Design Guidance for Emergency and Abnormal Checklists in Aviation

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It can be extremely challenging to develop effective checklists for use by flight crews during emergency and abnormal situations. Relatively little guidance is available from the human factors community and developers generally use aircraft system requirements, historical precedent, and their own best judgment to guide their design decisions. Through work at the NASA Ames Research Center, a model of emergency and abnormal checklist design, content, and use has been developed. This comprehensive model identifies all aspects that need to be considered and brings attention to some that are often unappreciated in emergency and abnormal checklist design (e.g., human performance limitations under stress).

Introduction

Developing a well-designed checklist for use by flight crews faced with an emergency or abnormal situation is no simple task. It must be easy to access, easy to read, and easy to use. Instructions should be concise but enough information must be provided so that actions are performed correctly and essential issues are considered. It must accommodate the demands of high workload phases of flight and the performance limitations experienced by humans when under stress. It should respond to the specifics of a system malfunction but also assist crews in their management of the overall situation.

Emergency and abnormal checklists used in civil aviation are typically presented to flight crews in paper or electronic formats. Aeronautical engineers and/or pilots generally develop them using aircraft system design, historical precedent, and their own preferences and best judgment to guide their checklist design decisions. Relatively little guidance from the human factors community regarding checklist design exists. What is available typically focuses on a limited number of design factors, such as typography (e.g., Degani, 1992), or is rather cursory and incomplete (see Burian, 2004).

Two of the most complete documents pertaining to checklists that are currently available can be obtained from the United Kingdom Civil Aviation Authority. The first, Civil Aviation Publication (CAP) 676, provides general guidance on the design, presentation and use of emergency and abnormal checklists and pertains primarily to those presented on paper (Civil Aviation Authority, United Kingdom, 2006). CAP 708 provides guidance as to the design, functionality and use of normal, emergency, and abnormal checklists that are presented electronically (Civil Aviation Authority, United Kingdom, 2005). However, neither of the CAP documents fully addresses all of the aspects that need to be dealt with when constructing paper or electronic emergency and abnormal checklists.

Practice Innovation

Through the Emergency and Abnormal Situations Study at the NASA Ames Research Center, a careful and detailed analysis of the design, content, and use of emergency and abnormal checklists used by Part 121 air carriers has been conducted. A wide variety of paper and electronic checklists has been systematically analyzed (Burian, 2005). Pilots, instructors, and checklist developers have been interviewed and observations of pilots using emergency and abnormal checklists during simulator training, as well as during operations on the line, have been performed. Information gleaned from these analyses, interviews, and observations has been combined with an understanding of human performance capabilities under stress and knowledge from the fields of human factors and cognitive psychology. Additionally, the operational demands of emergencies and the aviation environment have been considered resulting in the development of a comprehensive, conceptual model of emergency and abnormal checklist design, content, and use (Burian, 2006).

Findings

This conceptual model, though comprehensive, applies only to checklist presentation modalities currently used in civil aviation (i.e., paper and electronic checklists); emergency checklists that are presented aurally by a computer or in some other format are not included. Additionally, the model assumes that a pilot is responsible for completing all actions stipulated by a checklist. Thus, the model does not address the myriad of design, content, and use issues involved with automated checklists in which some or all of the steps of a checklist are completed by automation (such automated checklists are not currently used in civil aviation).

The model addresses three major aspects of emergency and abnormal aviation checklist design: 1) internal aspects such as format, layout, and wording, 2) external aspects such as the time criticality of a specific situation and human performance capabilities under stress, and 3) the degree to which a checklist meets the overall goal of guiding flight crew response to a situation (e.g., management of workload, communication and coordination with other parties, etc.). Each of these three aspects is described in more detail below.

Aspects that are Internal to Checklist Design. When developers consider “checklist design,” some of the “internal” aspects discussed below are what most often come to mind. Fourteen different but often inter-related “internal” features of checklist design have been identified and comprise this aspect of the model.

