Critical Documentation Design:

A Survey of Considerations for the Next Generation of Procedures Used in High-Risk Organizations

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CERTIFICATE OF APPROVAL

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ABSTRACT

Since the innovation of the pre-flight cockpit checklist first made Boeing's B-17 safe to fly, several high-risk industries have adopted the approach, to varying degrees. This paper reviews regulatory findings and recommendations from formal investigations following incidents across multiple high-risk industries to identify areas how checklists may be misused, misunderstood, or where they could have been of value to operators who didn't use them. The recommendations are then compared against current findings in information design and usability, and conclude with recommendations for how the future of electronic documentation may further improve the usability experience of operators and their teams, and ensure the safety of the public around them.

Keywords: information design, electronic interface, UI, interface design, checklist, procedure, aviation, maritime, oil and gas, hazardous materials, high-risk, regulatory review

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INTRODUCTION

As the presentation of safety-critical technical procedures changes from print to electronic formats, what best practices should be revisited or even newly defined?

ICAO's State of Global Aviation Safety report from 2019 states that "... the digital transformation of the aviation system must be guided to ensure that it generates ever higher levels of global interoperability and safety. To address this challenge it is necessary to go back to fundamental principles."

The concept of the pre-flight checklist was initially developed by Boeing after the 1935 crash of their Model 299 plane threatened to prevent them from obtaining a deal to supply the US military (Higgins, 2016). It was so successful in mitigating safety risks in dangerous environments that the concept of pre-flight checklists and structured operational procedures would be adopted by other groups within the aviation industry as well as other high-risk industries such as nuclear, military, and medicine.

Following a series of fatal aviation incidents in the 1970s, there was an abundance of focused research on the development of and human factors effects on safety procedures, which yielded the critical innovation of Crew Resource Management (CRM).

In recent years, much of the investigation around the drafting and implementation of operating procedures for high-risk environments seems to have disappeared, as though the lack of high-profile incidents lead us to believe that safety is a solved problem.

A NASA-contracted report (Degani, 1992) on best practices for typographical displays of cockpit documentation noted that there has been little focus given to the presentation of technical information in nuclear, maritime, flight-deck, and more high-risk environments. In its final note, the report predicted that visual recognition issues, under-examined in paper materials, would continue to go under-examined in digital counterparts.

Those digital counterparts have been so far slow to materialize, and there is an opportunity to thoughtfully assess what a digital version of normal and emergency procedure documentation should look like.

In this paper I will review previous research that has been conducted into technical procedure drafting and adoption, especially safety-driven innovations pioneered by aviation and high-risk industries. I will identify areas where historical work, much of it completed in the 70's and 80's and assuming paper or hard-copy procedures, needs to be reviewed and revisited in the context of modern electronic formats

I will review documented incidents in which checklists and procedures were deemed significant, and summarize current considerations in checklist applications derived from those incidents.

I will also identify areas deserving of additional investigation given advancements in information design and in screen-based displays. Electronic procedural documentation displays have the potential for dynamic information presentation. This paper will identify opportunities for improvements in procedural information, and touch on human-centered design considerations for electronic organization and findability of complex documents.

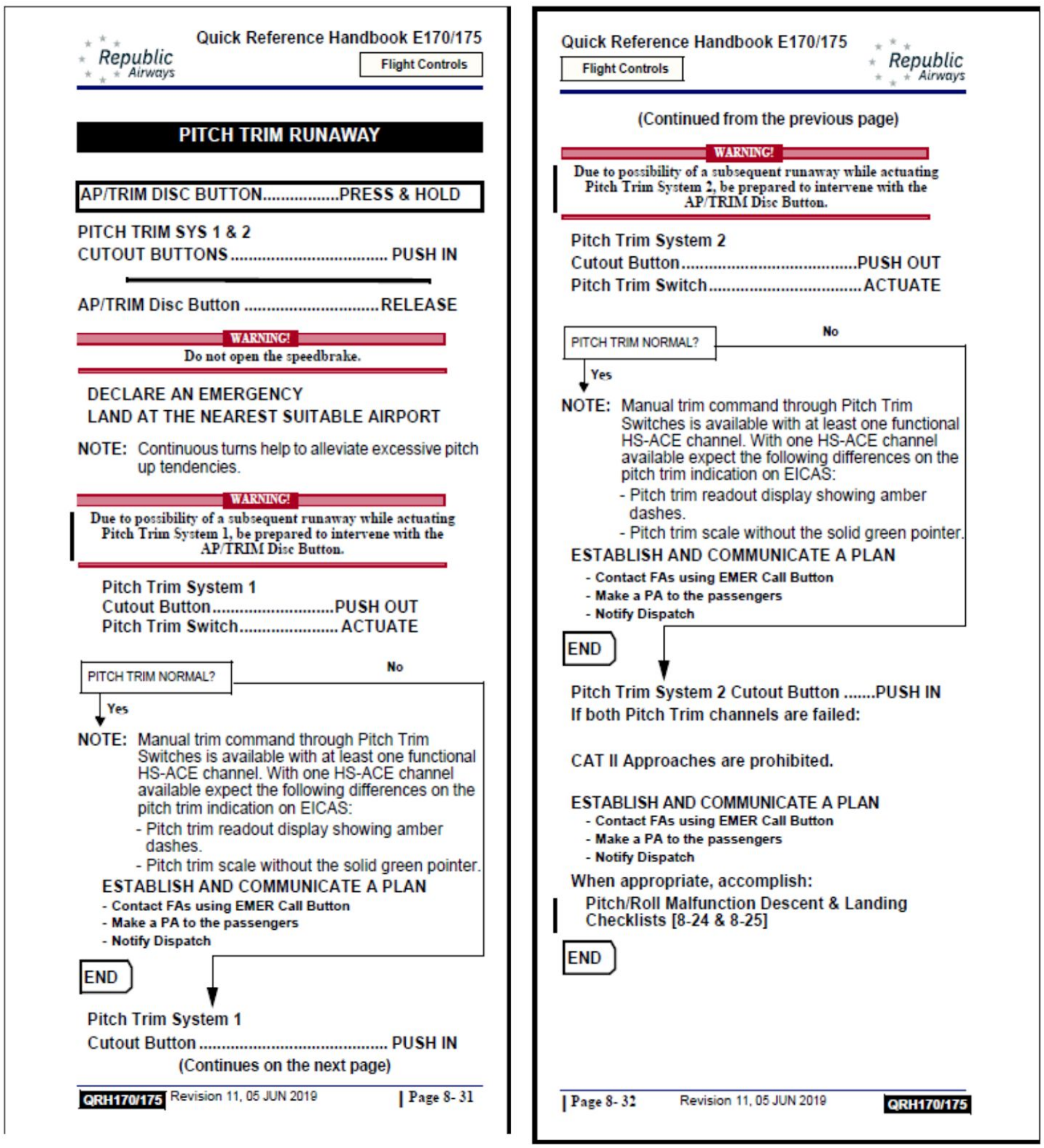
The paper will not explore considerations for documentation in languages that use an alphabet other than the Roman alphabet.

