerted Checklists in all Relevant Alerted and Other Un-alerted Checklists

These aspects were addressed or included in many of the checklists analyzed in this study but varied in the degree to which this was so, even within a single QRH.

The analyzed un-alerted Checklist Titles related to fuel leak and pitot-static blockage (Fuel Leak and Unreliable Airspeed/Airspeed Unreliable, respectively) are generally quite clear and unambiguous, though as described in the section above, the checklists themselves were sometimes difficult to locate in some QRHs.

Condition Statements are used in checklists in seven of the QRHs analyzed. In alerted checklists they can help the pilots better understand the meaning of an alert message that may not be particularly obvious or clear (Burian & Boorman, 2005). In un-alerted checklists Condition Statements help crews confirm they have accessed the desired checklist. Therefore, they tend to work best, particularly in un-alerted checklists, when they describe the conditions under which the checklist would be needed or used as they help the pilots determine if completion of the checklist is appropriate (Burian & Boorman, 2005). To fulfill this function, they must be clearly written and should specifically reference the emergency or abnormal condition or event (e.g., unreliable airspeed).

Lists or descriptions of symptoms or cues relative to an emergency or abnormal situation can also help in confirming that the un-alerted checklist is appropriate for use and can also further a diagnosis, such as determining the location of a fuel leak. All of the QRHs analyzed, except for the two for the CRJ-700, included such cues in their Fuel Leak checklists. There was greater variability across the QRHs in the degree to which cues or symptoms were used to assist with situation confirmation or diagnosis in the un-alerted checklists associated with pitot-static blockage.

Including a list of the wide variety of alerts that might be displayed in the un-alerted checklists for conditions that are not directly alerted themselves can help pilots be confident that they have correctly identified their situation. However, since crews might access the checklists associated with the various displayed alerts *first*, it would be beneficial if those alerted checklists also include reference to the un-alerted condition as a possible underlying or primary condition. Research may be needed to determine if this is feasible however, in the event that multiple un-alerted conditions may cause a particular alert to be displayed.

Many of the alerted and un-alerted checklists analyzed associated with a fuel leak do make reference to a variety of alerts and cues that might be presented throughout the flight deck but, as stated earlier, some do not provide much guidance to the pilots about how to integrate this information to develop an accurate picture of their overall situation. Very few of the alerted checklists analyzed associated with a blockage in the pitot-static system include such information.

Checklists for alerts associated with un-alerted situations should also help the pilots determine if they (the alerted checklists) and/or the un-alerted checklist should be completed. If a related un-alerted checklist should *not* be completed, the alerted checklists should clearly state that as well. Of the many alerted checklists analyzed that are associated with a pitot-static blockage, only a few send the pilot to accomplish the un-alerted Airspeed Unreliable checklist. None of the others provide any guidance as to whether the Airspeed Unreliable checklist is or is not to be completed.

4.3 Situations or Aspects of Situations that Haven't Been Anticipated During Checklist Development

There are three likely reasons why checklists, or checklist items, for various emergency or abnormal situations are *not* developed: 1) the condition has been determined to be extremely improbable by systems engineers; 2) the condition requires such an immediate and rapid corrective response by the pilots that no time exists for consultation of a printed checklist; or 3) oversight on the part of systems engineers and/or checklist developers.

The U.S. Federal Aviation Regulation §25.1309 Equipment, Systems, and Installations states, in part, that:

> (b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that—
>
> (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and
>
> (2) The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.

And that:

> (d) Compliance with the requirements of paragraph (b) of this section must be shown by analysis, and where necessary, by appropriate ground, flight, or simulator tests. The analysis must consider—
>
> (1) Possible modes of failure, including malfunctions and damage from external sources.
>
> (2) The probability of multiple failures and undetected failures.
>
> (3) The resulting effects on the airplane and occupants, considering the stage of flight and operating conditions, and
>
> (4) The crew warning cues, corrective action required, and the capability of detecting faults.[24]

AC 25.1309-1A (10.b., FAA, 1988), which describes various means that are acceptable for showing compliance with this regulation, defines emergency/abnormal condition failure probabilities for each flight hour (based on a flight of mean duration for the aircraft type) this way:

1. Probable failure conditions are those having a probability greater than on the order of 1×10^{-5}
2. Improbable failure conditions are those having a probability on the order of 1×10^{-5} or less, but greater than on the order of 1×10^{-9}
3. Extremely Improbable failure conditions are those having a probability on the order of 1×10^{-9} or less

It is highly likely that the absence of a checklist for the loss of all hydraulic systems in all of the QRHs analyzed in this study is because systems designers determined that such an event is extremely improbable, using the criteria above. A similar determination may have been made relative to the occurrence of a leak in the fuel tanks of the B737NG as developers of the Fuel Leak checklist explicitly state, in the checklist, that it is only for use of a leak in the engine as a tank leak would be "unlikely."