The first feature has to do with the physical properties and interface of the checklist or checklist system. Paper checklists are typically compiled in a manual referred to as the Quick Reference Handbook (QRH). The physical properties and interface of paper checklists and QRHs include such things as size, weight, type of materials used, ability for the QRH to be held in one hand (or not), as well as section divider pages, tabs, and similar features which pilots use to "operate" the QRH. Electronic checklists are typically presented on either a hand-held or laptop computer (sometimes as a part of an electronic flight bag) or are presented on a flight deck multi-function display unit. Touch pads, touch screens, computer mice, dedicated buttons (both hard and soft), and keyboards are the typical methods by which pilots interact with electronic checklist systems.

Organization and access pertain to how the pilots find their way to a desired checklist and how quickly and easily this can occur. Clearly, the physical properties and interface methods of an electronic checklist system or QRH will influence access, but so too will the kind, number, and organization of indexes, tables of content or checklist menus, and even the titles given to checklists. Some electronic checklists are linked to the aircraft caution and warning system and to various aircraft components through a system of sensors. Thus, when a particular alert is displayed, its related checklist is queued or displayed automatically, allowing very quick access indeed.

Another internal aspect of checklist design pertains to typography and use of symbology. Typography is probably the single checklist design feature that has been addressed the most often by the human factors community (Burian, 2004; Degani, 1992). Font size and type, boldface, italics and other such features of typography have direct relevance on the readability and legibility of checklists, particularly in low visibility situations such as when smoke is in the cockpit. Some checklists also include various symbols, such as stop signs to signify the end of a checklist. The degree to which these symbols are intuitive and conspicuous are important considerations related to their use.

Checklist layout, format, and display also strongly influence the usability and readability of checklists. Some checklist developers do not pay enough attention to the visual look of the checklist and the arrangement of items on the page, or use enough "white space" resulting in paper checklists that are hard to read and difficult to follow (Burian, 2005).

There are a multitude of other issues concerning the layout, format, and display of electronic checklists, many of which involve the overall ways in which the checklists function and the ways that crews are to complete items and navigate through the displays. One of the most important issues has to do with the size of the electronic display space, which affects the number of lines of text that can be shown at one time. Typically, electronic displays allow for far fewer lines of text to be shown on a screen than can be shown on a single page of a paper checklist. Thus, even short paper checklists become multiple "page" electronic checklists and designers must decide the best ways for crews to access all of the items within a single checklist, such as through scrolling or paging conventions.

Checklist length and workload are especially important emergency and abnormal checklist design features. Checklist length pertains to both the physical length of a checklist and the amount of time it takes to read checklist information and complete checklist actions (i.e., the "timing" length or duration). The evaluation of a checklist's workload requires a consideration of not only the physical effort involved in completing actions but also the cognitive complexity and mental effort required. The workload of an abnormal or emergency checklist cannot be evaluated in isolation, however. The workload and task demands related to various phases of flight where the checklist may be used must also be considered.

Many emergency and abnormal checklists are written with separate sets of steps to be completed depending upon the specifics of the situation being faced. Likewise, it is not uncommon for crews to be directed in one checklist to additional checklists or other information, such as aircraft performance tables, when responding to a single malfunction. Thus, navigation, progression and jumping refer to movement within checklists and between checklists and other types of information. They pertain to the number of these "jumps" required and the ability of crews to easily work through a checklist and locate the set of items, additional checklists, or other material needing to be accessed.

The navigation of electronic checklists also involves the functionality of the electronic checklist system as a whole. For example, when an item on an electronic checklist is completed, it might be replaced on the display with the next item to be accomplished or, conversely, a "current item box" might move from the completed item to the next item for accomplishment. The decision to use scrolling vs. paging conventions on electronic checklist displays also affects how crews navigate through electronic checklists.

Nomenclature and abbreviations involves the exact terms and labels used as well as the kind and number of abbreviations employed within checklists. Language, grammar, and wording pertain to verb tense, the use of active or passive voice, reading difficulty level, degree to which actions are compulsory (i.e., "must" versus "may") and even whether a checklist is written in English or in a different language.