EXISTING WORK

Boeing's innovation of the pre-flight checklist helped to overcome the stigma associated with their Model 299 plane (eventually renamed the B-17) after a demonstration flight led to the death of two crew members in 1935. The checklist went on to and to ensure that the human crew who would be operating such a complex device could do so safely. The success of the checklist in ensuring safety of the crew and the plane led to the wide adoption of the checklist across the aviation industry and it has since expanded into other high-risk fields such as medicine and nuclear operation. Formal procedures and documentation such as checklists are now widely used across high-risk industries such as aviation, nuclear, medical, and maritime in which a process failure may yield catastrophic results for worker, asset, or consumer.

The precise design of checklists is not consistent, even within an industry, as equipment manufacturers or business entities may develop their own. Example checklists for aviation and healthcare:

Figure 1. An aviation checklist designed for Republic Airways operations.



Republic Airways
Quick Reference Handbook E170/175
Flight Controls

PITCH TRIM RUNAWAY

AP/TRIM DISC BUTTON................PRESS & HOLD

PITCH TRIM SYS 1 & 2
CUTOUT BUTTONS.................................. PUSH IN

AP/TRIM Disc Button ....RELEASE

WARNING!
Do not open the speedbrake.

DECLARE AN EMERGENCY
LAND AT THE NEAREST SUITABLE AIRPORT

NOTE: Continuous turns help to alleviate excessive pitch up tendencies.

WARNING!
Due to possibility of a subsequent runaway while actuating Pitch Trim System 1, be prepared to intervene with the AP/TRIM Disc Button.

Pitch Trim System 1
Cutout Button...........................PUSH OUT
Pitch Trim Switch......................ACTUATE

PITCH TRIM NORMAL?
No
Yes

NOTE: Manual trim command through Pitch Trim Switches is available with at least one functional HS-ACE channel. With one HS-ACE channel available expect the following differences on the pitch trim indication on EICAS:
- Pitch trim readout display showing amber dashes.
- Pitch trim scale without the solid green pointer.

ESTABLISH AND COMMUNICATE A PLAN
- Contact FAs using EMER Call Button
- Make a PA to the passengers
- Notify Dispatch

END

Pitch Trim System 1
Cutout Button... PUSH IN
(Continues on the next page)

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Quick Reference Handbook E170/175
Flight Controls
Republic Airways

(Continued from the previous page)

WARNING!
Due to possibility of a subsequent runaway while actuating Pitch Trim System 2, be prepared to intervene with the AP/TRIM Disc Button.

Pitch Trim System 2
Cutout Button.....................................PUSH OUT
Pitch Trim Switch.................................ACTUATE

PITCH TRIM NORMAL?
No
Yes

NOTE: Manual trim command through Pitch Trim Switches is available with at least one functional HS-ACE channel. With one HS-ACE channel available expect the following differences on the pitch trim indication on EICAS:
- Pitch trim readout display showing amber dashes.
- Pitch trim scale without the solid green pointer.

ESTABLISH AND COMMUNICATE A PLAN
- Contact FAs using EMER Call Button
- Make a PA to the passengers
- Notify Dispatch

END

Pitch Trim System 2 Cutout Button ....PUSH IN
If both Pitch Trim channels are failed:

CAT II Approaches are prohibited.

ESTABLISH AND COMMUNICATE A PLAN
- Contact FAs using EMER Call Button
- Make a PA to the passengers
- Notify Dispatch

When appropriate, accomplish:
Pitch/Roll Malfunction Descent & Landing Checklists [8-24 & 8-25]

END

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Figure 2. The Surgical Safety Checklist developed by the World Health Organization (WHO).

Surgical Safety Checklist

World Health Organization | Patient Safety

Before induction of anaesthesia

(with at least nurse and anaesthetist)

Has the patient confirmed his/her identity, site, procedure, and consent?
- ☐ Yes

Is the site marked?
- ☐ Yes
- ☐ Not applicable

Is the anaesthesia machine and medication check complete?
- ☐ Yes

Is the pulse oximeter on the patient and functioning?
- ☐ Yes

Does the patient have a:

Known allergy?
- ☐ No
- ☐ Yes

Difficult airway or aspiration risk?
- ☐ No
- ☐ Yes, and equipment/assistance available

Risk of >500ml blood loss (7ml/kg in children)?
- ☐ No
- ☐ Yes, and two IVs/central access and fluids planned

Before skin incision

(with nurse, anaesthetist and surgeon)

- ☐ **Confirm all team members have introduced themselves by name and role.**
- ☐ **Confirm the patient's name, procedure, and where the incision will be made.**

Has antibiotic prophylaxis been given within the last 60 minutes?
- ☐ Yes
- ☐ Not applicable

Anticipated Critical Events

To Surgeon:
- ☐ What are the critical or non-routine steps?
- ☐ How long will the case take?
- ☐ What is the anticipated blood loss?