Because of the speed with which pilots must respond, it was not expected that checklists would be included in the QRHs analyzed for stall recovery or for determining that a stall warning was false. Surprisingly, one QRH did have a checklist for stall recovery and two others included such

---

[24] Current as of March 6, 2014, Downloaded March 9, 2014, from: http://www.ecfr.gov/cgi-bin/text-idx?SID=dedba50fa318b876b94bdea696ddb866&node=14:1.0.1.3.11.6.192.6&rgn=div8

information in their maneuvers sections. However, the recovery steps included in the checklist are to be performed from memory, rather than accomplished step-by-step during the actual recovery. The inclusion of this checklist/information in the QRHs allows pilots to confirm that they have considered everything necessary upon completion of stall recovery and are also easily available for review or study, which goes back to the philosophy of QRH use.

No information was identified in the stall recovery checklist or information with regard to detecting or responding to a false stall warning, but three other QRHs, representing two aircraft types, did include separate checklists to guide false stall warning response. Furthermore, two other QRHs include information—in checklists pertaining to air data computer system malfunctions—that a false stall warning might occur. Such cautionary information can be quite beneficial for pilots and is in keeping with the earlier suggestion that checklists include a list of the variety of alerts that might be associated with un-alerted conditions. In both circumstances the inclusion helps pilots to make sense of alerts and information presented to them, particularly when they are unexpected or don't seem consistent with or related to the underlying situation at hand.

A number of times during analysis it appeared that some issues or situations may have been overlooked by developers during the design of some checklists. For example, no QRH includes a checklist(s) that covers every type of primary flight control surface that might jam (aileron, rudder, stabilizer, elevator) and only four, representing three different aircraft types, include one or more checklists for some type of trim runaway event. It is unknown if system differences obviate the need for all of these checklists or if checklist designers have not considered their potential need. The fact that one QRH for several aircraft types does include one of these checklists whereas the other(s) analyzed for the same type do not suggests that it might be the latter.

Similarly, four Fuel Leak checklists, from three different aircraft types, are written for a leak in only one of two major locations (engine or tank) without any reference or items related to a possible leak in the other. In over half of the A320 or CRJ700 alerted checklists identified associated with possible alerts when a fuel leak exists, at least one carrier suggests considering a fuel leak but no such suggestion is made in the same checklists belonging to other carrier(s). Because these issues are addressed in one QRH but not the other of the same aircraft type, it appears that the lack of attention or reference may be due to checklist developer oversight.

Recall that across four aircraft types (all but the EMB190), no direction to consider or check for a fuel leak is made in 10 alerted checklists associated with a possible un-alerted fuel leak situation. Again, this omission could be due to i) checklist designer oversight, but could also be because ii) no reference is warranted or because iii) by the time the alert associated with the checklist is displayed, it may be of little use to try to rectify a fuel leak and attention instead should be devoted to other tasks, such a completing an emergency landing or ditching. If the omission is for either of the last two reasons, it would be beneficial to inform the crews in these alerted checklists that they should not attempt to accomplish the un-alerted fuel leak checklist, as discussed earlier.

It is highly concerning that only the dual engine failure checklists in the A320 QRHs and the single engine checklists in the EMB190 QRHs mentioned fuel leak as a possible issue. As described earlier, such a consideration is essential if pilots are to give their attention to the proper actions during their response to the dual engine failure event.

It was also observed that some checklists for some emergency or abnormal situations for likely events were lacking in some QRHs (i.e., checklists for an encounter with Volcanic Ash in the CRJ700 QRHs). Additionally, some checklists lacked consideration of issues relevant throughout all the phases of flight when the checklist might be needed, such as dual hydraulics system checklists that did not address the possible need to perform a missed approach and/or conduct a diversion, or the possible failure of hydraulics during ground operations.

Some checklists also appear to have been written with a variety of assumptions that may not be true about the events in which they might be used or the expected successfulness of checklist actions. For example, none of the dual engine failure checklists immediately direct the pilots to items for an emergency landing or ditching if the failure occurs close to the ground, and some dual engine failure checklists make no mention of what to do if engine relight procedures are unsuccessful for both engines. The pilots confronted with both of these situations will be left on their own to devise the best responses possible.

4.4 Cognitive and Workload Demands and Checklist Use

Not all abnormal situations involve substantially increased workload or stress. For example, a PACK trip is typically considered a relatively benign event (if it only occurs once) and the checklists for response to such a situation are generally fairly short. However, many other types of emergency and abnormal events, such as the ones whose checklists were a focus in this study, do entail increased workload and often increased stress as well. Highly trained motor skills, such as those used for a stall recovery, tend to remain relatively robust under stress (Staal, 2004). Cognitive skills, however, can be highly negatively affected by stress (Burian, 2014, Dismukes, et al, 2013, Staal, 2004). It is not uncommon for pilots to become task saturated, particularly when dealing with time-critical and demanding emergencies, and for them to end up lacking the ability to mentally “step back” and assess the status of the overall situation, which is necessary for sound decision making and appropriate workload management (Dismukes, Berman, and Loukopoulos, 2007).

