Information Management to Mitigate Loss of Control Airline Accidents

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Loss of control inflight continues to be the leading contributor to airline accidents worldwide and unreliable airspeed has been a contributing factor in many of these accidents. Airlines and the FAA developed training programs for pilot recognition of these airspeed events and many checklists have been designed to help pilots troubleshoot. In addition, new aircraft designs incorporate features to detect and respond in such situations. NASA has been using unreliable airspeed events while conducting research recommended by the Commercial Aviation Safety Team. Even after significant industry focus on unreliable airspeed, research and other evidence shows that highly skilled and trained pilots can still be confused by the condition and there is a lack of understanding of what the associated checklist(s) attempts to uncover. Common mode failures of analog sensors designed for measuring airspeed continue to confound both humans and automation when determining which indicators are correct. This paper describes failures that have occurred in the past and where/how pilots may still struggle in determining reliable airspeed when confronted with conflicting information. Two latest generation aircraft architectures will be discussed and contrasted. This information will be used to describe why more sensors used in classic control theory will not solve the problem. Technology concepts are suggested for utilizing existing synoptic pages and a new synoptic page called System Interactive Synoptic (SIS). SIS details the flow of flight critical data through the avionics system and how it is used by the automation. This new synoptic page as well as existing synoptics can be designed to be used in concert with a simplified electronic checklist (sECL) to significantly reduce the time to configure the flight deck avionics in the event of a system or sensor failure.

I. Introduction

In the period 2010 to 2014, the Commercial Aviation Safety Team (CAST) sponsored a study of 18 commercial aviation events that occurred within ~10 years prior to the study kickoff. The results identified 12 recurring problem themes involving loss of airplane state awareness (ASA) by the flight crew and suggested a number of intervention strategies [1]. CAST assessed these strategies for effectiveness and feasibility, and recommended Safety Enhancements (SEs) for the industry to implement [2]. Of these, six were deemed to require research to enable the enhancement. As part of its role in CAST, NASA initiated subprojects within the Airspace Operations and Safety Program to collaborate with the industry and the FAA to produce many of these outputs.

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The Automation and Information Management Experiments (AIME) were a series of NASA experiments conducted to address or achieve outputs defined within SE-207 [3] and SE-208 [4]. Together, the technologies under development and evaluation as part of the AIME series were intended to enable improved energy, automation, and/or system state awareness, as well as to provide new predictive capabilities with respect to these aspects of ASA.

As specified by CAST, the success criteria for all technology development research under SE-207 and SE-208 were to advance the technology readiness level (TRL) to five or greater. For the AIME experiments, this criteria was interpreted to be met by:

(1) demonstration of the technology in a relevant environment and across a span of conditions such as those encountered in the events studied by CAST; and,
(2) assessment that the technology with a pilot interface was judged usable and acceptable.

Demonstrations were supported by data to show that the technology performed its intended function with no unexplainable behavior or unintended consequences. These goals were accomplished for the research reported here using high-fidelity full-mission flight simulations. In these environments, not only can typical crew procedures and workload be replicated, but complex off-nominal situations such as those encountered during accidents could also be simulated. The simulations afforded the opportunity to test across a number of crews with disparate experience levels, expertise, and behavior tendencies.

The first AIME study (AIME 1) was completed in 2016, advancing and evaluating four technology concepts: a new flight-critical data synoptic page (referred to as the System Interaction Synoptic, or SIS) with simplified electronic checklists (sECL), predictive alerting of energy-related (PAE) events and display, automation mode change prediction and display (referred to as the Trajectory Prediction System, or TPS), and dynamic maneuver envelope (ME) estimation and display [5-11].

Completed in May 2018, the second AIME study (AIME 2) investigated three ASA concepts: enhanced synoptic (eSyn) pages, including SIS, used in conjunction with sECL, an enhanced airspeed control indicator, and stall recovery guidance [12-16].

The third AIME study (AIME 2.5), completed in February 2019, evaluated enhancements to three previously tested ASA concepts: SIS with sECL, PAE, and TPS [17]. Two indicators aimed at supporting the flight crew's awareness of energy state during loss of airspeed events were also evaluated: a synthetic vision primary flight display augmented with a flight path vector, speed error, and an acceleration cue and an aural airspeed alert that triggers when current airspeed deviates beyond a specified threshold from the selected airspeed [18].

The subject of this paper is a summary and lessons-learned from iterative research and development using sECL in conjunction with new and existing eSyn pages 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). This paper presents findings derived from questionnaire responses and subjective data measures including workload, usability, and acceptability as well as objective measures of effectiveness/efficiency in completing checklists and their impact on crew decision making. Observations of checklist usage are described when the majority of the pilots deviated from checklist procedures due to lack of understanding of a particular step. Coincidentally, the series of AIME studies were conducted over a 4-year period during which airlines redesigned checklists and developed focused training for dealing with unreliable airspeed information. Observations are detailed from some before and after comparisons. Recommendations for checklist design, synoptic page development, and technology support for determining sensor validity are described.