Checklist designers must also consider the purpose of a checklist, or sets of items within a checklist. Some checklists or, sets of items, are intended to fix a particular malfunction and restore a system to its normal operating condition. Another purpose might be to stabilize a malfunction and allow continued operation in an altered state. Designers must be clear about the intent of the checklist or sets of items within a checklist to ensure the checklist is as clear and logical as possible.

Whereas checklist purpose pertains to the intent of checklist actions relative to the status of aircraft system functioning, checklist item objectives pertain to the goal of each type of item within a checklist relative to communicating with and guiding the crew members who are completing the checklist. Twenty-five (25) different types of emergency and abnormal checklist items and elements have been identified (Burian, 2005) and they fulfill different objectives or fulfill similar objectives in different ways. For example, in paper checklists there are three types of items or elements that help to meet the objective of ensuring that the correct checklist has been accessed by the crew: 1) checklist titles, 2) condition statements or descriptions, and 3) reproductions of illuminated lights or alert messages. Checklist designers must be clear about their objectives throughout the checklist to make sure that the proper types of checklist items or elements have been used in its construction.

Determining the proper level of detail to include within checklists has always been a dilemma for checklist developers. Cognitive limitations experienced by humans when dealing with stress, concurrent task demands, and time pressure (e.g., decreased working memory capacity) underlie many of the errors made by crews when responding to emergencies (Dismukes, Berman, and Loukopoulos, 2006). Including more information in checklists can reduce memory load and other cognitive demands. However, the more information included in a checklist, the longer it becomes and the more time needed to complete it.

A checklist's engineering completeness pertains to whether all the necessary steps are included in the checklist and whether the steps included are, in fact, the correct actions to take. Closely related to engineering completeness is engineering coherence, which refers to whether or not checklist actions are presented in the correct order from the "perspective" of the aircraft and aircraft systems. For example, if a desired system response requires that action A is accomplished before action B, does step A appear before step B in the checklist? Engineering coherence also pertains to the temporal "spacing" of items on the checklist, again related to aircraft and aircraft systems requirements. If it takes an aircraft system 10 seconds to finish the action initiated by step A, and the action in step B must not be initiated prior to the completion of the step A action, does the checklist delay the crew from performing step B for at least 10 seconds after accomplishing step A?

The final internal aspect of checklist design is logical coherence. Just as engineering coherence pertains to checklist steps "making sense" to aircraft systems, logical coherence involves the degree to which checklist steps make sense to the pilots completing them. Several errors made by pilots during the accomplishment of checklists appear to be related to the confusing nature of some checklists and specific checklist actions (e.g., Burian, 2004). The logical coherence of a checklist can only be evaluated by examining the items within a checklist relative to each other.

Aspects that are External to Checklists and Procedures. The second major set of design features comprising the emergency and abnormal checklist model involves aspects that are "external" to the checklists themselves. Like the 14 internal design features described above, the following seven sets of external factors must also be considered and should influence the design and content of emergency and abnormal checklists.

One set of external considerations affecting checklist design pertains to the specific aspects of emergency or abnormal situations themselves. Emergency and abnormal situations vary in terms of degree of threat and level of time criticality, as well as the extent to which they are novel, ambiguous, and complex. For example, flight crews can typically handle excessive engine bleed air temperatures or pressures fairly easily and an emergency landing is generally not needed; including such landing guidance in the checklists for these conditions is unnecessary.

In addition to time criticality and situation complexity, checklist designers should also anticipate the amount of increase in workload a situation might cause for a crew. Similarly, situations such as an in-flight fire might cause the cascading loss of other systems. Workload and the probability of related, multiple, or cascading failures must be considered and should influence not only the length of checklists but also the guidance given to the crews about how to respond. For example, guidance to perform an emergency landing should be given early in in-flight fire checklists so that a descent can be initiated before the crew becomes incapacitated or control of the aircraft is lost.