There are a number of things that contribute to cognitive and workload demands during response to and management of an emergency or abnormal situation (Burian, 2014). In this study, only a few of those things as they relate to emergency and abnormal checklists were of interest. Some specific aspects of QRH, ECLS, and checklist design, content, functionality, and use that contribute to the following cognitive and workload demands were analyzed: memory, situation awareness, diagnosis, decision-making, and workload management.

Memory. The purpose of training is to inform, practice, and commit to long term memory information and actions necessary for operations under normal and emergency/abnormal conditions. Relative to the foci of this study, information stored in long term memory is retrieved when pilots recall that un-alerted checklists exist for a condition and find its title in an index and when they accurately remember and perform Memory Items. In commercial aviation, information stored in long term memory typically has been overlearned through repetitive practice. However, recall of this information when needed is still generally not perfect (e.g., Au, 2005) and the industry has undertaken different approaches in QRH, ECLS, and checklist design and flight deck alerting in response.

For example, as previously discussed, the inclusion of checklists in multiple places in several indexes with slightly different titles diminishes the requirement that pilots be able to recall the exact wording of a checklist's title to located it. QRCs are other tools that reduce a pilot's memory load and/or support consistent and reliable response to time-critical conditions.

Nine of the eleven QRHs analyzed had QRC information included with them, often printed on their covers, or as a separate card. The two QRHs with no QRC have the fewest combined number of Memory and Immediate Action Items: 6 and 8, for two different aircraft types. The number of Memory and Immediate Action Items, combined, in the nine QRHs with QRCs, across all the aircraft types, ranges from 10 to 129. How each of the QRCs is intended to be used by pilots is unknown. Are all items on the QRC to be performed from memory with the QRC then used to confirm correct accomplishment? Are only some items (i.e. Memory Items) to be performed from memory but other QRC items (i.e. Immediate Action Items) to be performed by reference to the QRC (if both are included on the QRC)? Are all items to be accomplished through referencing the QRC, i.e., none from memory? During analysis, little information was available relative to QRC use, and what was available was sometimes inconsistent with information shared by SMEs who were consulted at the air carriers. When under time pressure and stress, actions are far more likely to be performed consistently and accurately when their accomplishment is guided, such as through reference to a QRC (Hamman, 1997).

Three QRHs, representing three different aircraft types, have QAIs on their covers and two also have companion QRCs on separate cards. There does not appear to be any relationship between the numbers of checklists that include memory items in a QRH with the presence of a QAI on the QRH cover.

A high degree of variability was identified across the air carrier participants, even within aircraft type, with regard to which checklists warrant memory items and how many are necessary. This is not surprising as it appears that no research has been conducted which would help manufacturers and air carriers make these kinds of determinations.

It is likely that some types of memory items are easier than others to commit to memory and recall when needed. A few related actions can be grouped or "chunked" together, remembered almost as a sort of mantra, and performed as a flow or unit (Rosenbaum, Kenny, & Derr, 1983). However, checklist analyses revealed that many types of items other than action items are to be performed from memory, including Conditional/Decision Items that require evaluation and judgment, items specifying when certain actions are to be performed, and action items requiring crew communication and coordination as they are accomplished. Additionally, even a grouped or "chunked" set of action items are vulnerable to error as interruptions or distractions during their performance break the flow connecting them and may lead to some being forgotten (Rosenbaum, et al., 1983). The longer the flow, i.e., the more action items that have been grouped together for accomplishment, the greater the risk of interruption (Dismukes, et al., 2007).

Situation Awareness, Diagnosis, and Decision Making. Sophisticated alerting systems on aircraft can do much to help pilots stay abreast of non-normal system parameters and inform the crew when many types of emergency or abnormal conditions exist. Linking the alerts with Checklist Titles for those conditions streamlines the process in determining the correct checklist to complete. Sometimes a particular constellation of alerts may confuse pilots though, particularly those presented when the underlying condition they pertain to is un-alerted. As discussed earlier, informing pilots of the alerts and cues they may see relative to un-alerted conditions can be highly beneficial.

This may require a somewhat different approach to checklist design than might currently be undertaken. For example, instead of considering the content of each checklist individually, checklist designers could imagine various types of un-alerted conditions, with multiple variations of each—for example, fuel leaks in several different locations with different speeds of leakage, different types of blocked pitot-static scenarios, and so on. In each variation, systems and checklist designers would consider the alerts and cues that might be presented to the crews and this information would be incorporated into the un-alerted checklists. Consideration of the relationships between the alerted and un-alerted checklists would also be made and items informing the pilots of these relationships would be added, i.e., which checklists should and should not be completed in the various scenarios. In this approach or any others concerning the development of these alerted and un-alerted checklists, it is, of course, essential that the systems experts involved have a thorough understanding of the alerting system logic, knowing what parameters would cause the various alerts to be presented, terminated, or inhibited.