To Anaesthetist:
- ☐ Are there any patient-specific concerns?

To Nursing Team:
- ☐ Has sterility (including indicator results) been confirmed?
- ☐ Are there equipment issues or any concerns?

Is essential imaging displayed?
- ☐ Yes
- ☐ Not applicable

Before patient leaves operating room

(with nurse, anaesthetist and surgeon)

Nurse Verbally Confirms:
- ☐ The name of the procedure
- ☐ Completion of instrument, sponge and needle counts
- ☐ Specimen labelling (read specimen labels aloud, including patient name)
- ☐ Whether there are any equipment problems to be addressed

To Surgeon, Anaesthetist and Nurse:
- ☐ What are the key concerns for recovery and management of this patient?

This checklist is not intended to be comprehensive. Additions and modifications to fit local practice are encouraged. Revised 1 / 2009 © WHO, 2009

Ensuring Procedures are Used

Despite the observed benefits of following structured documentation, it has been noted that even paper procedures are not always followed by the human operators. When things go well, deviation from procedures can go unnoticed and unresolved; when there is a documented incident or accident, these deviations become apparent (Degani, 1998).

A survey of 91 turbojet hull-loss accidents indicate that a significant cause of one-third these cases was crew deviation from operational procedures (Lautman and Gallimore, 1998). In nuclear, the process of following procedures have been described by operators as 99% boredom and 1% panic, and it has been noted that "[o]perators do not feel that procedures aid their performance; rather they feel that procedures are a cumbersome irritation" (Zach, 1980). Recent research has identified that despite the consequences of work in high-risk industries and the abilities of written procedures to provide support, challenges of perceived usefulness to a workforce who may be experienced in a simple, repetitive procedure, and the logistical and physical challenges of using procedures around personal protective equipment (PPE) hamper their use (Sasangohar, 2018).

Much research has been performed on how to ensure optimal adoption of procedures. This research includes in the years since, including human factors which lead to instances where the person or people following the procedure might not complete the procedure, or might not complete it correctly. This research has often informed the structure and implementation protocols of technical procedures, as operating under an incorrectly-completed procedure may be no different than operating with no procedure at all, as in the Model 299 crash.

The readability of the procedures themselves has not been such an object of curiosity. An existing NASA report offers a set of recommended best practices for typography, including fonts, color, imagery, and information organization (Degani, 1992), but noted a lack of specific research in the area.

The bulk of previous research has centered around paper documentation. Previous recommendations to avoid dot matrix printing and to use anti-glare lamination are dated, and unlikely to remain relevant.

As studies have indicated there are differences between optimal characteristics for print-based and screen-based design, a logical question is what readability differences exist between print and electronic procedures. Given the range of electronic formats available to deliver information (phone, tablet, computer, wearables, custom devices), it is important to recognize the variety of ways information may be formatted when it reaches a viewer, and to establish some best practices for design.

Human and Cognitive Factors

A summary of accidents at Los Alamos National Laboratory supported a strong correlation between the improper use of procedures and the events themselves, and describes that there may be hundreds of unsafe conditions underlying every incident or accident (Frostenson, 1995). In 2009, the US Department of Energy (Shah, 2018) published in its Human Performance Handbook that about 80% of all events could be attributed to human error, and 20% to equipment failure. The majority of the human errors “stem from latent organizational weaknesses” (Silverman, 2009).

Causal factors leading to checklists that weren’t used or were used incorrectly include the expertise of the user, complexity of the task, and frequency of the task (Williams, 2017), checklists that took too long to use and did not appear to offer a benefit thanks to duplicating of steps, appearing unrelated to the organization asked to use them, or asking people to coordinate the work differently to fit a checklist (Fourcade, et al, 2011). Checklists work most effectively when designed specifically for individuals or a team who is to use them, so that each user has a part and is a contributor (Higgins & Boorman, 2016).

Social science research has flourished in the last several decades, spurred by Tversky and Kahneman’s 1974 seminal research which identified instances where human beings consistently demonstrate judgment that goes against logic and probability. The work has been extrapolated to the fields of attention and effort, as presented in summative reporting on situational awareness assembled by Guy, et al, in 2000 and mode awareness (Andre & Degani, 1997).

Cognitive biases can impact even a seemingly straightforward task if the instructional text frames an action as positive or negative. The framing effect (Tversky & Kahneman, 1981) is a cognitive shortcut that leads people given the same task people to act differently depending on the paradigm assigned to the task, and suggests that the way that the task is presented can be important to its outcome. Prospect theory has shown to impact the decision making of engineers (Siefert, 2011) and human operators who are interacting with a machine (de Souza, et al, 2016).

Crafting Checklists

Not all tasks should be given checklists, but checklists are a tool that’s short and to the point, made to support a reliable safety culture, made by the organization that expects to use it (Thomassen, 2011). Development of a checklist is ideally performed by developing content and format, reviewing timing of the task and the checklist content, beta testing, iterating, and (if a checklist has been developed by a large organization for a small team) local modification (Weiser, et al, 2010).

Basic information about a checklist should be clear and visible to avoid confusion, particularly in case of emergency. A good practice would be to name an emergency checklist with the same name as seen on an associated warning light (Burian 2004). The title should be clear and accurate, page headers / footers should include the procedure title and revision information, page numbers should clearly indicate when a final page has been reached, and if a procedure is temporary there should be an expiration date clearly noted (Brune & Weinstein, 1981).

