Impact of Advanced Synoptics and Simplified Checklists during Aircraft Systems Failures

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***Abstract*—Natural human capacities are becoming increasingly mismatched to the enormous data volumes, processing capabilities, and decision speeds demanded in today's aviation environment. Increasingly Autonomous Systems (IAS) are uniquely suited to solve this problem. NASA is conducting research and development of IAS - hardware and software systems, utilizing machine learning algorithms, seamlessly integrated with humans whereby task performance of the combined system is significantly greater than the individual components. IAS offer the potential for significantly improved levels of performance and safety that are superior to either human or automation alone.**

A human-in-the-loop test was conducted in NASA Langley's Integration Flight Deck B-737-800 simulator to evaluate advanced synoptic pages with simplified interactive electronic checklists as an IAS for routine air carrier flight operations and in response to aircraft system failures. Twelve U.S. airline crews flew various normal and non-normal procedures and their actions and performance were recorded in response to failures. These data are fundamental to and critical for the design and development of future increasingly autonomous systems that can better support the human in the cockpit. Synoptic pages and electronic checklists significantly improved pilot responses to non-normal scenarios, but implementation of these aids and other intelligent assistants have barriers to implementation (e.g., certification cost) that must be overcome.

Keywords*—*flight crew error, aviation safety, synoptic displays, automation, automation surprise, unreliable airspeed, hydraulic systems failure

I. INTRODUCTION

It is known that natural human capacities are becoming increasingly mismatched to the enormous data volumes, processing capabilities, and decision speeds demanded in today's aviation environment [1]. Autonomy is uniquely suited to solve this problem where intelligent machines are seamlessly integrated with humans so that task performance of the combined system is significantly greater than the individual components. By creating human-autonomy teaming and associated technologies, levels of safety and performance above and beyond that provided by either one singularly can be achieved, especially during off-nominal events or in conditions where less experienced or knowledgeable operators are involved. If this approach to human-autonomy teaming successfully raises the level of safety and performance experienced in aviation today, then there should be an increase to the acceptance of autonomy and the implementation of autonomy systems in aviation.

The power and capabilities of machine learning algorithms, perception and sensing systems, and computing systems are increasing exponentially; however, the fundamental technologies and guidance for autonomous systems in aviation operations are missing. Under the Aviation Operations and Safety Program (AOSP), Safe Autonomous Systems Operations (SASO) project, NASA Langley Research Center (NASA LaRC) conducted development of Increasingly Autonomous Systems (IAS). IAS are hardware and software systems, utilizing machine learning algorithms, that have the responsibility to meet defined goals with little or no direction, but with appropriate levels of involvement, from a human. The research focused on autonomous concepts and technologies designed to replicate the performance of an expert pilot in monitoring, assessing, and decision-making functions that will, during nominal and off-nominal situations, continuously identify risk, and determine/prioritize actions needed to mitigate risk. NASA, through this work and others, intends to develop guidelines for the human-autonomy interfaces through which these autonomous concepts and technologies will communicate/interact with, and assist the pilot to safely accomplish the basic aviate, navigate, and communicate tasks in-flight. These technologies would support a crew especially when insufficient system knowledge, flight crew procedures, or

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NASA's Airspace Operations and Safety Program, Safe Autonomous Systems Operations Project.

understanding of the aircraft state decrease the pilot's ability to respond, especially in failure situations or situations for which standard operating procedures do not exist.

A simulation experiment was conducted to begin the development and validation of IAS concepts and technologies under nominal, off-nominal, and emergency conditions. This work was directed toward the identified National Research Council barrier [2] of "How can we assure that advanced IAS – especially those systems that rely on adaptive/nondeterministic software – will enhance rather than diminish the safety and reliability of the National Air Space (NAS)." The specific IAS concept tested was the use of advanced synoptic pages and simplified electronic checklists (ECLs) for pilot use during routine air carrier operations and in response to aircraft systems affected by a failure (e.g., loss of hydraulic system) or loss of flight critical data (e.g., reliable airspeed information).

II. BACKGROUND

The following background provides motivation for advanced synoptic and simplified ECL research as an IAS concept for a Boeing 737 and provides aircraft system description details only as necessary to understand the failures, hydraulic leak and blocked pitot tube, manipulated in this experiment.

A. *Boeing 737*

The Boeing 737 family of aircraft was first flown in 1967 and over 10,000 aircraft have been built. Three variants, 737 Classic, 737 Next Generation, and 737 Max, have been developed from the original 737 design. The 737-800 is from the Boeing 737 Next Generation series but systems and display configurations are not representative of current generation advanced aircraft like the Boeing 787 or the Airbus A350. For instance, the aircraft does not have integrated electronic checklists (ECLs) or system synoptic pages (i.e., graphical depiction of aircraft systems). The lower display unit is sometimes flown with nothing displayed or sometimes flown with a system status page shown. Checklists are typically displayed on a portable electronic device issued to each crew member (i.e., Electronic Flight Bag, EFB) and the quick reference handbook (QRH) is typically in paper form in the cockpit although some operators are using QRHs on their EFBs.