One area of specific focus during AIME testing was on the sensing and detecting of unreliable airspeed information, what failures had occurred in the past, and where pilots may still struggle in determining reliable airspeed when confronted with conflicting information during actual flight operations. Architectures are described for sensing, processing, and distribution of airspeed information to both pilots and the automated systems. Technology concepts are presented including a new synoptic page called the System Interaction Synoptic (SIS) that details the flow of flight critical data through the avionics system and how it is used by the automation. A second area of synoptic research was studied during the AIME testing – enhancing existing synoptic pages by providing failures and effects of failed systems - to improve automation state awareness by the crew during non-normal flight events such as a hydraulic system failure. These eSyn pages are designed to be used with sECL with the intent to significantly reduce the time to configure the flight deck avionics in response to a failure [5, 6, 13, 14].

II. Background

A. Information Sources

Avionics systems provide information to pilots and automation components based on flight parameters that are sensed, stored, datalinked, or input by pilots themselves. Sensed parameters are often an analog signal coming from a mechanical sensor. In addition, the information may have a mechanical actuator associated with the sensor. Although these systems are more reliable than the first-generation sensors, they are still not as reliable as digital components and because they interact with a complex atmospheric environment, they can be damaged by environmental issues (e.g., rain and volcanic ash, or mechanical damage from bird strikes and rough handling during maintenance). Multiple sensors are typically utilized in large aircraft to provide redundancy as a degree of protection from erroneous sources of information.

Redundancy helps meet strict safety criteria but it is not perfect. The design must be shown to have no common mode failures or failures where the same failure is propagated across all the redundant components. In the case of some of the mechanical sensor components, this has not proven true in operation [19] because of behaviors never imagined by the system designer. For instance, an aircraft where a static air data sensor was taped over for maintenance while washing and the tape was never removed.

Dual sensors have now been replaced with systems that had three components and the most recent aircraft designs often have quad redundancy. Redundancy is not necessarily perfect or the solution to this problem. Redundant systems are designed to vote out one or more non-functioning systems. Nonetheless, even in the modern systems, some environmental conditions have affected all the mechanical sensors, often at the same time. High altitude super-cooled liquid has overwhelmed pitot systems and volcanic ash cloud has blanketed all systems at once. Although not highly probable, if the sensors fail in such a way as to report the same value, it is possible that a good sensor can be outvoted by two or more bad sensors. The closer the systems fail in the same time and conditions, the more likely that they will fail with the same value.

Because some sensors fail due to external conditions, the computational elements within the sensor system may report the calculated values as valid data and the information is not flagged as erroneous or invalid. The information is then processed in all the downstream systems and presented to the pilot as though the information is valid. Although the probability may go down with respect to a common mode failure, there are documented instances of all three angle-of-attack (AOA) vanes failing in flight with exactly the same value [20].

Highly skilled pilots can handle conflicting information by relying on holistic monitoring of all information available. For example, when presented with conflicting attitude information, they will typically check if the aircraft is changing heading or altitude. When presented with conflicting airspeed information, they will reference the aircraft attitude and power settings to see which airspeed makes more sense. This technique can be effective even if there is no redundant sensor for each piece of information. Some modern systems have used other available sensor data to provide backup information to pilots (e.g., airspeed calculated from AOA and altitude provided from the global positioning system, or GPS) and some research suggests similar ways to detect anomalous information, going beyond just the sensor value to determining the validity of data using aircraft models [21].

B. Unreliable Airspeed

As described previously, classical methods of redundancy and failure mitigation can become problematic in dealing with mechanical sensors. Unreliable airspeed, in particular, has been a leading cause of crew difficulty. Unreliable airspeed can lead to systemic failures that are difficult to understand, often manifesting themselves with both overspeed and stall warnings simultaneously, leaving no simple, effective troubleshooting method. This problem has been addressed in training [22], procedural and checklist design, and in hardware and software design mitigations.

Hardware and software mitigations have been employed on some newer aircraft designs. Sensor probes have been redesigned to be more reliable in a wider range of conditions. Sensor redundancy has been increased by multiple units and disparate placement on the aircraft. Processing has been used to compare and eliminate detected failures. These techniques can be effective but these systems are not immune to common mode failures in the mechanical sensor systems.

C. Automation Complexity

Mechanical system complexity in aircraft has given way to digital complexity where computers determine how to manage propulsion, electrical, hydraulic, environmental, and aircraft control. The digital systems are more reliable than the electro-mechanical systems they have replaced. This shift in what pilots can control has changed training as well. Memorization of all system components and a complete knowledge of how to operate the system has been replaced with strict checklist utilization and limited troubleshooting steps. Synoptic page design had been developed for the primary systems on the aircraft and has been updated to reflect the limited control for checklist verification, but limited information is available for pilots to determine the flow of information or what information is used in any of the automated systems. Digital flight decks were first designed so information was not shared side-to-side unless there was a specific pilot action. As sensor processing across multiple redundant systems increased in usage, this information was hidden from the pilot, and often the information management of sources was switched automatically without pilot knowledge.