Checklists should be drafted with a clear understanding of who the individual using it will be; a single checklist should be written for a single user (Brune & Weinstein, 1981). Elements of checklist such as imperative action verbs may have specific, easily recognizable treatment (Weiringa & Farkas, 1991).

Procedure language should be selected for clarity and consistency and (in the case of procedures which will be used by teams) must foster communication that's clearly understood. To that end action steps and the language that defines them are often restricted and specific. Operators stumble when a procedure task put to them is phrased in a way that doesn't fit their mental model of expected behaviors, when a task put to them is phrased in a way that doesn't make clear how to complete the task, and when a procedure task is phrased in the negative (Korean Atomic Energy Research Institute, 2005).

Experienced users of checklists who have experiences with numerous types of checklist designs have noted that the design must be adapted to surroundings including to expected noise, light conditions, and vibrations (Thomassen, 2011); a current example is that smoke and fire checklists should be crafted using a larger than normal font size to improve readability in low-vision conditions (Burian, 2004).

Attention to Visual Design

A NASA-contracted report on best practices for typographical displays of cockpit documentation (Degani, 1992) noted that there has been little focus given to the presentation of technical information in nuclear, maritime, flight-deck, and more high-risk environments.

Some additional investigation has been given to the design elements of the checklist, including Burian's reviews of incidents relating to formatting and layout: she notes that the layout of procedure elements should take into consideration whether elements may be missed: warnings embedded in a place that may be skipped, notes about a step placed too far away from the step to which they refer (Burian, 2004). Checklists that refer to another checklist should be reviewed to ensure that the correct title is used for the additional checklist, and a special format should be reserved for checklist titles, to avoid confusion about what is highlighted for emphasis and what is pointing the user to a new document (Burian 2004).

In its closing statement, Degani's 1992 report noted that a lack of attentiveness to the question of typography in paper documentation, which had been found to cause the 1987 crash of Continental Express Flight 962, would predict a lack of research into the visual presentation of electronic information. If elements of a checklist require input from another operator, they should be explicit in both formatting and language (Burian, 2004) to avoid a decision being made without enough information.

Designing For Dynamic Technologies

An obvious concern when turning from presenting information on a standard piece of paper at 8 ½" x 11" to an electronic screen is that the screen might have a variety of sizes and resolutions. Early research into presenting text on an electronic screen typically concluded that unlike quality print where serif shapes made for clear text, electronic screens should use sans serif fonts to overcome a lack of definition when it came to font presentation. Since the introduction of very high resolution technologies such as Apple's retina display devices, these early conclusions are out of date.

While skeumorphic design can be expected in an initial pass at electronic procedural documentation, resulting in something that looks like a paper checklist on a digital screen, the possibilities for the improvement in design of procedures are significant.

Thanks to SCADA and Internet of Things (IoT) integration, there is an opportunity for any electronic presentation of procedure information to display a summary of essential system information, and help trained users to more quickly diagnose a system condition that would not be obvious if the only reference an operator had was a checklist. Degani, et al. (2009) note that "although one may have access to considerable amounts of data … real knowledge can only be achieved when this data is relevant and well organized". They turn to an exploration of the sunburst chart to illustrate complex relationships between many systems, and admit that these are views that a well-trained professional can (with experience) quickly interpret. As systems evolve, an interface for finding specific checklists within a library may make use of visualization techniques that deal with 'document clusters' that apply visualization across themes or core content (Gan, 2014).

METHODOLOGY

As there has been little technical research performed on critical safety documentation design, two types of information were researched: safety-related information and information design research.

For this paper, the following eight (8) high-risk industries considered were: (i) agriculture, (ii) aviation, (iii) construction, (iv) health care, (v) maritime, (vi) nuclear, (vii) oil and gas, and (viii) military when looking at available safety-related information.

Safety-related information was acquired primarily through gray literature sources, and includes the results of formal investigations into incidents across high-risk areas. While the accuracy of self-reported information is unreliable, available self-reported data is included for identification of additional human-centered factors, per Degani's 1998 observation that not all deviations from procedure result in an incident.

A five-step process was used to review safety concerns and incident reports, including (i) database selection, (ii) identification of search terms, (iii) criteria for the exclusion of results, (iv) manual review of selected report data, (v) a comparison of incidents returned to remove duplicate results if encountered in multiple databases. Results were tracked in industry-specific tables, which kept at minimum an incident ID, date of the original event, summary of events, and link to associated report documentation; if the database included keyword search functionality, the keyword(s) which returned a specific entry were also noted.

Eight (8) databases were selected for a results search. These databases are government-hosted collections of either formally investigated or self-reported incidents, and cover a variety of high-risk fields.

The following databases were identified for investigation for this research:

Figure 3: Databases used for reviewing incidents and accidents in high-risk work.

Industry	Incident Resource	Keyword Search?	Records Returned	Total Records	Years
Agriculture	The fatalities database put together by National Institute of Occupational Safety and Health (NIOSH)'s Fatality Assessment and Control Evaluation (FACE)	Unavailable	N/A	451	1985 - 2020
Aviation	National Transportation Safety Board (NTSB) incident report database	Unavailable	N/A	508	1965 - 2019

	Aviation Safety Information Analysis and Sharing (ASIAS)'s World Aircraft Accident Summary database	Yes	21	607	1990 - 2016
	National Aeronautics and Space Administration (NASA)'s Aviation Safety Reporting System (ASRS)	Yes	716	Unknown	1975 - 2020
Construction	Occupational Safety and Health Administration (OSHA) accident search database	Yes	173	Unknown	2002 - 2019
HazMat Transport	National Transportation Safety Board (NTSB) incident report database	Unavailable	N/A	168	2002 - 2019
Maritime	National Transportation Safety Board (NTSB) incident report database	Unavailable	N/A	375	1974 - 2020
Pipeline	National Transportation Safety Board (NTSB) incident report database	Unavailable	N/A	142	1969 - 2020

No available readily-searchable databases were identified for the following high-risk industries: (i) health care, which uses pre-operative checklists before surgical procedures; (ii) military, which uses checklists for tasks such as before entering combat; (iii) nuclear, which works with checklists as part of regular plant operations.