Hydraulic pressure at 3000 psi is normally provided by two systems, each with an engine-driven pump and an electric pump, and designated System A and System B. A standby system is provided with an electric pump for redundancy. The systems are designed in the event of a failure to load-shed, yet maintain sufficient functionality. Either Hydraulic System A or B can power all flight controls with no decrease in airplane controllability. System A also provides hydraulics for landing gear, ground spoilers, alternate brakes, Engine 1 thrust reverser, Autopilot A, normal nose wheel steering, and power transfer unit. System B provides hydraulics for leading edge flaps and slats, normal brakes, Engine 2 thrust reverser, Autopilot B, alternate nose wheel steering, landing gear transfer unit, autoslats, yaw damper, and trailing edge flaps. System A failures may require alternate gear extension and System B failures may require alternate flap extension. (The failure used for the experiment was a System B failure that required alternate flap extension. Alternate flap extension utilizes an electric motor and flap extension takes a much greater amount of time, requiring advanced planning for the approach and landing.)

The air data systems uses two air data modules to provide pitot and static pressure data to the air data inertial reference unit. An alternate pitot and static probe are used to drive standby instruments. The air data inertial reference system calculates airspeed, altitude, pitch, roll, heading, true airspeed, ground speed, and temperature among other parameters and provide that information to the display interface unit for display on the pilot forward displays. The display interface unit compares flight critical data and provides alerts to the pilot. If airspeed calculated from one system is different than the other system, an IAS DISAGREE message is displayed on both pilot primary flight displays (PFDs). (The failure used for this experiment was a blocked left pitot tube resulting in unreliable airspeed indications on the left PFD.)

B. *Automation Complexity*

Current generation advanced aircraft like the Boeing 787 or the Airbus A350 added design elements to improve the pilot's ability to handle system failures and their understanding of their impacts. Manufacturers have integrated checklists and provided synoptic pages that are helpful to pilots in troubleshooting failures. Integrated interactive ECLs are now standard on the latest aircraft and are even presented on the forward displays in some aircraft [3]. To create these capabilities, automation complexity has increased. These systems are also still dependent on sensor systems that may introduce unforeseen consequences when failures occur.

Data shows that complex system failures continue to challenge airline pilots, even in the latest generation of aircraft [4] [5]. When the status of an item can be verified by the system, the ECL step is automatically completed. Although checklists have been integrated and made interactive, the overall checklist design has not changed from the paper versions of the past. One issue with the current electronic checklist system is that it based on annunciated failures. If the failure is not annunciated, for example the unreliable airspeed due to a blocked pitot tube used in this experiment, the appropriate checklist is not immediately displayed and the crew is required to find the correct checklist manually. Even though many current aircraft in revenue service do not have integrated checklists, most airlines currently utilize portable electronic devices for checklists and reference information.

Synoptic pages were developed after the introduction of EICAS. The lack of synoptic information [6], [7], [8], [9], [10], [11] on older aircraft was identified as an issue, especially in working complex system failures where a failure presented multiple symptoms like electrical failures or engine failures. Synoptic pages were initially designed to represent systems controlled on the overhead panel [12]. In general, they show an electronic version of electro-mechanical legacy systems. These synoptic pages do not show flight critical data (e.g., airspeed, altitude, attitude, position). They are not required to be displayed but allow the crew to reference the synoptic while completing the checklist.

As electro-mechanical systems and engines have become more reliable, much of the pilot decision-making during troubleshooting has been reduced. Computer systems on the other hand have become exceeding complex. No information is currently available to help pilots in troubleshooting computer systems and the software connectivity generally hides all the information flow from the pilot [13].

C. *Unreliable Airspeed*

Modern aircraft design is predicated on systems providing redundancy and managing failure modes such that critical failures are eliminated. For many systems, this provides a good design decision and provides for automation and alerting to adequately help in diagnosing failures. Failure mode effects are analyzed [14] and any catastrophic failures are mitigated. This analysis identifies and eliminates common mode failures that cause multiple redundant systems to fail the same way.

The effectiveness of these systems can be negated by their dependency on mechanical sensors that creates an impact across all systems in the same way. The airspeed probes appear to be one such system. Failures due to maintenance [15], volcanic ash accumulation [16] and high altitude icing events [17] are just some ways where the system has not worked as designed, often with catastrophic consequences.

Experienced pilots gather information from multiple redundant sources to determine which conflicting information is correct. This experience was often gained from knowledge acquired during their early training with systems that are not as reliable as they are today. Without that knowledge, troubleshooting becomes more difficult. The situation is often aggravated due to proximity of turbulence and reduced visibility that contribute to the confusion of conflicting information. To address this problem, airlines and the FAA focused significant effort in recognition of unreliable airspeed [18], and manufacturers redesigned checklists by adding some of the knowledge steps that experienced pilots use. Studies [7] show that airline pilots still have significant confusion regarding airspeed failures.