Most manufacturers, the original checklist designers in most cases, already consider the variety of secondary alerts that may be presented as a consequence of a primary problem and inhibit the secondary alerts/integrated electronic checklist, indicate in the QRH that certain (secondary) alerted checklists should not be completed, and/or integrate any pertinent items from the secondary checklists into that for the primary alert (Burian & Boorman, 2005). In the analyses conducted in this study, it did not appear very often that, as described above, there has been a more global consideration of variations of some un-alerted conditions resulting in un-alerted checklists that include information about alerts that might be presented so as to help pilots make sense of what they are seeing on the flight deck.

Interestingly, decision making during critical events may be the most straight-forward when time is short and options are few (e.g., US Airways 1549; NTSB, 2010b). Although beyond the scope of the current study, alerting systems and ECLSs that help pilots distinguish between primary conditions and secondary/consequential conditions and to prioritize among multiple alerts contribute greatly to pilot decision making during complex and multifaceted emergency and abnormal situations. Pilots could benefit from guidance about how to respond to emergency situations that spawn a vast number of alerts due to multiple failures (e.g., Qantas 32; ATSB, 2013); in most cases, is the best course of action to accomplish all or as many of the associated checklists as possible?

Just as alerts can help pilots obtain awareness of the initiation of an emergency or abnormal condition, pilots must assess the effects that corrective actions are having and continually maintain their awareness of the situation overall. Opt-out gates in emergency/abnormal checklists are powerful ways to remind pilots to assess the “big picture” and refresh their awareness of a situation’s status. Many examples exist of accidents where the pilots were overloaded and were so focused on dealing with a specific task or malfunction that they lost sight of the overall situation (Dismukes, et al., 2007). However, it can be difficult for checklist designers to decide when, where, and how often to include opt-out gates in checklists, and in which checklists they might be most appropriate for inclusion. Emergency and abnormal situations are dynamic but currently, checklist content is largely static; pilots evaluate op-out gates when they come to them during checklist accomplishment. They may see no need to opt-out at the time the opt-out item is reached but later on in the checklist, when it would be highly appropriate to do so, they may forget about opting out because they are task saturated and lack the mental “bandwidth” to remember and be able to mentally step back and assess the overall situation.

An opt-out gate in an emergency/abnormal checklist does not necessarily mean that the checklist is to be abandoned. If the Get-in, Stay-in philosophy of checklist design has been followed, an opt-out gate may simply redirect the pilots to later actions in the same checklist such as when an opt-out gate directs users to jump to the emergency landing or ditching items at the end of a dual engine failure checklist if the event occurred close to the ground, such as on climbout (see US Airways 1549; NTSB, 2010b). No such opt-out gates, however, were discovered in any of the Dual Engine failure checklists analyzed in this study.

<u>Workload and Workload Management</u>. As described in Section 3 and earlier here in Section 4, the structure, organization, functionality, and content of ECLS and QRHs have a direct relationship on the amount of work entailed in their use. For example, the "one-stop shopping" approach to QRH construction allows the pilots to locate in one place all the information they might need during response to emergency and abnormal situations. Checklist-related workload is also affected by the numbers and types of menus and indexes, how indexes and menus are organized and accessed, use of tabs, divider pages, section TOCs, how navigation through checklists is facilitated, and the like. (Checklist navigation will be discussed in the section below.)

Just as "one-stop shopping" allows the pilots to stay in one manual or ECLS for all information needed during emergency/abnormal situation response, the Get-in, Stay in philosophy of checklist design incorporates all items and information from other checklists that might be needed through the end of the flight. Thus, it helps to streamline the management of the overall situation through landing. Lest a QRH become too large, this philosophy is only applied in checklists for situations that have probable implications for the remainder of a flight such as an in-flight fire, in-flight hydraulics failures, dual or single engine failures, fuel leaks, and the like. Stand alone or integrated ECLS have no such space and weight limitations and could, theoretically, adopt this philosophy of checklist design for a greater range of situations, if so desired.

In this study it was found that very few checklists were designed according to the Get-in, Stay-in philosophy. As mentioned earlier, it is possible that the philosophy is not well known or that checklist designers to not appreciate its advantages in terms of pilot workload and error reduction. If pilots don't have to jump among multiple locations within a manual, among multiple materials, such as emergency/abnormal and normal checklists, or between an ECLS and a companion QRH, they are far less likely to jump to the wrong place, forget to accomplish actions on one of the checklists, or accomplish actions in the wrong order.