Several databases had no keyword search functionality; in these cases, entries into the database were copied and a subset of incidents were examined.

For databases which had keyword searches, a set of keywords were used. The initial keyword searched was 'checklist' (and variant 'checklists'). If that failed to provide a significant return of results, second-tier keywords were attempted. Keywords that supplied results included 'procedure' and 'process'. 'Document', 'documentation', 'human factors', 'misheard', 'read', 'misread', and 'misunderstood' returned no results in any of the queries.

After the safety incidents were reviewed for root causes identified and/or safety recommendations made, they were categorized by type of issue. Where this research is primarily concerned with the visual design of procedural documentation, if an information design issue existed with another issue, the incident was classified as one driven by Design of Information, even if there were additional factors.

Figure 4: Categorization of incident types.

Category	**Types of incidents**
Design of Information	*Visual design; findability of information; intentions needed to be clarified*
Environmental Factors	*Environmental factors impacting the operators' ability to follow procedure*
Human Factors	*Operator elected to deviate from procedure that could reasonably have been followed*
Problem with Process / Procedure	*Formal procedure didn't exist, or was missing significant information*
Other	*Miscellaneous*

The type of causes identified above were then used to direct investigation into design considerations that could be at work. Root causes for the incidents were then posited to be impacted by one or more of the following types of issues: **document content design** such as typography, **presentation of the document** considerations such as material or layout, **human comprehension errors** such as recall-related issues. Finally, the **format** (digital or paper) of documentation was taken into consideration.

To determine potential document content design concerns that merit further research, Degani's 1994 recommendation for procedure design considerations was consulted. For information presentation considerations, Lidwell's text on universal principles in design was referenced. When human comprehension errors were identified, Don Norman's works on memory and human-centered design issues were referenced. For electronic interface challenges, Ruiz et al.'s summary of functional user design principles was used to identify areas of design that could be at work.

Once design considerations related to the safety incidents' root causes were identified, a second search of peer-reviewed journals was conducted, targeting the types of information design issues raised by the root cause analysis review. This mapping and resultant gaps were used to define a range of best practices readily available to procedure design currently, and to highlight opportunities for further research.

RESULTS

Safety Documentation

Incident investigation reporting could vary significantly across high-risk industries, even within the same overarching organizations. It was also observed that in incidents involving employees or private individuals, there were generally few conclusions drawn, and the typically brief report acted as a statement of record that an event had happened without delving into contributing factors. When an incident did or could have impacted the environment or members of the public, the incident report was more robust.

The type of information returned by one entity's investigations or data sets within a single high-risk industry was typically consistent with itself and was used to establish qualitative trends within a group of reports. Due to the lack of consistency in reporting across industries, no general conclusions could be drawn about high-risk incidents and the impact on the readability of procedural information.

Use of Checklists In High-Risk Industries

While the aviation industry pioneered and still uses checklists, not all of the high-risk industries examined appear to make use of them. Every industry with available incident reports to be examined had incident reports that described specifying procedures, training, or regulations that should be updated.

Figure 5: Industries with reports that were found to mention checklists.

Checklists frequently mentioned	**Checklists infrequently mentioned**	**Checklists not mentioned**
Aviation	Agriculture	Construction
	Pipeline	HazMat
		Maritime

Industries Where Checklists are Commonly Mentioned

Aviation incidents

Of the 21 incidents returned by keyword search in the ASIAS database, 100% were reviewed. 5 were removed from the research for relevancy.

Of the remaining cases:

- 10 of 16 (63%) of the results were due to human factors where checklist procedures were not followed correctly or were not performed,
- 5 of 16 (31%) of the results were due to a lack of available process / procedures, and
- 1 of 16 (6%) of the results were due to environmental factors though a procedure was correctly followed.

The NTSB reports tended to have recommendations and categorizations that identified multiple types of primary causes. This sample contained the only reports that identified design problems and lack of information delivered by a complex system to the user.

Of the 518 reports available in the NTSB database, 59 (11%) were reviewed. 11 of these were reviewed and removed as they were safety bulletins that either applied to an incident that was reported separately or there was no clear understanding of the investigation that had spawned it.

Of the incidents reviewed:

- 26 of 48 (54%) described Human Factors considerations such as fatigue, election not to use a checklist, decisions that go against pilot and crew training, etc.,
- 14 of 48 (29%) described incidents in which environmental or equipment factors played a role, such as birdstrike, instrument meteorological conditions, or equipment malfunction,
- 11 of 48 (23%) described incidents in which a proper procedure was unavailable or had not been created (“Process / Procedure”),
- 7 of 48 (15%) described incidents which described Other or Unknown causes, such as incidents where there was not enough information to make a decision, equipment owners being dishonest, or a hazard-culture which encouraged daredevil flying, and
- 4 of the 48 (8%) made mention of information design improvements that could help the user; these were all related to instrumentation or meteorological information available to operators.

Self-reported incidents: Following a keyword search of “Checklist” in the Summary field, the ASRS returned 716 results. Of those, 114 records (~16%) were reviewed, spanning the years 1988 - 2009. 52 of 114 (46%) indicated that checklists were used appropriately as a part of the incident, and were discarded from further review. This included checklists used in a way that solved a problem as well as uses that did not solve the problem.