With increased automation and systems reliability, many pilots can go an entire career without experiencing a failure. When failures do occur, the rarity may foster confusion, especially if the failure is complex. Although synoptic pages are available on some aircraft to help pilots to understand systems, there are limited synoptic or pictorial diagrams regarding the flow or interdependency of information derived from sensor processing or on the effects of failed systems. The lack of data/information flow representations led to the development of the technology and procedural concepts discussed in this paper.

D. Recent Accident and Incidents

Over a ten-year period from 1996 to 2006, 300 accidents cited incorrect instrument indications in the findings of the investigation report. These data support incorrect cockpit indications as a significant contributor to loss of control inflight (LOC-I) accidents worldwide and as part of CAST's work in counter-measures for the loss of airplane state awareness. This paper concentrates on anomalous air data information as a causal factor, and the following accidents and incidents are a small sample to illustrate the extent of the problem:

- On 21 November 2013, after a flight from Singapore, an Etihad Airways Airbus A330, A6-EYJ landed at Brisbane airport and was taxied to the terminal. Approximately 2 hours later, the aircraft was pushed-back from the gate for the return flight to Singapore. The captain rejected the initial take-off attempt after observing an airspeed indication failure on his display. The aircraft taxied back to the terminal where troubleshooting was carried out, before being released back into service. During the second take-off roll, the crew became aware of an airspeed discrepancy after the V_1 decision speed and the take-off was continued. Once airborne, the crew declared a MAYDAY and decided to return to Brisbane where an overweight landing was carried out. Engineering inspection after the overweight landing found that the Captain's pitot probe was almost totally obstructed by an insect nest, consistent with mud-dauber wasp residue. The pitot obstruction had occurred during the 2 hour period that the aircraft was on the ground at Brisbane and was not detected during troubleshooting after the initial rejected take-off.
- Air France Flight 447 – an Airbus A330 - crashed while enroute from Rio de Janeiro to Paris on June 1, 2009. While at altitude, the air data probes were likely overwhelmed by ice crystals or super cooled water droplets and the autopilot disconnected. The flight crew stalled the aircraft while attempting to troubleshoot the conflicting instrument indications amid erroneous stall indications.
- Qantas Flight 72 - an Airbus A330 - made an emergency landing on October 7, 2008 near Exmouth, Australia after a couple of uncommanded sudden pitch down maneuvers caused serious onboard injuries. An AOA sensor was determined to be the cause.
- XL German Airways Flight 888T – an Airbus A320 - crashed in the Mediterranean Sea off the French coast on November 27, 2008. The aircraft was involved in a maintenance flight when two of the three AOA sensors froze while at altitude. During the descent, one of the maneuvers the crew was checking was to observe the envelope protection system's operation to avoid a stall. The two bad (i.e., frozen) AOA sensors outvoted the good sensor and the aircraft stalled and the crew did not recover.
- Aero Peru Flight 603 – a Boeing 757 - crashed after maintenance failed to remove tape from the static ports. The crew was unable to determine correct airspeed information while flying at night.
- Brigenair Flight 310 – a Boeing 757 - was a charter flight from the Dominican Republic to Germany. The aircraft crashed shortly after takeoff on February 6, 1996 while the pilot struggled to determine correct airspeed information. The cause was determined to be a blocked pitot tube from an insect nest.
- In April 1991 the crew of a large corporate jet encountered anomalous airspeed indication on the Captain's instrument on the previous flight. The subsequent flight was at night and during climb out the First Officer's instruments appeared to increase to a high speed and the overspeed clacker warning sounded. After reducing power, the Captain's instrument showed a decrease in speed and because of the previous flight, the crew assumed the Captain's airspeed was the problem. The aircraft subsequently stalled and although disoriented, the crew eventually recovered and landed safely. Maintenance confirmed the First Officer's central air data computer had failed.

- Northwest Flight 6231 – a Boeing 727 - crashed near Buffalo, New York on a positioning flight shortly after takeoff. The National Transportation Safety Board determined the probable cause as the crew's inability to recognize the high AOA and low airspeed of the aircraft resulting in a stall that was unrecoverable. The pitot heat switch was found in the off position.

III. Technology Concepts

This paper details elements of the AIME experiments that addressed CAST safety enhancement, SE-208, Output 1b, which calls for "displays that show, in a simple, integrated manner (e.g. a synoptic), the aircraft flight-critical data systems in use by automated systems and primary flight instruments, for both the mode currently selected and any impending mode transitions expected per design of these systems" [4]. On some aircraft, a set of synoptic pages are available on Multi-Function Displays (MFDs) and each provides graphical and textual information regarding the status of major subsystems. For example, seven such pages are available for pilot selection on the B-787 including: Electrical, Hydraulic, Fuel, Air, Door, Gear, and Flight Controls. Although not yet available on many aircraft types, the synoptic concept is explicitly mentioned by CAST as recommended for consideration in SE-208 research.

The synoptic concept research conducted under the AIME series of experiments explored eSyn pages with associated sECL. The sECLs are versions of ECLs that have been shortened when used in conjunction with the eSyn pages without any loss of information. Two types of eSyn pages were evaluated:

(1) New synoptic pages for failures in which no relevant synoptics exist; and,
(2) Enhancements to existing synoptic pages (e.g., Hydraulic, Flight Controls) to depict and provide additional information regarding failures and effects of failed systems.