When applying the Get-in, Stay-in philosophy, it is important that *all* the relevant information from the checklists or information being included is integrated (Dismukes, et al., 2007; NTSB, 1996). In this study, for example, although 10 QRHs incorporate at least some information regarding alternate or manual gear extension in the dual hydraulics failure checklists analyzed, only one appears to include all the relevant information from the separate alternate gear extension checklist, including steps to take if the gear does not extend or only extends partially.

4.5 Checklist Navigation

Checklist navigation involves not only linear movement through a checklist, progressing step by step as each one is accomplished and the next one is reached, but also jumping within a checklist past inapplicable items to others that are and jumping out, and sometimes back in, to and from other checklists, materials, or information. Checklist navigation and the amount of jumping required are dependent upon a number of factors. The first is the modality of checklist presentation; closed loop items on integrated ECLS and inhibiting unnecessary secondary or consequential checklists streamline the process greatly. Depending upon how it is programmed, ECLS can also integrate items and information from multiple checklists in a way that appears seamless to the pilot (Burian & Martin, 2011).

Checklist navigation is also very much influenced by the philosophy with which the QRH, ECLS, checklist, and related materials, have been developed. One-stop shopping, Get-in Stay-in, inclusion of opt-out gates, consideration of a wide range of circumstances that might require additional or alternate actions or information, assumptions about the effectiveness of checklist procedures—each affects how pilots will move through the various materials consulted during emergency/abnormal situation response as well as how many separate things will need to be accessed.

A variety of ways currently used to facilitate this navigation in the checklists analyzed in this study were reviewed earlier. Most items that support this activity, such as single Conditional/Decision Items and Exclusive Conditional/Decision Item Sets, require that some sort of evaluation or choice be made. Obviously, the more branches available and the more jumping required, the greater the mental workload involved in accomplishing the checklist and the greater the opportunities for error. Thus, various formatting and graphical conventions are used to facilitate the identification of not only the Conditional/ Decision Items themselves, but also in identifying the subordinate items that go with the various decision branches and in directing the pilots to those items.

Although items, formatting, and graphics associated with navigation and jumping in the checklists analyzed were identified and described, a table-top analysis of the checklists, such as what was conducted in this study, cannot truly evaluate their effectiveness in supporting checklist navigation. That can best be accomplished through an observation of pilots actually using the materials. Even so, in this study the following observations pertaining to checklist navigation were made:

- It was sometimes difficult to follow flow lines, particularly when they continued across multiple pages, several ran in parallel to each other because of nested Conditional/Decision and subordinate items, and when they connected to both the right and left sides of items (right and left margins).
- Exclusive conditional sets were most easy to evaluate when they were presented or identified as a set in some way, rather than when each item was presented without any indication that its complement(s) (other item(s) in the set) was presented later in the checklist.
- In a few checklists analyzed, the pilot is sent to a second checklist that immediately sends the pilot to a third. It was not clear why the jump to the second checklist is necessary.
- Conditional/Decision Items, despite the inclusion of special graphics or formatting, were sometimes missed when they appeared very near the "checklist continued" item/Checklist Title repetition at the top of a second or later checklist page in the QRH. Spacing between the Conditional/Decision Item and the indentation of the subordinate items contributed to the eye jumping directly to the subordinate items.
- Some Conditional/Decision Items are compound or complex which can be more difficult for pilots to correctly evaluate when under stress.
- All checklists, but particularly an ECLS, should have a way to "undo" an incorrect evaluation of a (open loop) Conditional/Decision Item. In other words, the subordinate

items for all potential evaluations of a Conditional/Decision Item must be available or easily accessible in case an incorrect evaluation of the item has initially been made. The ECL allows this, as of course do all paper checklists, but it unclear how this is managed on the ECAM.

Jumping within a checklist should not necessarily be considered an undesirable thing; indeed, jumping within a checklist means that checklist designers have tried to anticipate many of the circumstances under which the checklist and alerted actions might be needed to provide a degree of customization and the best support possible to the pilots. What is essential, however, is that during checklist development all the various path ways through the checklist should be validated and that mechanisms used to facilitate jumping are thoroughly vetted and evaluated in a simulator under situations as similar to those experienced during a real event as possible.

Even so, to reduce workload and the potential for error, jumping should be minimized or streamlined whenever possible. For example, during an emergency/ abnormal situation if an action should be performed when the aircraft is in icing conditions and there is no discernable penalty if action is performed when the aircraft is *not* in icing conditions, the Conditional/Decision Item asking if the aircraft is in icing conditions could be eliminated and the pilot simply directed to complete the action. Research is needed to help identify the most effective ways to facilitate emergency/ abnormal checklist navigation, particularly when they are presented in paper and stand-alone ECLS modalities.