Of the remaining cases:

- 28 of 62 (~43%) indicated that there was a distraction or an interruption of note while the checklist was being run, and considered “Environmental Factors”
- 13 of 62 (~21%) indicated that one or more checklists were altogether not used, or were not completed though they mentioned no external stimulus; these cases were considered “Human Factors”

The other ~34% of cases tended to describe “Design of Information” issues, leading to problems in comprehension of the information provided:

- 11 of 62 (~18%) described content or clarity issues within a checklist,

- 5 of 62 (~8%) described an incorrect checklist used due to issues identifying a correct checklist,
- 3 of 62 (~5%) described problems finding the correct checklist at all,
- 2 of 62 (~3%) described problems with the design and layout of the checklists,

When there was a distraction or an interruption noted, this was typically followed in one of two ways as part of the self-reported narrative: a pilot or first officer would lose their place or forget to finish the checklist and miss something critical that would impact the flight, or else the list itself was a distraction and they would not notice missing something happening simultaneously, such as the plane taxiing past where it was supposed to turn.

High-Risk Industries Where Checklists are Infrequently Mentioned

Agricultural incidents and the use of checklists

Out of 451 records from the NIOSH Fatality Assessment and Control Evaluation database, 52 records (11.3% of total entries) were examined, spanning the last eight (8) years. None of the incidents described checklists as being used.

A secondary finding in a significant number of agricultural fatalities was that individuals involved were working alone when the incident occurred. A common recommendation is the establishment of a process for checking in with others.

Of the cases reviewed, 88% of the incidents were assigned to "Problem with Process / Procedure", as workers were found to be using machinery and equipment in a way inconsistent with manufacturer's recommendations, or operating in an unsafe environment without proper protection and planning.

- 25 of 52 (48%) of fatalities involved large farm machinery or vehicular incidents,
- 9 of 52 (17%) of fatalities involved asphyxiation upon entering a confined space,
- 7 of 52 (13%) of fatalities involved electrocution or problems with small equipment, and
- 5 of 52 (10%) of fatalities were the result of work with trees and animals.

"Other" incidents not listed here included death by an unidentified cause, and death by improvised modification to equipment used.

Concerning checklists and the design of information specifically:

- 0 of 52 records indicated that checklists were already in practice.
- 0 of 52 records indicated that trouble with a checklist contributed to an incident.
- 2 of 52 (4%) recommended creating checklists to support safe practices, such as job hazard analysis and working with large machinery.

Pipeline incidents and the use of checklists

The NTSB results included Pipeline failures as tracked and investigated by the NTSB typically resulted from a complex confluence of issues such as engineering or construction flaws combined with incomplete or nonexistent procedures.

The database included 142 total records, including briefs and full reports; of the 44 records examined, 1 was preliminary, 1 was missing documentation, and 2 were briefs that would later be supplemented by full reports. 40 of 138 (29%) of records were reviewed.

Of the cases reviewed:

- 36 of 40 (90%) of incidents were related to the pipeline operators' nonexistent or incomplete procedures, though given the nature of the work there was a common secondary contributing factor of how the system was designed or constructed ("Process / Procedure"), and

- 4 of 40 (10%) of incidents were caused primarily by the incorrect construction or design, ("Human Factors").

Concerning checklists specifically:

- 6 of 40 (15%) records included mention of checklists
    - ⅔ of these were observations that checklists did not exist, and
    - ⅓ were that call center checklists existed but were not always used.

Industries Where Checklists are Not Mentioned

Construction

The OSHA database used contained reports that applied to employee deaths while on the job. These reports contained a statement of events, some information about the individual(s) injured, and fines levied against the employer. As it did not contain the more robust reporting seen in incidents that involve members of the public or the environment, reports did not typically contain information on any contributing factors, had few details in general, and offered no particular recommendations against future incidents.

Keywords "Process" and "Procedure" used in OSHA's database returned 173 incidents, 56 involving fatalities. 25 of 173 (~14% of total) OSHA records on construction incidents were reviewed, the incidents spanning 2018 and 2019. 12 of the 25 incidents reviewed included fatalities.

Of the cases reviewed:

- 14 of 25 (71%) involved a injury or death due to a fall or improper use of equipment ("Process / Procedure"),
- 10 of 25 (20%) involved the environment changing or equipment malfunction and causing injury or death ("Environmental Factors"), and
- 1 of 25 (4%) cause was unknown ("Other").

Concerning checklists specifically:

- 0 of 25 records mentioned checklists or the presentation of information.

Hazardous materials transport

40 of 40 (100%) incident report entries from the NTSB's database were reviewed for mention of checklists. Several entries were missing the report or lacking recommendations; these, as well as a preliminary and a summary entry, were discarded, resulting in 31 incident report entries.

Of the cases reviewed:

- 29 of 31 (94%) identified a need for improving transportation, maintenance, and loading / unloading processes or procedures, ("Process / Procedure")
- 1 of 31 (3%) had a finding of needing improved emergency response training, and ("Other")
- 1 of 31 (3%) involved a member of the public who didn't realize she was transporting a hazardous material ("Other").

Concerning checklists and the design of critical information specifically:

- 0 of 31 records mentioned checklists.
- 2 of 31 records mentioned improving the delivery of information and status of materials being carried, including clear and obvious instruction on how to prepare hazardous materials for transport, clear indication of the current contents of a tanker, and ensuring that information about a hazardous load would be readily visible even if a tanker was rolled over.

Maritime

49 of the NTSBs 470 (10%) incident reports were reviewed for this work. As written up, the majority of maritime incidents included root causes but did not include recommendations. The incidents described frequently were summarized as a series of multiple weaknesses leading to failure.