These enhancements may allow the simplification of associated electronic checklists by removing information now provided on the eSyn display and improve understanding of complicated system dependencies where reading of text could lead to confusion or oversight.

For some types of failures, there is no relevant existing synoptic. In these cases, a new synoptic page could be defined. The example used for this research was loss of flight critical data (e.g., airspeed) provided by the air data system and inertial reference units. A new eSyn page, referred to here as the SIS, was created that graphically depicted whether flight-critical data was valid, the operational state of the sources of the data, and the effects on systems that received the data.

Unique eSyn pages are associated with specific aircraft faults indicated by an EICAS message. The eSyn color scheme matches that of the other synoptic pages. Data or data paths shown in green indicate valid data, those shown in white indicate operable data but with reduced quality, and those in amber indicate invalid data. The eSyn is available to the flight crew as a quick-look reference regarding failures and their effects throughout the flight.

Associated with the EICAS notification and the eSyn page is a sECL. This shortened checklist is intended to be used with the eSyn to enable the pilot monitoring (PM) to complete the non-normal ECL in less time and with greater understanding of failure effects.

A. System Interaction Synoptic

The SIS is designed as an additional tab on the Synoptics display, with associated simplified checklists within the Electronic Checklist function. The original SIS indicators and functions are illustrated in Figures 1 and 2. The system components and architecture shown in Figure 1 represents the Research Flight Deck (RFD) at NASA LaRC (note: the system components are modeled after the Boeing 757-200 aircraft which is the RFD simulation model; this graphic would be different but a similar concept for the B-787, or other aircraft). The SIS was the first attempt to provide a synoptic page that showed the information flow of flight critical data that is used by the automation systems and for display to each pilot. Figure 1 shows the normal case where all the data flow is green, and the display and automation structure is shown by a cyan schematic.

Figure 2 represents the change to the SIS that would occur if there is a failure of the air data computer (ADC) system. Both ADC boxes are colored amber. The automation and pilot displays now use backup data from AOA and GPS where that data is represented by white flow lines. Note that the flight control system is in a secondary mode represented by an amber message and the flight director, autopilot, and autothrottle systems are inoperative, also represented by amber text and an amber box around the glareshield panel where those controls are located. Selecting the Electronic Flight Bag (EFB) symbol (Fig. 2) on the SIS would bring up the associated sECL on that EFB. The checklist was simplified by removing information now displayed on the SIS.

The SIS page and sECL were tested with other technologies in AIME 1 [5-11] and those results are detailed in Section V of this paper.

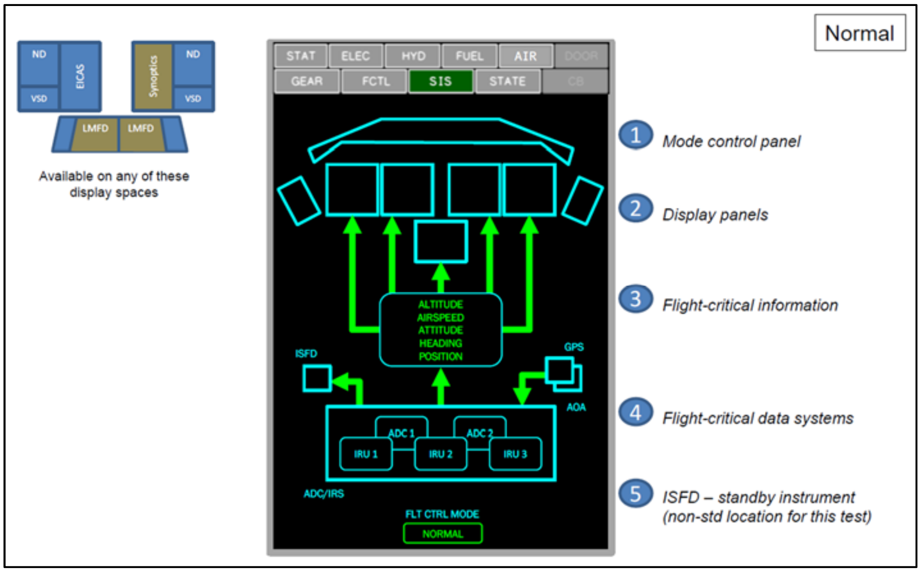

Fig. 1. SIS indicators and functions on the synoptic display (normal conditions).