Diagnosing airspeed failures continues to affect even the most modern aircraft [19]. System designers have only recently started using multiple sources of information when alerting pilots for air data issues. One manufacturer derives a synthetic airspeed and GPS-provided altitude for detected failures. Although blocked pitot tubes events are rare, the resulting erroneous or unreliable airspeed failure mode can be catastrophic. In a simulator session with two recently certified aircraft, the blocked pitot failure was shown to still present issues. Both aircraft systems use voted air data to present information to the pilot and the exact source is not shown to the pilot. Failure of one pitot probe does not produce any flight deck effect nor is the pilot informed of the failure in either aircraft system. Failure of the second pitot probe produced no flight deck effect in either aircraft system. One aircraft system provided an advisory message and the other aircraft system provided no information to the pilot. Failure of the third and final pitot probe in one aircraft system provided switching to a backup-calculated airspeed on the left primary flight display and a caution message to both pilots. The other aircraft system displayed a caution message that the only remaining correct system - the standby airspeed display - was failed and the automation continued to remain engaged and followed the incorrect information. If descending, the aircraft continued to add full power and continued to increase the actual speed of the aircraft past design limits. The behavior exhibited in the simulator is expected to reflect actual aircraft behavior since aircraft software is used in both. This is just a single example of how complex systems can be, even to an experienced design engineer who has days or weeks to evaluate a problem.

III. METHOD

An experiment was conducted to evaluate advanced synoptic pages with simplified checklists as an IAS concept to better support pilots during complex and time-sensitive air carrier flight operations. Twelve U.S. airline crews flew various normal and non-normal procedures and their actions and performance were recorded in response to failures. These data are fundamental to and critical for the design and development of future increasingly autonomous systems that can better support the human in the cockpit.

A. *Experiment Design*

The experiment used a between-subjects design to evaluate synoptic pages with simplified ECLs as an IAS for 737-800 aircraft during nominal and off nominal flight conditions. Each crew flew 3 runs, one nominal and two off nominal, for this experiment. The nominal run was a complete flight from takeoff to landing and was used as a baseline run for workload, crew resource management, and other subjective measures. The off-nominal runs flown resulted in either a left hydraulic systems failure or unreliable airspeed information for the left PFD.

Two display configurations were evaluated – a “baseline” with standard B-737 displays and interactive ECLs, and an “advanced technology” that incorporated advanced synoptic pages to the B-737 displays and used simplified interactive ECLs. Although the 737 aircraft design does not use interactive ECLs, this functionality was added for this study so that checklist usage was not an experimental variable.

The nominal run used the advanced technology display configuration and was always presented as the first flight. Each crew experienced both failures but only one failure with the baseline and one with the advanced synoptic pages with simplified ECLs. The baseline display configuration was always used for the second run and the advanced configuration for the third run. The off nominal runs were equally distributed among the crews, resulting in 6 crews having the hydraulic failure for run 2 and unreliable airspeed for run 3 and 6 crews having the unreliable airspeed for run 2 and hydraulic failure for run 3.

Both display configurations used standard 737-800 displays (PFDs, Navigation Displays, NDs, and EICAS) on the upper display units. They differed in what was displayed on the Systems page shown on the lower display unit (standard 737 systems or advanced synoptic) and the checklists (standard or simplified) displayed on the EFB.

The baseline display configuration used the standard 737-800 systems page on the lower display unit (Fig. 1) and standard checklists on the EFB.

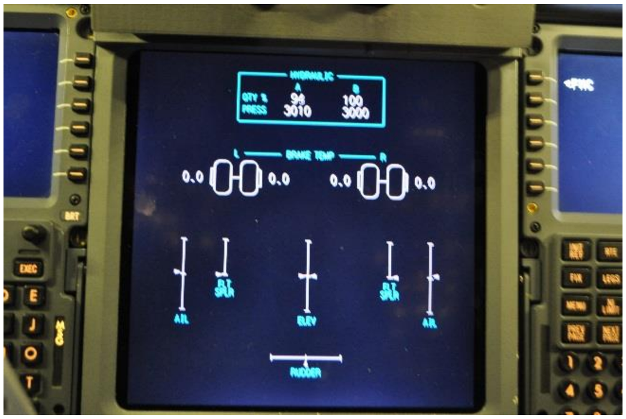

Figure 1. System Page on Lower Display Unit

The advanced technology display configuration used new and enhanced synoptic pages designed to work with simplified ECLs. Advanced synoptic pages provided graphical depiction of systems affected by a failure or loss of flight critical data. Checklists were simplified by removing notes that described in textual form which items were failed or degraded as they were now available on the synoptic. There was no loss of information as the pilot uses the synoptic page(s) and simplified checklist in conjunction with each other. Table lookup items such as minimum advisory landing distances based on runway condition were provided on the synoptic instead of requiring pilot lookup and interpolation of data in QRH tables; thus, saving valuable time to run a non-normal checklist. Fig. 2 shows the fuel synoptic page that was presented on the lower display unit when using the advanced synoptic design. Fig. 3 shows the fuel synoptic page when a hydraulic failure occurred. Note that the fuel synoptic remained and additional information was provided about the failure. The advanced display configuration used automatic switching of the synoptic displays during a failure. Fig. 4 shows the system interactive synoptic (SIS) on the lower display unit for any failure of flight critical data that was displayed on the normal pilot displays. This synoptic shows that the left PFD has unreliable airspeed information (due to the blocked pitot tube). The NASA-developed SIS supplements checklists by graphically providing information on flight critical data that would otherwise be communicated in text.