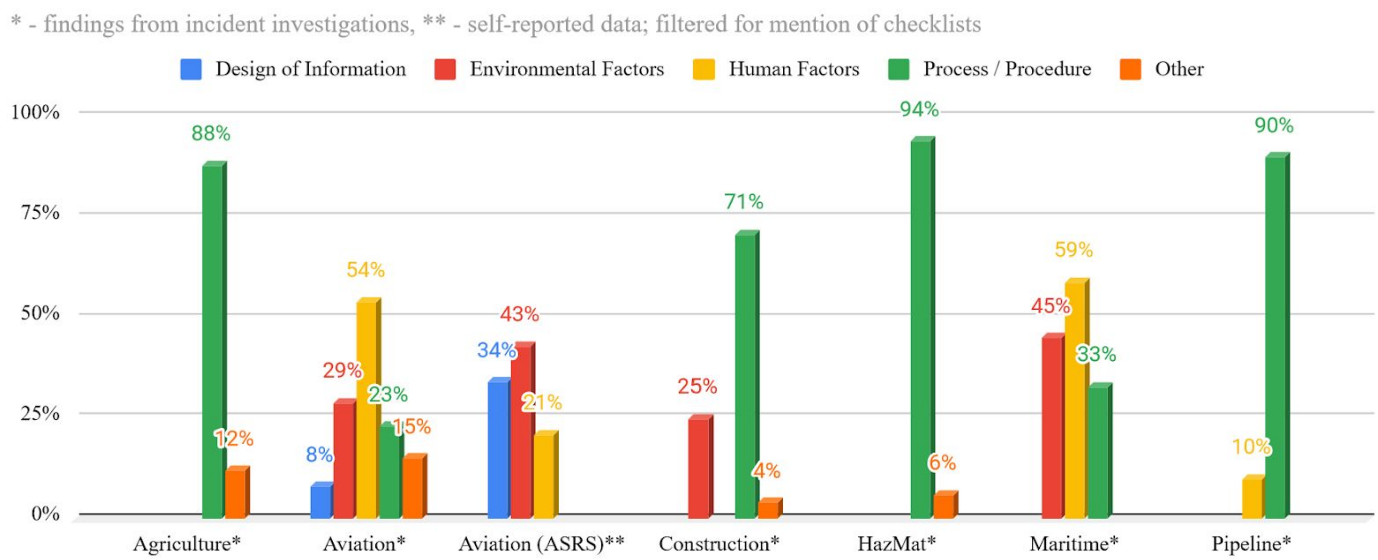
Of the cases reviewed:

- 29 of the 49 (59%) reports reviewed described Human Factors such fatigue, poor judgment, and a failure to follow known procedures,
- 22 of the 49 (45%) reports identified poor configuration of equipment, broken equipment, or environmental changes, and
- 16 of the 49 (33%) identified omissions in or lack of Process / Procedure, including but not limited to maintenance, safety, operations, and emergencies.

Concerning checklists and the design of critical information specifically:

- 1 of 49 incidents described a crane that impacted a bridge and noted that there was not enough information about the bridge readily available to make a good decision.

Figure 6: Types of Incidents, Categorized by Primary Contributing Factors



Incident Type Summary

When reviewing the causes of aviation industry incidents, the language used by both practitioners and regulators suggested consideration for the practical experience of the pilot and crew, including information received and whether it could reasonably be acted on.

Formal aviation and maritime incident reporting describes a complex interrelated series of events that were factors for incidents.

In agriculture and construction reports, where injuries and hazards were contained to a small group at a job site, the incidents often described a series of events rather than reviewed them for human factors or a flawed understanding of the work to be performed.

In hazardous materials transport and pipeline industries, engineering-centric industries whose incidents would impact the environment and members of the public in a failure, the recommendations often leaned heavily on process or procedure fixes. These regulatory agencies did not typically describe the actions or understanding of the individuals involved. Significantly in hazardous materials work, a large segment of the incidents reviewed happened during loading and unloading of materials where presumably direct human involvement is highest.

Checklist Format

None of the resources reviewed described a checklist either in electronic or analog form. Given the history of checklists and the issues described with findability, it is posited that the typical checklist in use today is a physical document.

Checklist Design Concerns

While the use of checklists was observed in aviation and pipeline incidents and recommended for use in agricultural, aviation, and pipeline remediation, the only database that was found to identify specific checklist design considerations was the ASRS self-report system.

Problematic checklist design can lead to a lack of awareness that a checklist has not been properly completed when (i) the **incorrect checklist was not recognized** and it was completed in place of the correct one, or (ii) a user can **lose their place or fail to complete a checklist** and not realize it.

Checklist design can offer challenges to a user when (iii) a correct checklist is hard to **confidently locate or identify**, and may not even be in a checklist but may be in a different format, (iv) individual call and response combinations are **hard to read,** or (v) a **series** of checklists is hard to follow.

Additional Information Design Concerns

Additional information design concerns identified by this research include:

High-consequence incidents can occur when **a system does not clearly advertise a status change** to the operator. This is a significant part of the results and feedback from investigations that grounded Boeing 737 fleets in the NTSB's ASR-19-01, but also has been cited in AAR-1401 and to a lesser extent AAR1701, where information about a depleted resource was not affirmatively conveyed to the pilot.

Important information about **a novel environment** not properly delivered to a worker in a high-risk position can lead to an incident. This includes accurately displaying the height of bridges and identifying appropriate highway venues for transport. While a worker may be able to operate their equipment well, any high-risk work that takes them into a new situation and changes the environment brings additional risk.

Immediate and clear information about high-risk work as **encountered by the public and by first responders**. This includes quickly and efficiently informing individuals about the existence, status, and handling of a hazardous material in their situation.

Electronic Design

Electronic Critical Documentation Design

An initial conversion from analog to electronic critical documentation will mimic the familiar view and structure of a paper checklist, to facilitate ease of transition between technologies. Some good typographical general guidelines previously identified for critical documentation (Degani, 1992) may be carried over, but consideration should be given to the presentation elements impacted by a self-illuminated screen as opposed to non-glare laminated paper.