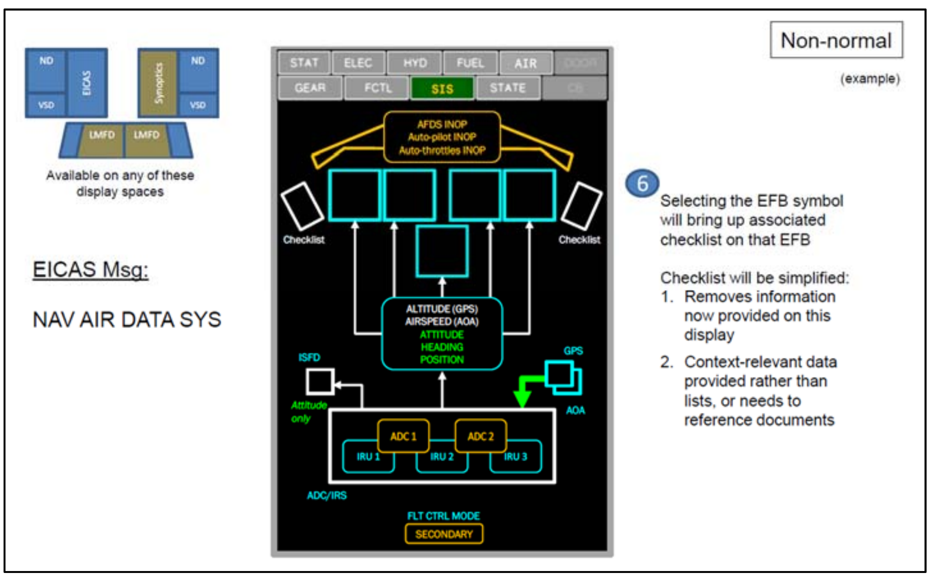

Fig. 2. SIS indicators and functions on the synoptic display (non-normal condition).

B. Modified Synoptic Pages

A test was conducted in the Integration Flight Deck at NASA LaRC using a Boeing B-737-800 flight deck and models to evaluate eSyn pages with sECL as an increasingly autonomous system for routine air carrier flight operations and in response to aircraft system failures [23]. A B-737-800 flight deck does not have 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 Flight Bag (EFB).

The original SIS page (discussed above in AIME 1) was modified slightly, see Fig. 3, to represent B-737 systems, and adding lookup values for pitch and power settings representative of aircraft weight and atmospheric conditions to facilitate unreliable airspeed checklist usage [23]. This pitch and power information was added after observations from pilots performing the checklists in the first AIME experiment.

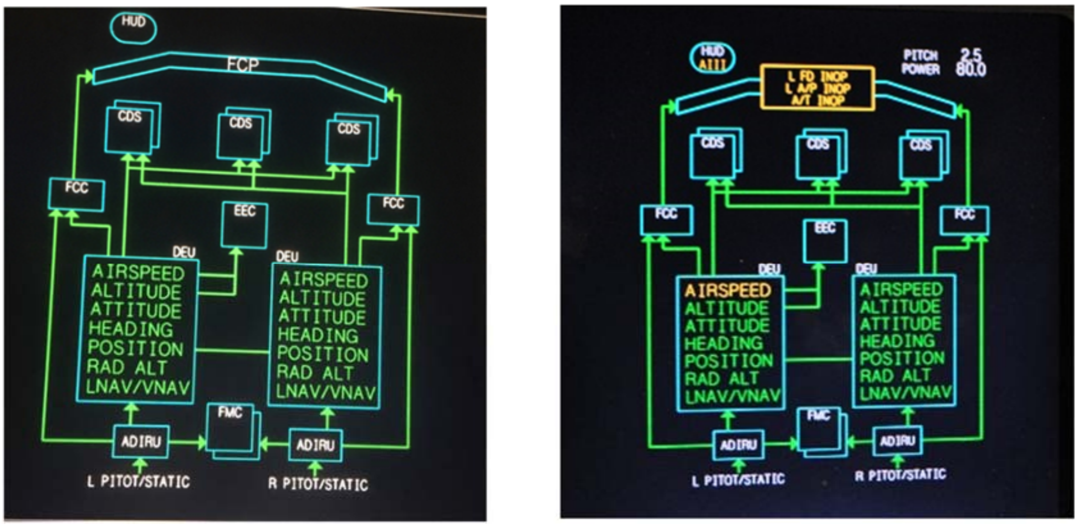

Fig. 3. SIS for B-737 System – normal conditions (left picture) and left airspeed failure (right picture).

In addition to the SIS page, a new combined system synoptic (CSS) page was added for the IFD experiment. This synoptic page, see Fig. 4, is represented as a fuel system synoptic page in normal conditions (left picture) and a combined fuel and hydraulic system synoptic page during non-normal conditions (right picture). In the experiment a hydraulic failure was utilized to test the new CSS page ideas. Pictorial schematic information was added to the hydraulic schematic and each component affected by the failure was displayed in amber (Fig. 4, right picture). Information was then graphically depicted that supplemented or eliminated notes in the normal checklist. The graphic information had an added benefit, as the notes information was then available for constant review for the rest of the flight. The eSyn (SIS or CSS) pages were shown on the lower display unit and the associated sECL were provided on outboard-mounted EFBs. This experiment used B-737 rated pilots who were not familiar with synoptic pages in general. [Note: This test was not formally a part of the AIME experiment series but results from it did influence the iterative AIME synoptic concept research.]