4.6 Assumptions about Amount of Time Available and Action Effectiveness

Some of the checklists analyzed in this study appear to have been developed with the unstated assumption that a certain amount of time would be available for item accomplishment. In many cases, these assumptions may be ones in which the checklist developers were unaware that they even had. Examples of such assumptions are Dual Engine Failure checklists that have many items devoted to methods for relighting the engines but no immediate direction to prepare for an emergency landing or ditching if adequate time for engine relight is unavailable. Similarly, three Fuel Leak checklists analyzed include items directing a diversion to the nearest suitable airport in the middle or at/near the very end of the checklist. Some checklists analyzed also appeared to have been written with an expectation that the actions to be performed would be effective or successful, such as the Dual Engine Failure checklists that do not have items to perform if neither of the engines can be re-started.

By their very nature, the identification of underlying assumptions such as these that may affect decisions about the design and content of emergency and abnormal checklists may be difficult to identify. After their initial design, checklists, and the pilots who use them, benefit when checklist developers conduct an analysis specifically targeted toward catching unintended assumptions.

4.7 Checklists for Use in NextGen Operations

Checklists associated with some types of NextGen Operations were analyzed in this study: GPS Spoofing, RNP, and Data Comm. These three were chosen for study because they relate to aspects of NextGen that are already implemented.

All five of the aircraft types included in this study have alerts or indications that can be used to identify a possible spoofing attack, although some are rather subtle and/or are outside the pilot's primary field of view, i.e., on a page on the FMC (Berman, et al., 2014). Furthermore, the thresholds that trigger some of these alerts may be inadequate for NextGen operations, such as an alert to verify the aircraft's position that is triggered only after the GPS indicated position differs from that of other sources by more than 12 miles. In this study, checklists that might be used in the event of a possible GPS spoofing attack were identified in the QRHs for A320 and EMB190 aircraft but not in QRHs for the other three aircraft types.

Not surprisingly, all of the QRHs include checklists associated with malfunctions of equipment necessary for navigation and for issues associated with RNP or RNAV RNP AR approaches if the aircraft and air carrier is authorized for those operations. The checklists and information relative to RNP or RNAV RNP AR approaches indicate what should be done operationally if the required navigation precision cannot be met (e.g., break off the approach) but rarely do they address fixing or attending to a malfunction associated with this failed performance.

As stated before, Data Comm is not yet used within North American airspace but seven of the QRHs analyzed do include checklists for datalink/ACARS related issues. The B777 aircraft engage in oceanic operations where Data Comm is already in use and several of the carriers use ACARS to communicate with company dispatchers. Other than those checklists involving a re-set of the datalink/ACARS associated computer, there are no items in these checklists for the pilots to perform if datalink/ACARS fails. In the planning for NextGen, Data Comm failures will be dealt with by reverting to voice communications. This may be an acceptable fall back arrangement if the failure exists for a single aircraft. If the failure exists on the ground side however, affecting all aircraft in a particular sector, or multiple aircraft due to environmental conditions, it might quickly become untenable, especially given the closely spaced operations envisioned under NextGen.

Although three NextGen specific checklists are discussed here, in truth almost all of the checklists included in ECLSs, QRHs and analyzed in this study have relevance for NextGen operations. No matter how well planned and designed, emergency and abnormal situations will continue to occur during NextGen. The content of checklists for these situations may or may not need to change, but procedures must be in place for emergency aircraft, and the aircraft in the surrounding airspace, to allow the emergency aircraft to quickly descend and/or turn without conflict when an emergency descent or diversion is necessary. Likewise, procedures will need to be in place so that tightly scripted arrivals at an airport can accommodate a diverting aircraft or an aircraft that has an emergency upon landing.

5.0 Concluding Remarks

It is not uncommon for air carriers and manufacturers to make adjustments, changes, and additions to emergency and abnormal checklists. It is because of their critical role in helping to guide pilot response to demanding situations that developers work to make the most effective checklists possible. Well-crafted emergency and abnormal checklists of any mode of presentation—integrated ECLS, stand-alone ECLS, paper—can be very difficult to develop and each mode brings its own design challenges. A table-top evaluation of emergency and abnormal checklists can identify a number of possible issues with regard to their design, both positive and negative. However, these possible issues are verified and checklist use and functionality are best assessed through walkthroughs and through part-task and, if necessary, full mission simulation evaluations using qualified pilots under conditions that are as realistic as possible.

By necessity, this study was focused fairly narrowly on just a few issues and checklists, primarily associated with two of the checklist design factors often causing the greatest challenges for checklist designers and pilot users: i) identifying and accessing the correct checklist and ii) navigation through the checklist and other materials needed. Prioritization of checklists/response in multiple failure conditions is a third, highly challenging area for designers and pilots but is beyond the scope of the present study.