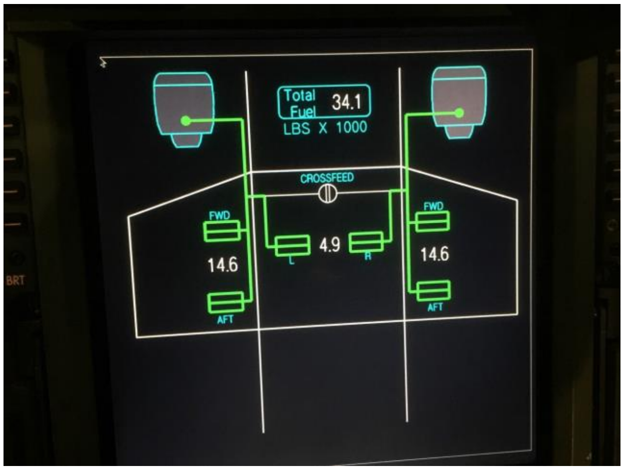

Figure 2. Fuel Synoptic Page on Lower Display Unit

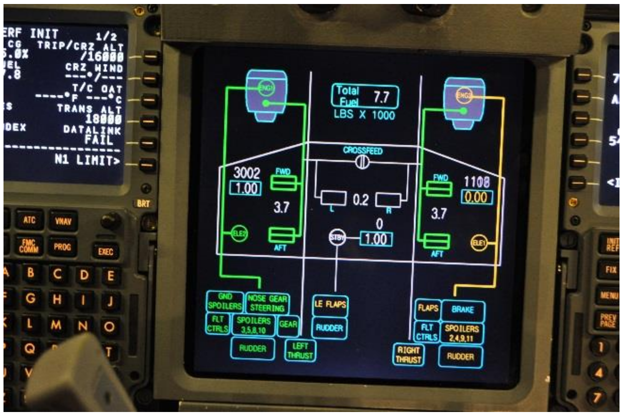

Figure 3. Fuel Synoptic Page with Hydraulic Failure Shown on Lower Display Unit

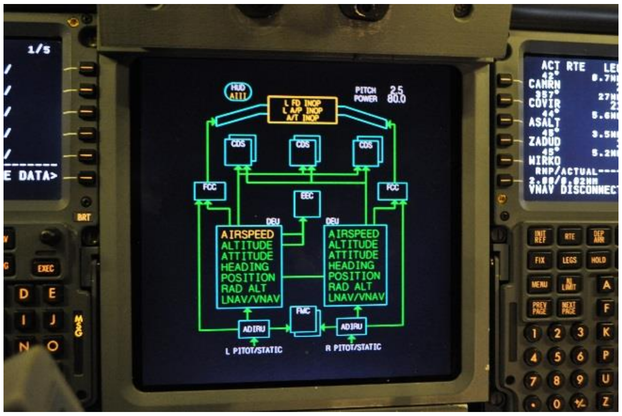

Figure 4. System Interactive Synoptic Page on Lower Display Unit

B. *Failures*

The hydraulic failure was modeled as a large leak, at a rate of 6 gallons per minute, in the System B reservoir. When the reservoir quantity dropped to less than 21.0% capacity, the System B hydraulics failure was annunciated to the flight crew through illumination of the: a) ENG 2 (engine-driven pump) and ELEC 1 (electric-motor-driven pump) LOW PRESSURE lights on the forward overhead hydraulic panel; and, b) Left and Right side MASTER CAUTION lights and HYD system annunciator light on the glare shield annunciation panel. Approximately 30 seconds later, the System B Flight Controls LOW PRESSURE light illuminated on the forward overhead flight control panel and the MASTER CAUTION lights and FLT system annunciator light illuminated on the glare shield. Additionally, if the B side autopilot was engaged, it automatically disconnected and the autopilot disconnect horn would sound. When the B side quantity was fully depleted, the temperature of the Electric Motor Driven Pump ramped from 200 degrees to 235 degrees over 2 minutes, causing the Hydraulic Pump OVERHEAT light to illuminate. The A side autopilot was still available after the failure. This failure renders the following items inoperative: Autopilot B, two flight spoilers on each wing, yaw damper, trailing edge flaps normal hydraulic system, leading edge flaps and slats normal hydraulic system, autobrake, normal brakes, engine 2 thrust reverser normal hydraulic pressure, and alternate nose wheel steering. This failure requires a FLAPS 15 landing and alternate flap extension. The time required to extend to flaps 15 is approximately 2 minutes with alternate flap extension method.

Unreliable airspeed indications were caused by a blocked pitot tube on the left side of the aircraft. The blockage occurred while climbing through 15,500 feet on the departure. The difference in the indicated airspeed value shown on the left PFD and the right PFD caused the IAS DISAGREE light to illuminate in approximately 10 seconds. The indicated airspeed on the left PFD increasing into the overspeed region caused an erroneous overspeed clacker warning which sounded continuously.

C. Apparatus

The experiment was conducted in the NASA Langley Research Center (LaRC) Integration Flight Deck (IFD) simulator, Fig. 5. The study was conducted in full motion with the IFD articulated on top of a hexapod hydraulic motion system. The IFD simulator cab is populated with flight instrumentation, including the overhead subsystem panels, to replicate a B-737-800. This facility incorporates fully functioning pilot controls with representative force feel and a stick shaker system, a flight management system, and 6 representative flight displays (2 PFDs, 2 NDs, EICAS display and lower system display). EFB displays are installed outboard on each pilot's side and were used to display interactive ECLs to the crew. A collimated out-the-window scene is produced by an Evans and Sutherland Image Generator graphics system providing approximately 200 degree horizontal by 40 degree vertical field-of-view at 26 pixels per degree.