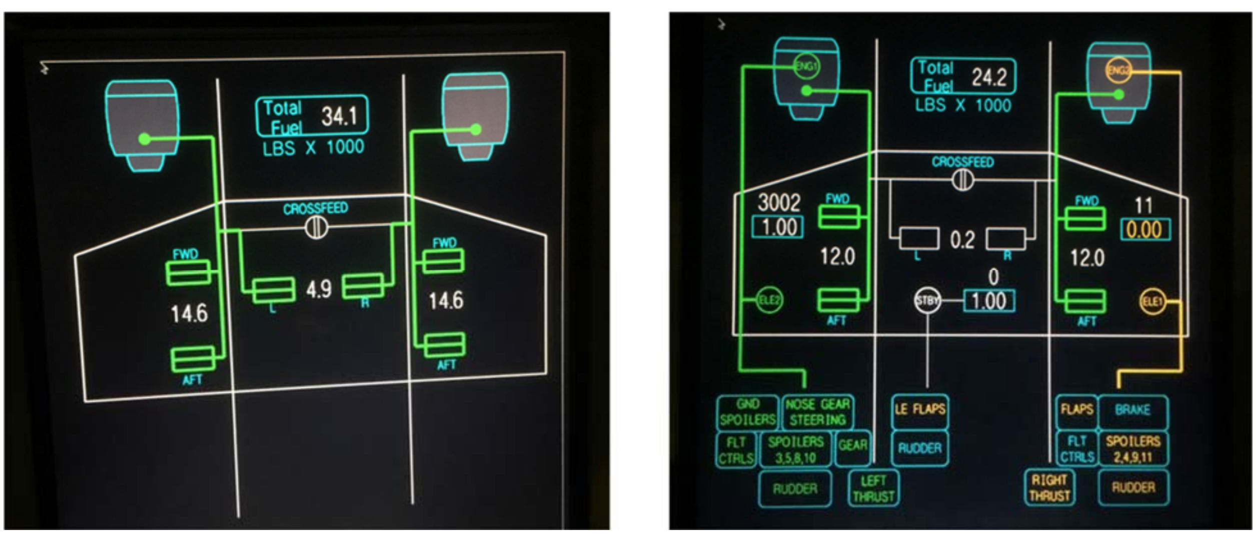

Fig. 4. New B-737 combined system synoptic in normal conditions (left picture) and non-normal conditions (right picture).

Versions of these modified synoptic pages were tested in the RFD in AIME 2 with synoptic pages based on the B-757 systems (see Fig. 5). The RFD has existing hydraulic and flight control synoptic pages, so they were modified (i.e., enhanced) to depict additional information regarding hydraulic failures and effects. Additional information was added to the new SIS page and existing hydraulic and flight control synoptic pages (see Fig. 5) to remove more notes from the checklists. The sECL was provided inboard on the lower MFD. In previous SIS testing, crews commented that an inboard, centrally located position for electronic checklists would be preferred over an outboard location. The modified SIS and enhanced existing synoptic pages used with sECL were tested with other technologies in AIME 2 [12-16] and those results are presented in Section V.

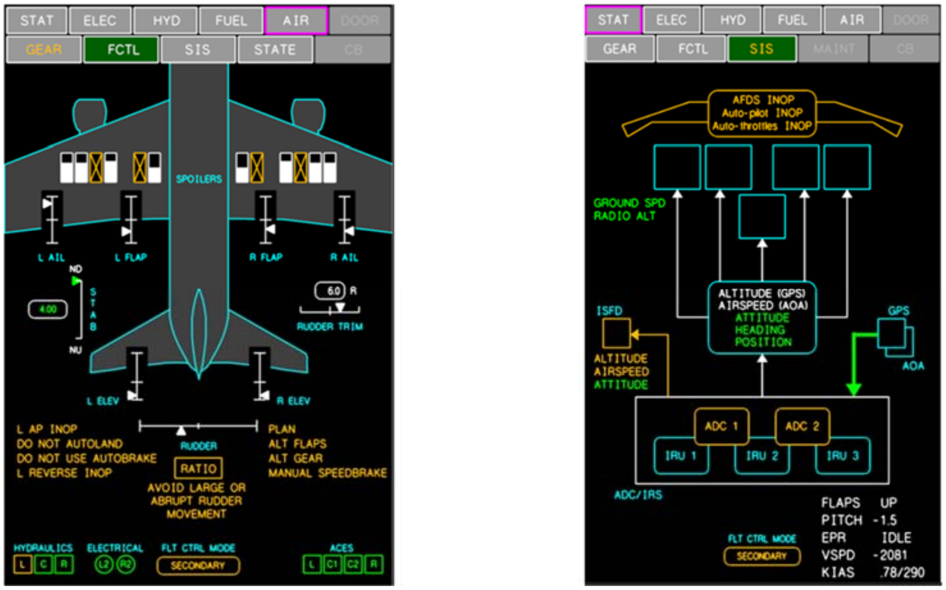

Fig. 5. Enhanced hydraulic system synoptic (left picture) and SIS (right picture) in AIME 2.

C. Current System Interaction Synoptic Page

The SIS page was further modified after AIME 2 to provide limitations in addition to the note information. Landing configuration information was added as textual information on the display in addition to the pitch and power settings that were used, see Fig. 6. The SIS page now provides an immediate indication of all the information for continued safe flight, all the effects of the current failure on the flight critical data, any automated or manual switching of flight critical data for the automation systems or the flight deck displays, and any configuration changes and runway landing distance effects, if any, for the approach and landing phase. The modified SIS used in conjunction with simplified ECLs (Fig. 7) was tested with other technologies in AIME 2.5 [17-18] and those results are presented in Section V.