Equally relevant as Degani's typographical guidance is early work on designing for the web, which pioneered new rules for presentation of information via electronic screens (Williams, 2000). Early research into text legibility on electronic screens did not have the benefit of the high-resolution screens readily available today. The early-2000's recommendation for sans serif font no longer applies now that retina displays accurately mimic the resolution of print and key serif cues can be properly rendered; instead, a font design that makes particular and telling distinctions between characters by height of vertical and width of letter, as well as one with a predictable level of contrast supports speed and ease of reading (Wilkins, 2020). Large fonts are already used for supporting low-visibility situations such as smoke (Burian 2006), and the ability to increase font sizes on demand should be included.

Concerning "light mode" and "dark mode" displays, light mode displays have been found to offer faster processing for at-a-glance reading among users with normal (or corrected-to-normal) vision while dark mode displays can help to overcome imparied vision (Dobres 2017). Due to vision requirements in the aviation industry it may be preferable to force the light mode format, but in the case of other industries it may be more practical to support both light and dark mode.

Since as of this writing screen real estate is not standardized, consideration should be given to how much text needs to be immediately available to a reader and use that to provide guidance on establishing standard hardware. Oquist and Goldstein's (2003) work into visualization of readable text on a small screen can be leveraged for checklists, given that checklist documentation is a condensed set of instructions.

Improved Electronic Critical Documentation Functionality

Electronic critical documentation also has the potential to overcome several of the usability issues observed in research with some basic interactivity and good practices in user interface design. As collated and summarized in Ruiz, et al's 2020 unification of usability:

The most-oft recommended principle of "Offer informative feedback" could help to address observed operation challenges such as systems that do not provide enough information, loss of place in a checklist, and "Design dialogs to yield closure" can also assist with failing to complete a procedure. This can be a simple matter of highlighting or marking a row in a checklist when it's complete, and providing a checklist complete status when the entire document is satisfied, or a more complex system integration with available SCADA functionality.

Given the issues seen commonly with executing a series of checklists, such as lack of clarity, the common design principles of "Simple and natural dialog", and "Provide a good conceptual model of the system" apply. Additionally, "Help the users recognize, diagnose, and recover from errors" is important. A visual representation of overall progress through a known series of checklists (list 2 of 3, eg.), will help to orient the user as to whether their current issues require attention beyond what's on this screen, and search functionality, hyperlinking, and breadcrumb tracks can help a user to quickly find what they are looking for and understand where they are.

During the flight, if a user is confused at a step, electronic documentation offers the ability to tag or mark the step to be flagged with the checklist subject matter experts, whether immediately or as part of a post flight sign out. This functionality supports "Iterative design to remove usability problems" and can help people to remember that something was unclear.

ADDITIONAL RESEARCH TOPICS

What hardware is suitable for electronic critical documentation in high risk industries?

When considering the logistical implementation of electronic critical documentation, it is likely that the documentation would need to be presented in a self-contained delivery mechanism, one that can withstand loss of power (aviation), is intrinsically safe in the event of ignitable vapors (pipeline and gas), water-resistant (maritime), and one which can optimally notify users of and receive updates during work but will also have a self-contained database of available information in the case of a loss of network. A device with hands-free functionality would permit its use while pilots are working to control a yoke, for example. The hardware must not be perceived as cumbersome to use - a device that feels unresponsive, can't be easily put down in the case of handheld mobile, is subject to problems with glare, or is unintuitive is a device that erects barriers to its use.

Evaluating the user experience of additional high-risk industries that use checklists

Additional high-risk industries which use checklists but were not examined as part of this research should be revisited: (i) similar to NASA and its ASRS, the Joint Commission receives self-reports from health care facilities regarding serious or sentinel events centered around patient care, (ii) the Nuclear Regulatory Commission (NRC) receives and summarizes daily nuclear incidents, and (iii) the US military, which uses checklists for a variety of operations such as pre-combat evaluation.

Based on the findings from the aviation industry's official and self-reports, it may be predicted that the formal incident assessment may not place much weight on the design of available information in an event. Additional qualitative research would benefit from access to self-reporting databases, or direct work with the individuals who are expected to use checklists as part of their jobs.

CONCLUSION

Across high-risk industries, where incidents can quickly lead to fatalities among the workers and members of the public, there are inconsistencies in how incidents are reviewed, analyzed, and to what degree recommendations are made to avoid future incidents. While some industry analysis acknowledges the human factors and usefulness of information elements in an incident, this awareness is not uniformly demonstrated in reports. While a failure to act in accordance with a written process or manufacturer's instructions is a common thread, there is little formally noted by industry regulators to evaluate whether the failure to act was because an individual was not properly aware of procedures or if they chose to take a shortcut.

Indeed incident analysis reports may not fully describe the element that readily available information plays even when those involve identify it as relevant, such as in the case of the US Navy deciding to replace its confusing touchscreen controls after fatal incidents including with the USS John McCain (BBC, 2019); the formal investigation in that case pointed to crew confusion and lack of coordination.

There is demonstrated interest from high-risk sectors in the creation and integration of critical operations procedures during routine and emergency work. While there was once significant investigation into procedure use in terms of human factors and information quality, there was not a lot of thought given to a critical review of the visual presentation. Additionally, perhaps given the lack of high-profile safety incidents, there is not much quantitative research from the last few decades.

Unfortunately, it's the last few decades that have seen the biggest transformations regarding the way that information is delivered to users. Hope is not lost, however, as other industries such as online sales, news, and advertising networks have worked heroically to better capture the electronic viewer's attention and communicate a message quickly and effectively. The new disciplines of UI / UX, the continued relevance of Don Norman's "The Design of Everyday Things", thoughtful consideration of human-automation interface design such as proposed by Hemann and Degani (2002), and similar human factors and usability-driven studies that directly address delivering electronic information to the operator can be leveraged to support high-risk, high-consequence procedure-based work, especially when regulators begin to examine incidents through the lens of human understanding, or a lack thereof.

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