One of the strengths of the analyses conducted in this study is the comparison of approaches taken by developers of ECLSs, QRHs, and checklists within the same and across different types of aircraft. Great lengths were taken to protect proprietary information as much as possible but still provide useful information, illustrations, and points of comparison so that all participants and other interested parties may be able to consider the approaches taken by others.

6.0 References

Air Accidents Investigation Branch. (2010). Report on the accident to Boeing 777-236ER, G-YMMM at London Heathrow Airport on 17 January 2008. Aircraft Accident Report 1/2010.

Anderson, M. S. (2013). *GPS Spoofing.* Communications and GPS Navigation Program Office (PMW/A-170). United States Navy.

Au, H. (2005). Line pilot performance of memory items. In *Proceedings of the 13th International Symposium on Aviation Psychology*, Oklahoma City, Oklahoma.

Australian Transport Safety Bureau. (2013). *In-flight uncontained engine failure overhead Batam Island, Indonesia, 4 November 2010, VHOQA, Airbus A280-842.* ATSB Transport Safety Report, Aviation Occurrence Investigation – AO-2010-089 Final.

Aviation Accidents Prevention and Investigation Department. (2004). *Accident Investigation Final Report, All Engines-out Due to Fuel Exhaustion, Air Transat, Airbus A330-243 marks C-GITS, Lajes, Azores, Portugal, 24 August 2001.* Final Investigation Report 22/ACCCID/2001. GPIAA, Government of Portugal.

Aviation Safety Reporting System. (2001). Search Request Number 6133. NASA Ames Research Center, Moffett Field, CA.

Berman, B., Kochan, J. A., Burian, B. K., Pruchnicki, S., Silverman, E., & Christopher, B. (2014). Flight deck alerting: Functions, characteristics, and implications for NextGen. NASA Technical Memorandum. Manuscript in progress.

Bureau d'Enquêtes et d'Analyses. (2012). Final Report on the accident on 1st June 2009 to the Airubs A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro – Paris. BEA, France.

Burian, B. K. (2004). Emergency and abnormal checklist design factors influencing flight crew response: A case study. In *Proceedings of the International Conference on Human-Computer Interaction in Aeronautics 2004*, Toulouse, France: EURISCO International.

Burian, B. K. (2006). Design guidance for emergency and abnormal checklists in aviation. In the *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. San Francisco: HFES.

Burian, B. K. (2010). *Aircraft emergencies: Challenge and response*. Keynote Presentation at the 9th International Symposium of the Australian Aviation Psychology Association. Sydney, Australia: AAvPA.

Burian, B. K. (2013). *Emergency and Abnormal Checklist Items and Elements.* Unpublished manuscript.

Burian, B. K. (2014). Emergency and abnormal situations: Demands, human performance, and checklists. NASA Technical Memorandum. Manuscript in progress.

Burian, B. K., Barshi, I., & Dismukes, K. (2005). *The challenge of aviation emergency and abnormal situations.* NASA Technical Memorandum, NASA/TM-2005-213462.

Burian, B. K. & Boorman, D. J. (2005). Boeing non-normal checklists: The Boeing 777 electronic checklist and quick reference handbook (2nd edition). Technical Document, Boeing Commercial Airplane Group.

Burian, B. K. & Geven, R. (2005). *B737 Non-normal checklists: A comparison study.* Presentation at the 13th International Symposium on Aviation Psychology, Oklahoma City, Oklahoma.

Burian, B. K. & Martin, L. (2011). Operating documents that change in real-time: Dynamic documents and user performance support. In G. A. Boy (Ed.), The handbook of human-machine interaction: A human-centered design approach (pp. 107-130). Farnham, Surrey, England: Ashgate.

Casner, S. M., Geven, R. W., & Williams, K. T. (2012). The effectiveness of airline pilot training for abnormal events. *Human Factors, 55*(3), 477-485.

Dismukes, R. K., Berman, B. A., & Loukopoulos, L. D. (2007). The limits of expertise: Rethinking pilot error and the causes of airline accidents. Aldershot, Hampshire, England: Ashgate.

Dismukes, R. K., Goldsmith, T. E., & Martinez-Papponi, B. (2013). *Selective review of stress literature: Implications for pilot performance.* Contractor Technical Report for the Federal Aviation Administration.

Federal Aviation Administration. (1988). Advisory Circular 25.1309-1A. *System Design and Analysis.* 6/21/88. ANM-110.

Federal Aviation Administration (2007a). *Flight Standards Information Management System (FSIMS),* 8900.1, Change 0. Volume 3: General Technical Administration. Chapter 32: Manuals, Procedures, and Checklists for 14 CFR Parts 91K, 121, 125, and 135. Section 1: Background and Definitions. Downloaded March 10, 2014:

http://fsims.faa.gov/PICDetail.aspx?docId=8900.1,Vol.3,Ch32,Sec1 .