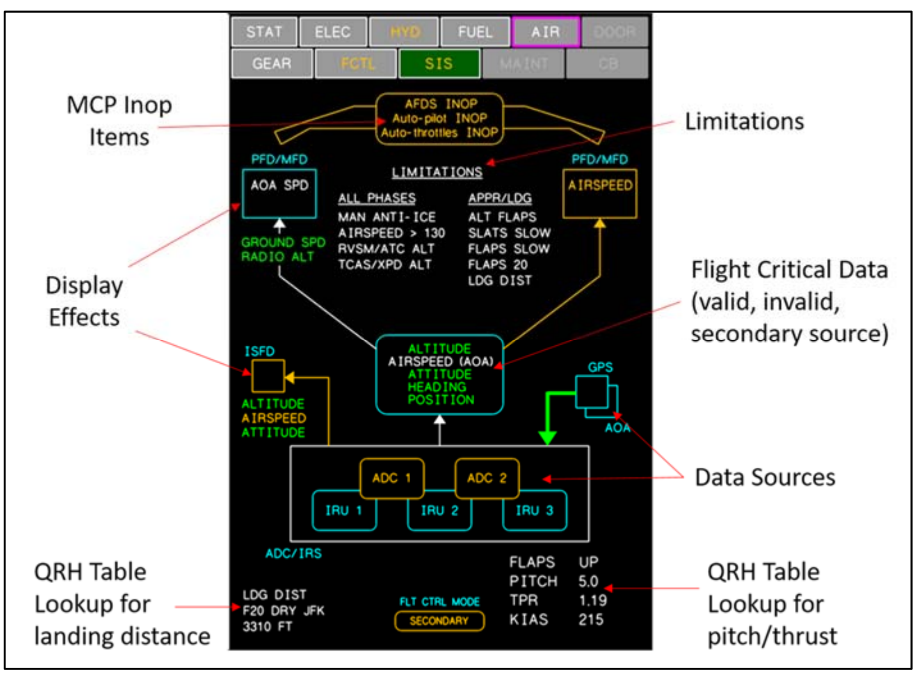

Fig. 6. SIS elements in AIME 2.5.

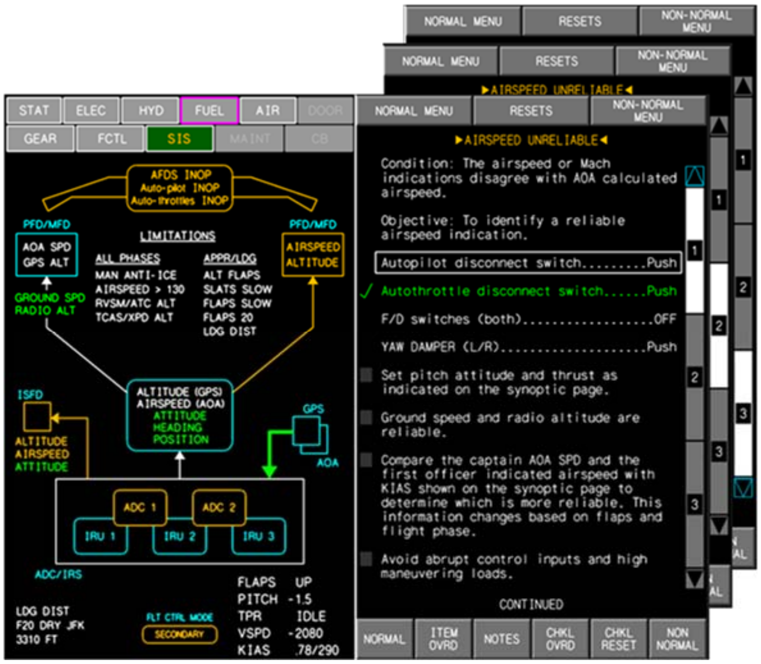

Fig. 7. SIS with sECL used in AIME 2.5.

D. Simplified Checklists

Checklists designed to be used with synoptic pages such as discussed in the previous sections may be simplified since much of the auxiliary information contained in the checklist is now represented graphically (or as text on the graphical display). For complex checklists, the reduction in checklist size can be dramatic. For example, the unreliable airspeed checklist was reduced by fifty percent and a six page checklist was reduced to three pages. Further, when looking across a number of different checklists, it was found that the critical checklist steps can often be elevated to the first page. When flight crews are dealing with all the dynamics of a real emergency, this can mean the difference between getting the steps done before interruption by air traffic control or other tasks or distractions.

E. Procedural Changes

Today's checklists are utilized the same way that paper checklists have always been used. They are standalone troubleshooting procedures and supplemental information is provided from the quick reference handbook (QRH). Synoptic pages are sometimes recommended to help understand the checklist procedure; but they are not required. In some flight deck implementations the electronic checklist is placed on the multi-function display surface as where the synoptic page is normally represented.