Figure 5. Integration Flight Deck Simulator

D. Participants

Twenty-four pilots (12 crews), representing three airlines, participated in this experiment. Each pilot held an Airline Transport Pilot rating and was current in the 737-800 aircraft as either Captain or First Officer. Crews were paired from the same employer to minimize inter-crew conflicts in Standard Operating Procedures (SOPs) and Crew Resource Management (CRM) training. All participants were male, except for one female. The Captains' average age was 55 years with an average of 27,000 total flight hours and 2,800 flight hours in the 737-800. The First Officers' average age was 49 years with an average of 9.000 total flight hours and 1,700 flight hours flying as 737-800 First Officer.

Pilot flying (PF) and pilot monitoring (PM) roles were assigned based on the experimental matrix.

E. Training

Pilots were type rated and qualified in the B737-800 and the simulator was a faithful representation of the aircraft so no aircraft specific training was expected or received. An extensive briefing about the new technologies being evaluated was provided on the first morning, followed by a training session on how to utilize the synoptic pages and interactive ECLs. Since integrated ECLs and synoptic pages are not standard on the Boeing 737 aircraft, a familiarization run from takeoff to landing provided a further training opportunity and to re-enforce use of ECLs and synoptic pages for normal and non-normal electronic checklist usage..

F. Procedures

The route of flight flown by the pilots consisted of the DOCTR3 departure from the Ronald Reagan Washington National Airport (KDCA), proceeding enroute at 17,000 feet, then flying the CAMRN4 arrival into the John F Kennedy International Airport (KJFK), which connected to special RNP RNAV procedure for Runway 13 Left at JFK. The route duration was approximately 45 minutes.

The entire flight was flown as a baseline run from takeoff to landing to provide a basis and context for the non-normal or failure runs. The hydraulic failure started near top of descent on the CAMRN4 arrival. For the unreliable airspeed indication, the flight departed from KDCA on the DOCTR3 departure and unreliable airspeed indications were experienced in the climb.

Material representing some of the information provided by flight dispatch was given to the pilots, to include a detailed flight plan, weather forecasts, and applicable Notices to Airmen.

Normal aircraft flow was modeled for a portion of the eastern United States and the New York area. Scripted and computer generated Air Traffic Control (ATC) voice communications was provided for all modeled aircraft and frequencies, including normal communication with the experimental crew. Non-normal and emergency communications was provided by a staff member. Aircraft were landing on Runways 13 Left and 22 Left and departing Runway 13 Right at KJFK.

IV. RESULTS

This section provides detailed results that compared and contrasted electronic checklists with synoptic pages and simplified checklists while handling blocked pitot tube and hydraulic system failures.

A. Failure Handling

For the right hydraulic failure scenario, the leak began two minutes after the descent portion of the approach on the

CAMRN4 arrival started. Approximately 90 seconds later, the hydraulics failure was annunciated through the MASTER CAUTION lights to the flight crew. All twelve crews correctly identified the failure, declared an emergency, and coordinated with ATC as they deemed appropriate to handle the failure (enter holding, descend, vectors to final, etc.). An ATC communication error was observed for a crew using conventional ECLs without synoptic pages to handle the hydraulic failure. The crew mistakenly accepted a clearance ("DIRECT to COVIR") meant for another aircraft. ATC tried several times to get them back on course but crew did not acknowledge the error in their read-back of the clearance.

For the unreliable airspeed indications, indicated airspeed on the left PFD started increasing during the climb through 15,500 feet due to a blocked pitot tube. The difference between the left and right indicated airspeed values caused an IAS DISAGREE annunciation to be displayed on each PFD. The left indicated airspeed increased into the overspeed value. In response to the overspeed, the auto-throttle system reduced thrust causing a decrease in the aircraft's airspeed, which was correctly shown on the right PFD (the non-failed side). Seven of twelve crews declared an emergency, of which five had advanced synoptic information and two did not. The one crew with advanced synoptic information that did not declare an emergency was the only crew that descended in response to the erroneous overspeed warning and they subsequently experienced an actual overspeed event.

B. *Checklist Usage*

Time-to-complete the correct checklist was used as a metric for quick and proper troubleshooting of equipment problems. For the System B Hydraulic failure, it was an alerted failure with annunciation on the flight deck that had a direct entry in the QRH with the Loss of System B checklist. The time-to-complete metric for the Loss of System B checklist included time to execute all checklist items up to the deferred items in the Approach, Alternate Flap Extension, and Before Landing checklists.

As discussed, the checklist usage for Blocked Pitot Tube condition was problematic because the first annunciation, IAS DISAGREE, points to a checklist with the only action "Refer to the unreliable airspeed checklist", which required crews to manually find the Unreliable Airspeed checklist. Fig. 6 shows a box plot of the time to complete hydraulic system B checklist and Fig. 7 shows a box plot of the time to complete unreliable airspeed checklist.