Federal Aviation Administration. (2007b). Advisory Circular 90-100A. *U.S. Terminal and En Route Area Navigation (RNAV) Operations.* 3/1/07, AFS-400.

Federal Aviation Administration. (2009). *NextGen mid-term concept of operations for the national airspace system.* Air Traffic Organization NextGen & Operations Planning, Research & Technology Development, Air Traffic Systems Concept Development.

Flight Safety Foundation (2005). Flight crew procedures streamlined for smoke/fire/fumes. *Flight Safety Digest, 24*(6), 31-36.

Hamman, W. R. (1997). *Quick Reference Checklist (QRC) United Airlines Validation Study.* Denver, CO: United Airlines.

Kochan, J. A., Breiter, E. G., & Jentsch, F. (2004). Surprise and unexpectedness in flying: Database reviews and analyses. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 48*(3), 335-339.

Kochan, J. A., Tomko, L., & Burian, B. K. (2014). Anticipated Operational Anomalies under NextGen. Unpublished document.

National Transportation Safety Board. (1989). *Aircraft Accident Report – Aloha Airlines, Flight 243, Boeing 737-200, N73711, near Maui, Hawaii, April 28, 1988.* Report Number NTSB AAR-89/03. Washington, DC: NTSB. (NTIS No. PB-89-910404).

National Transportation Safety Board (1990). *Aircraft Accident Report. United Airlines Flight 232 McDonnell Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989.* NTSB/AAR-90/06, PB90-910406.

National Transportation Safety Board (1993). *Aborted Takeoff shortly after Liftoff, TWA Flight 843, Lockheed L1011, N11002, John F. Kennedy International Airport, Jamaica, New York, July 30, 1992.* NTSB/AAR-93/02, PB93-910402.

National Transportation Safety Board. (1996). *Aircraft Accident Report – Ground Spoiler Activation in Flight/Hard Landing, Valujet Airlines Flight 558, Douglas DC-9-32, N922VV, Nashville, Tennessee, January 7, 1996.* Report Number NTSB AAR-96/07. Washington, DC: NTSB.

National Transportation Safety Board (1998a). *Aircraft Incident Report, American Trans Air Flight 406, Boeing 727-290, N775AT, Indianapolis, May 12, 1996.* Accident Docket. Washington, DC: NTSB. (CHI96IA157).

National Transportation Safety Board (1998b). *Aircraft Accident Report – In-flight Fire/Emergency Landing, Federal Express Flight 1406, Douglas DC-10-10, N68055, Newburgh, New York, September 5, 1996.* Report Number NTSB AAR-98/03. Washington, DC: NTSB.

National Transportation Safety Board. (2010a). *Aircraft Accident Report, Loss of Control on Approach, Colgan Air, Inc., Operating as Continental Connection Flight 3407, Bombardier DHC-8-400, N200WQ, Clarence Center, New York, February 12, 2009.* NTSB/AAR-10/01, PB2010-910401, Washington, DC.

National Transportation Safety Board. (2010b). *Aircraft Accident Report, 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, New Jersey, January 15, 2009.* NTSB/AAR-10/03, PB2010-910403, Washington, DC.

Nguyen, J. H., Bacon, L. P., Rorie, R., C., Herron, M., Vu, K-P. L., Strybel, T. Z., & Battiste, V. (2011). How data comm methods and multi-dimensional traffic displays influence pilot workload under trajectory based operations. In the *Proceedings (Part II) of the 2011 Human Computer Interaction International Annual Meeting,* Orlando, FL.

Rosenbaum, D.A., Kenny, S.B., & Derr, M.A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 86-102.

Safety Regulation Group. (2013). *CAP 413: Radiotelephony Manual,* Edition 20. Civil Aviation Authority – United Kingdom.

Staal, M. A. (2004). Stress, cognition, and human performance: A literature review and conceptual frame-work (Rep. No. TM-2004-212824). Moffett Field, CA: Ames Research Center.

Stokes, A. F., & Kite, K. (1994). *Flight stress: Stress, fatigue, and performance in aviation*. Burlington, VT: Ashgate.

Thackray, R. I., & Touchstone, M. (1983). Rate of initial recovery and subsequent radar monitoring performance following a simulated emergency involving startle. FAA Technical Report No. DOT/FAA/AM-83/13, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, USA.

Transportation Safety Board of Canada (2003). *Aviation Investigation Report A98H0003, In-flight Fire Leading To Collision with Water, Swissair Transport Limited McDonnell Douglas MD-*

11 HB-IWF, Peggy's Cove, Nova Scotia 5nm SW, 2 September 1998. Gatineau, Quebec, Canada: TSB of Canada.

Walters, J. M., & Sumwalt, R. L. (2000). *Aircraft accident analysis: Final reports*. New York: McGaw-Hill.