Checklists should also be designed to conform with air carrier standard operating procedures (SOPs) and aviation regulations. However, crews should be reminded in checklists that SOPs and regulations can and should be violated to the extent necessary if the safety of the aircraft and crew warrants doing so in an emergency. In 1996, the first officer of a DC10 began to slow to an airspeed of 250 knots to comply with regulations requiring 250 knots or less below an altitude of 10,000 feet. The captain on this flight urged the first officer to "keep the speed up," violating this regulation, because they had an uncontrollable cargo fire on board and were performing an emergency descent and landing (National Transportation Safety Board (NTSB), 1998).

Other operational requirements, such as those related to different phases of flight, dealing with adverse weather (including icing conditions), and flying over mountainous terrain or oceans, comprise another set of external checklist design factors influencing emergency and abnormal checklist design. The failure of an engine during flight has different implications for the crew when the aircraft is at cruise altitude over the Rocky Mountains as compared to when the aircraft is at cruise altitude over Kansas. Both kinds of implications need to be accounted for in the checklist for this condition. Similarly, pilots have encountered difficulties when checklists they were to use in response to a hydraulic failure were written for such failures in flight rather than when the hydraulics failed while the aircraft was taxiing on the ground (Aviation Safety Reporting System, 2001). Checklist designers need to make sure that actions are included in a checklist for all phases of flight during which the checklist might be needed.

Human performance capabilities and limitations under high workload and stress are often not fully considered by designers when developing emergency and abnormal checklists. High workload and stress have negative effects on a human's ability to hold and manipulate information in working memory, perform mental calculations, and to shift mental sets when performing different tasks concurrently (Burian, Barshi, & Dismukes, 2005). And yet, it is not uncommon to find checklists that require crews to perform multiple steps from memory and to mentally perform complex mathematical calculations in response to system malfunctions (Burian, 2005).

Furthermore, when under stress, humans have a natural tendency to fixate on cues that are associated with a particular threat, such as a fuel gage with a rapidly decreasing quantity indicated. This fixation or tunneling can cause crews to miss other cues and information that has importance for their emergency or abnormal situation, and to lose perspective on the status of the overall situation, i.e., situation awareness (Burian, Barshi, & Dismukes, 2005). Checklist designers can accommodate this normal human behavior by including items within checklists that remind crews of information they may not easily recall and other cues they should attend to as they respond to a particular situation.

In multi-crew cockpits there are a variety of <u>social and cultural influences on crew performance, behavior and checklist usage</u>. This is certainly true under normal operating conditions but also during emergency and abnormal situations, even if only one crew member accomplishes all of the checklists. It is not uncommon for two crew members who do not share the same native language or culture to share the cockpit. In these circumstances, cultural or language barriers may interfere with good crew communication and coordination necessary for emergency situation response. Crew members who do not speak English fluently may have difficulty understanding some of the guidance or information printed in checklists and checklist designers must be particularly cognizant of this when writing checklist items.

Checklist developers also need to consider the number of crew members who will be involved in accomplishing checklist items. One crew member may complete emergency and abnormal checklists without the input or involvement of any other crew members. On the other hand, one crew member may be primarily responsible for checklist accomplishment but another may monitor or even be fully engaged in assisting with checklist completion. In three-person cockpits, it is not uncommon for two or even all three crew members to be involved in the completion of steps within emergency and abnormal checklists. When it is necessary for more than one crew member to be involved in accomplishing a checklist action, checklists should specifically identify the titles or role of those crew members (e.g., pilot flying) and note the level of their required involvement (Burian, 2004).

It should go without saying that <u>aircraft systems requirements</u> will significantly influence the content of emergency and abnormal checklists. Through a failure modes and effects analysis (FMEA) engineers and pilots determine the ways in which a system might fail and the actions necessary to either return the system to a normal operating state or to stabilize it and allow for its operation in an alternate mode. Additional information about how various actions should be performed and any operating limitations that exist are also identified for inclusion in checklists.