Crews completed the Loss of System B checklist (up to deferred items) significantly earlier (F(1,10)=8.13, p=0.017) when using the advanced hydraulic synoptic with simplified checklists (Median, M = 4.7 min) compared to conventional ECLs without synoptic (M = 8.0 min). There were no crew errors when using the advanced hydraulic synoptic with simplified checklists during an hydraulic failure. However, one out of six crews made an error while using conventional ECLs without synoptic during a hydraulic failure. Specifically, the crew did not check the non-normal configuration landing distance table in the Advisory Information section of the Performance Inflight chapter.

Comparing checklist usage with and without advanced synoptic and simplified checklists, an ANOVA revealed significant differences for time-to-complete Unreliable Airspeed Checklist (F(1,10) = 8.81, p = 0.014). Crews completed this checklist significantly earlier when using the advanced synoptic page with simplified checklist (M = 2.5 min) compared to conventional ECLs without synoptic (M = 6.6 min).

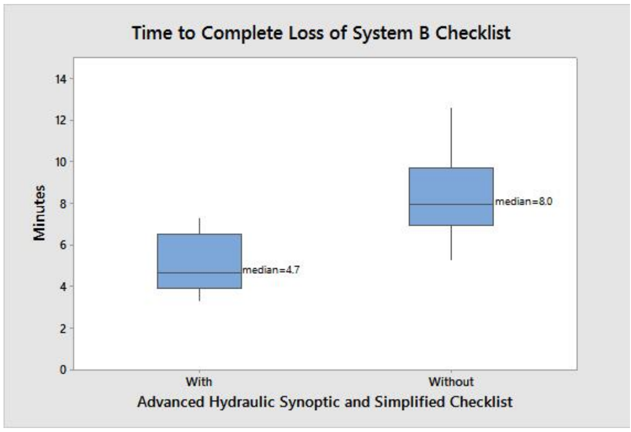

Figure 6. Time to Complete Hydraulic Checklist

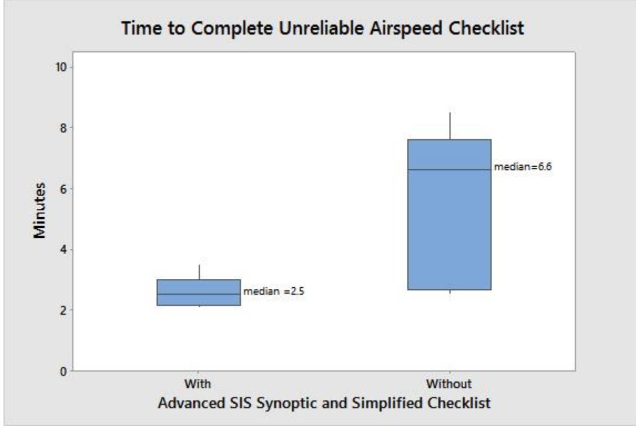

Figure 7. Time to Complete Unreliable Airspeed Checklist

C. *Workload, Perceived Safety of Flight and Crew Resource Management*

The NASA Task Load Index (TLX) captured a subjective rating (0 [Low] to 100 [High]) of perceived task load. There are six subscales of workload represented in the NASA TLX: mental demand, physical demand, temporal demand, performance, effort, and frustration level [20]. The overall score results of this measure were examined to investigate task load variation. Perceived safety of flight was self-assessed after each run using a seven point Likert scale with a rating of 1 being "completely unacceptable," a rating of 7 being "completely acceptable," and a rating of 4 being "neutral." Similarly, CRM Ratings for Shared Awareness of Situation were subjectively provided by the PF and PM after each run using a seven point

Likert scale with a rating of 1 being “strongly agree”, a rating of 7 being “strongly disagree”, and at rating of 4 being “neutral”.

Workload is shown in Fig. 8 for the hydraulic failure and Fig. 9 for the airspeed failure. For the hydraulic failure runs, pilots rated their overall workload as being moderate as reflected in the PF (median rating of 48) and PM (median rating of 39) TLX ratings. There were no significant PF or PM workload differences between the baseline and advanced synoptic with simplified ECL configurations. Workload for the unreliable airspeed runs was rated as being moderate for both PF and PM and there were no significant workload differences between the baseline and advanced synoptic with simplified ECL configurations.