There are other issues related to the aircraft and aircraft systems that also should be considered when developing emergency and abnormal checklists, however. The relationship of the checklists to the aircraft caution and warning system may influence the titles of emergency and abnormal checklists and may even influence how the checklists may be accessed. Malfunction cues that may be ambiguous or misleading warrant the inclusion of extra information in checklists to assist flight crews in making a differential diagnosis to ensure that they complete the correct checklist for their situation. Similarly, checklists for conditions that are known to have a high rate of false warnings (e.g., some types of smoke detectors) should include procedures for determining the reliability of the alert.

Checklists should also include guidance as to the proper level of automation for crews to use in response to some types of emergency and abnormal situations. This information is particularly important for inclusion in checklists for flight control problems. Automation can be confusing for crews to use even under normal operating conditions (Sarter & Woods, 1995); it can even be more confusing when aircraft systems are operating in degraded states.

The final set of external checklist design factors pertains to the various <u>philosophies and policies</u> held by those who develop these checklists, <u>flight crew training</u>, and <u>economic constraints</u>. For example, one US air carrier has adopted the "get in-stay in" philosophy regarding emergency and abnormal checklist use. This means that all information the crew might need to see a situation through to its completion is included with or integrated into a single emergency checklist. All normal checklists for descent, approach, and landing, aircraft performance data, and any steps from other emergency and abnormal checklists that would be needed are presented to the crew in one location. The checklists of most other US air carriers may require a good deal of jumping between multiple emergency and abnormal checklists, normal checklists, aircraft performance data, and even other manuals.

The errors that flight crews make while flying on the line or during training can influence the design and content of emergency checklists, too—for both good and bad. Errors can highlight checklist items that are confusing, incorrect, or missing. However, it is easy for checklists to become bloated as they are chocked full of items intended to keep crews from making any conceivable error, no matter how remote the possibility, or to provide a basis for protecting an air carrier from liability in the event that an accident occurs.

Economic constraints can affect the design and use of checklists in a variety of ways. For example, the use of color in printed checklists may be limited and carriers may decide not to switch from paper-based checklists to electronic checklist systems because of the initial expense. Financial constraints may also limit the number of individuals available to develop, edit, validate, and publish checklists, which can have an adverse affect on the consistency and presentation of the final checklist products.

Although space limitations preclude a more complete exploration of each of these external aspects, what may already be apparent is that they are not only inter-related to some degree with each other, but are also inter-related with many of the "internal" aspects described above (see, for example, the description of checklist level of detail as it relates to human performance capabilities and limitations).

Overall Purpose of Emergency and Abnormal Checklists. The final major aspect of emergency and abnormal checklist design that comprises the model pertains to the degree to which a checklist serves its overall purpose: to guide and direct flight crew response to an emergency or abnormal situation. For example, does a checklist assist crews to manage and distribute workload, maintain awareness of the overall situation, make appropriate decisions accordingly, and facilitate communication and coordination with other parties such as ATC and cabin crew? Checklist actions should also be evaluated regarding the degree to which they are consistent with and complement any checklists or procedures used by cabin crews when responding to the same emergency or abnormal situation.

Discussion

What should be apparent, even in such a brief introduction to this model of emergency and abnormal checklist design, content, and use, is that there are a significant number of issues representing a wide range of topics that need to be considered when developing emergency and abnormal checklists for flight crews. The fact that so many factors are inter-related and that tradeoffs between some will be required makes the task of developing these checklists all the more daunting. However, developing a comprehensive model that identifies and explores all aspects of emergency and abnormal checklist design only fulfills one of the goals for this work. A handbook currently in development (Burian, 2006) also presents a thorough discussion of design tradeoffs as well as best practices and guidelines to assist checklist developers, instructors, pilots, and regulators when developing and evaluating emergency and abnormal checklists to ensure that they are the most effective tools possible.

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