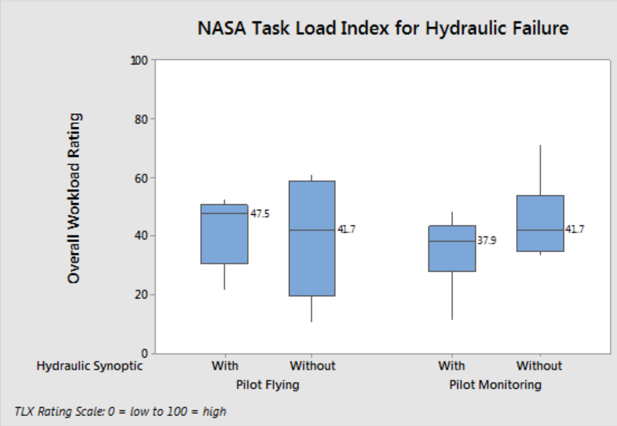

Figure 8. Workload Hydraulic Failure

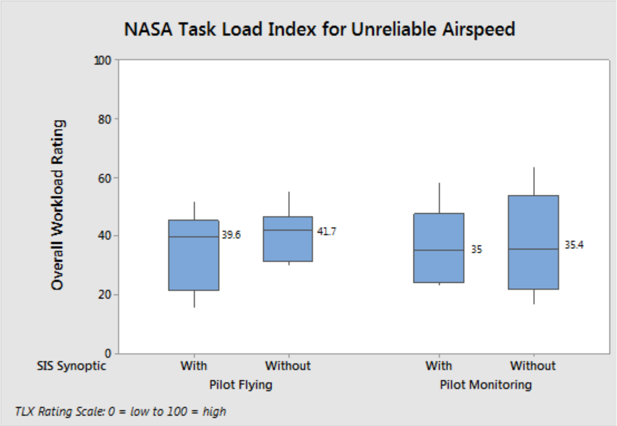

Figure 9. Workload Airspeed Failure

Visual inspection of the pilot subjective data revealed no significant perceived safety of flight ratings differences due to having a hydraulic synoptic (median safety rating of 6 for with and without synoptic). Pilots rated their perceived safety of flight as being acceptable (overall mean rating of 6.2) for the hydraulic failure runs. Likewise, visual inspection of the perceived safety of flight ratings for the unreliable airspeed runs showed no significant differences due to having SIS synoptic (median rating of 6 for with and without synoptic). Pilots rated their perceived safety of flight as being acceptable (overall mean rating of 5.9) for the unreliable airspeed runs.

CRM ratings for Shared Awareness showed a slight improvement for the PM for both the unreliable airspeed and hydraulic failure runs when the synoptic was present (median rating of 1 with synoptic and 2 without synoptic); however, no CRM differences were noted for the PF for either failure condition. Pilots agreed that they had a “shared awareness of situation” for the hydraulic failure (overall mean of 1.7) and unreliable airspeed runs (overall mean of 1.5).

D. System Usability Scores and Pilot Observations

The System Usability Scale (SUS) questionnaire [21] was used to gauge how pilots assessed the perceived usability of the interactive ECL and the advanced synoptic with simplified interactive ECL. SUS scores were calculated and could range from 0 to 100, but they were not percentile ranks. SUS scores can be associated with specific letter grades and adjective ratings [22]. A SUS score between 63 and 80.3 is considered a “good” design and a score above 80.3 is considered an “excellent” design.

Pilots, in general, found the design of the synoptic and simplified ECL to be an excellent pilot interface tool (Fig. 10, median SUS score of 90) for dealing with non-normal flight situations like a hydraulic failure or unreliable airspeed indications. Similarly, with a median SUS score of 80, pilots thought the interactive ECL design, even without synoptic pages, was a good one for dealing with non-normal events.

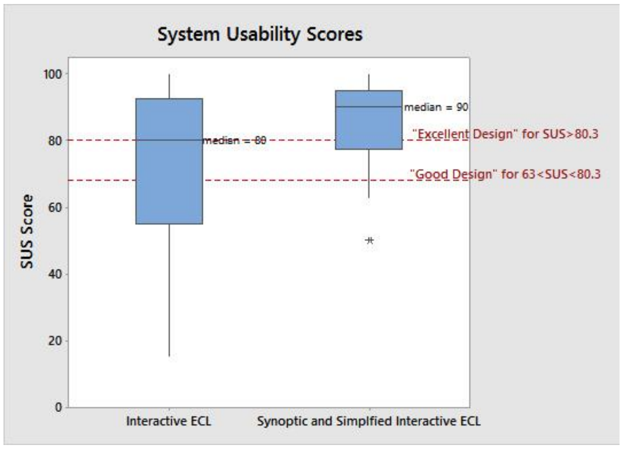

Figure 10. System Usability Scores

Pilot comments collected during post-test debriefings support these good to excellent design usability scores for interactive ECL and synoptic pages.

“Synoptic pages were very beneficial during a non-normal for the flying pilot. During the hydraulic system failure, I was able to clearly see which other systems had been affected and were no longer functioning. It speeded up the process of running through a non-normal checklist and I was more aware of what was/was not functioning.”

“Synoptic pages help us see what is actually functioning and being able to address it quicker. It increases our awareness of actual aircraft state.”

"In a non-normal, the combination of synoptic pages and interactive checklists decrease the pilot workload quite significantly. It allows us to focus on flying the airplane."

"Interactive checklists, I think would be beneficial in making sure a checklist item is not accidently omitted. They clearly show what has/has not been accomplished. They are more streamlined and decrease pilot workload especially in high-traffic, busy environments."

V. DISCUSSION

Troubleshooting strategies differed greatly between crews. Prior to initiating the checklist, some crews executed actions from memory while others contacted ATC. The crews that contacted ATC first tended to be interrupted more frequently while accomplishing the checklist, therefore took longer to finish the checklist. Crews that initiated memory items took longer to start the checklist. For instance, descending with unreliable airspeed indications before accomplishing the checklist masks the problem and often creates conflicting information. The crew that descended using the incorrect airspeed on the left PFD created an additional problem by actually overspeeding the aircraft while troubleshooting the issue.

The advanced synoptic pages and simplified ECLs support better and quicker decision making for the unreliable airspeed scenario with the training provided during the experiment. Typically crews would be provided more extensive training for new technology added to the flight deck. In this scenario, the fact that five of six crews declared an emergency with the advanced synoptic page when only two of six did for the standard ECL is significant. The one crew with synoptic page and simplified ECL that didn't declare an emergency descended before looking at the display or the checklists, significantly delaying the start of the checklist, and resulting in an aircraft overspeed. All crews, regardless of synoptic page or not, declared an emergency for the hydraulic failure scenario due to the need for alternate flap extension and expedited handling.

The time to complete the appropriate checklist was significantly reduced in both failures when crews were provided with advanced synoptic technology. Although no procedural steps were removed, the checklists were simplified by removing notes that described in textual form which items were failed or degraded. Instead, the items were depicted graphically on the synoptic page. This alone can result in significant reduction in the length of the checklists and has a number of added benefits, even when the entire checklist is only reduced by one page. Key checklist steps are often elevated to the first page of the checklist when notes are reduced. The airspeed checklist was reduced by a half and the hydraulic by one forth. The step to cross check airspeed indicators was elevated to the first page from the second page which quickly allows pilot to determine if a reliable airspeed indication is available. The synoptic page provides graphical information on which indicator has failed and provides known pitch and power settings for use in maintaining aircraft control while conducting the procedure instead of relying on table information that requires interpolation.

For the hydraulic checklist, the information to plan a flaps 15 landing, plan for alternate flap extensions and the non-normal landing configuration distance were elevated in the checklist and all the notes were depicted graphically on the synoptic page. The PF does not have to comprehend what the PM is reading and the information is available on the synoptic page throughout the rest of the flight and can be reviewed at any time. Some pilot comments were:

- "The picture depiction of the problem was absolutely awesome. The situation awareness and safety enhancements of such a system display make exponentially safer aviation environments."
- "Synoptic pages were very beneficial during a non-normal for the flying pilot. During the hydraulic system failure, I was able to clearly see which systems had been affected and were no longer functioning."

Most of the pilots were unfamiliar with interactive checklists since they had flown mainly the 737 aircraft. Some comments about the checklists in general were:

- "The interactive technology is great and I look forward to seeing it in the cockpit."
- "Interactive checklists, I think would be beneficial in making sure a checklist items is not accidently omitted."
- "Love the electronic checklists."

There were some deficiencies noted as well, especially with placement of the checklist on outboard EFB displays and the lack of dedicated checklist screens. Some of these have already been addressed in current aircraft as the checklists can be displayed on the forward displays in both the B-777 and B-787 aircraft as well as the A350. Some pilot comments were:

- "You should be able to switch between approach/arrival plate and checklist (normal) without exiting menus."
- "Another challenge I faced with the use of checklists had to do with the side window location of the electronic flight bag. Most current aircraft have them on the forward screens. When I was flying with the hydraulic issue and the Captain was reading the checklist, he was looking away from me when talking and the checklist was all the way across the cockpit."

VI. CONCLUSION AND FUTURE RESEARCH

Based on the pilot comments and the system usability measures where synoptic pages with simplified electronic checklists received high marks, this technology should be considered for all aircraft. Synoptic pages have been present in the industry for over 20 years but barriers remain for the widespread adoption. Certification costs remain high for aircraft systems but there are training and aircraft type rating issue to be considered as well.

A risk-based approach for certification is now in place for Part 23 aircraft, perhaps the same thing can be applied to Part 121 aircraft for secondary information like synoptic displays allowing reductions in certification costs. Training costs and a common type rating are often discussed as barriers when flight decks are upgraded like the B737-800 although synoptic pages were shown in this experiment to be easy to use and provided a safety benefit.

Synoptic pages are not required items, even in aircraft where the displays are part of the type certificate. They may be displayed and used with checklists but they are not required. If synoptic pages replace items on the checklist, they will now be required items with additional certification costs.

Modern cockpits with large landscape displays that can be segmented into multiple multifunction displays are capable of providing synoptic and checklist pages on the forward displays that would not interfere with the ND and would allow for charts and other items to reside on the electronic flight bags without switching back and forth. This will be further investigated.

Further study is needed to explore how far the integration of checklists and synoptic pages can proceed to provide the optimum mix of compactness and word reduction. The display used for the synoptic in this study was a combined system synoptic where the normal fuel page was augmented for failures. This implementation is different than separate synoptic pages utilized in certified systems and some pilots commented on the clutter and that the failure was not highlighted enough due to the normal elements remaining on the display. Methods to declutter displays need to be carefully evaluated.

Finally, the entire design of the Unreliable Airspeed checklist and pilot understanding of the checklist designers thought process shows some issues. Even after airline specific training in unreliable airspeed, pilots struggle in working the procedure. No guidance is given for allowing the aircraft to stabilize when changing pitch and power settings, or why they are given one set of numbers and then a short time later are given yet another set. The auto-throttle and autopilot are disconnected which requires the PF to manually fly aircraft and attempt to stabilize the airspeed while the crew conducts the checklist, a challenging task that has been shown to have problematic results. . Notes are provided in the checklist stating that the flight path vector symbol may not be valid, but there is only one small case where that is true and the symbol is a great help when trying to maintain aircraft control. Some airline specific procedures vary on this step as well. This issue also requires further thought and study.

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