If synoptic pages are used to eliminate notes and other checklist elements, the synoptic pages will be required elements and will need to be displayed at the same time as the electronic checklist. This technology will create procedural changes in the way pilots handle system failures, but the benefit is the significantly reduced time to complete complex checklists and a greater pilot understanding of what needs to be done and why. For the pilot flying, especially if manual flight is required until the troubleshooting procedure is complete, graphical information increases the likelihood of comprehending the effects when used in conjunction with information provided by the pilot monitoring (i.e., observations described in the results section show that the flying pilot does not always pay attention to all the notes text in complex procedures. Other demands for his attention have higher priority).

IV. Test Overview

A. Facility and Environment

The AIME series of experiments utilized the RFD simulator (Fig. 8) within the Cockpit Motion Facility at NASA LaRC. The RFD was originally designed as a B-757 flight deck, but it was modified to create the CAST-recommended reference test condition of B-787-like displays, interfaces, and functions. As such, the simulator is configured with four 10.5-inch Vertical (V) by 13.25-inch Horizontal (H), 1280x1024 pixel resolution color displays, tiled across the instrument panel. The RFD also includes dual Rockwell Collins HGS-6700 HUDs, MCP, FMS, and EFBs for Pilot Flying and Pilot Monitoring. Two five-camera Smart Eye™ head and eye tracking systems are installed to quantify both crew member's head movement and eye-gaze behavior. Both eye tracking systems data outputs and the simulator state data output are time-synchronized.

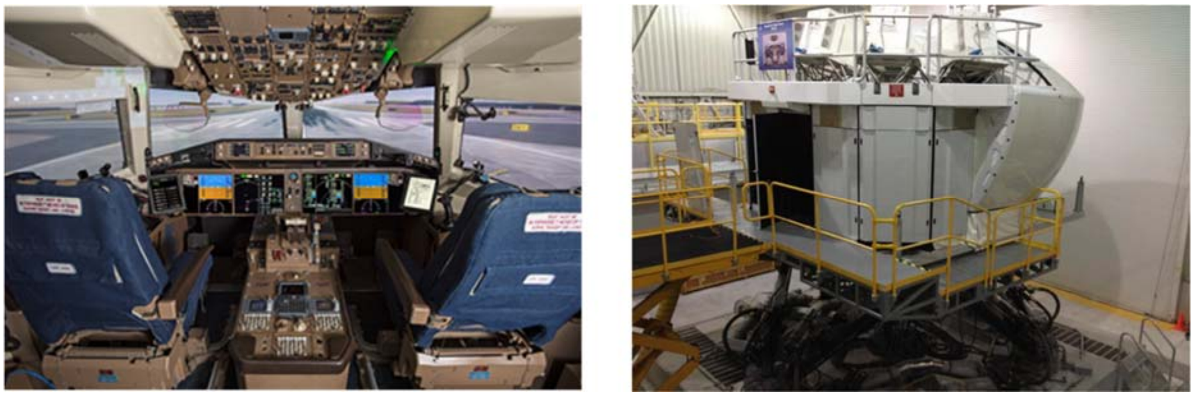

Fig. 8. RFD simulator interior (left) and exterior (right).

The full-mission RFD utilizes a Boeing B-757-200 aircraft aerodynamic model. Unlike Boeing aircraft, when hand-flying, the pilots use sidestick inceptors and these are directly linked as if mechanically connected. The autothrottle system backdrives the throttle handles to directly reflect the power setting commanded to the engines. Take-off, go-around (TOGA) buttons and autothrottle disconnect buttons are placed on the throttle handles. A collimated out-the-window (OTW) scene is produced by a Rockwell Collins Image Generator (IG) graphics system providing approximately 200 degrees (deg) H by 40 deg V field-of-view at 26 pixels per degree.

AIME flight scenarios spanned a range of conditions designed to help expose state awareness issues where the technologies under evaluation could prove useful. The scenarios were designed to emulate some of the causal factors reported in accidents involving loss of ASA. They were also intended to immerse flight crews in a complex operational environment with high-density traffic, adverse weather, digital data link services, synthetic vision systems, area navigation/required navigation performance operations. In addition, off-nominal (and complex) situations such as unexpected weather events, traffic deviations, equipment failures, unexpected clearances, and changes to flight plans were emulated in the scenarios. These features provided a realistic operational environment, albeit a complex one, in which flight crews may have little prior experience or training. However, prior similar experiments have shown crews can learn and perform well with limited exposure to this environment [24]. Scenario flight times were about 15-20 minutes.

B. Enhanced Synoptic Pages and Simplified Electronic Checklists Scenarios

1. AIME-1 Scenarios

Four non-normal events [6] were flown to evaluate the SIS with sECL technology and were based on actual ASA events: Air France (2009), Adam Air (2007), Midwest Express (2005), and Iceland Air (Baltimore, 2002). Two of the events emulated a failure within the pitot-static system due to icing/blockage of the pitot and/or static ports, and failure of the pitot heat system. Airspeed and altitude become unreliable for the blocked pitot-static system and airspeed becomes unreliable for the blocked pitot system. For the loss of air data test conditions, four EICAS warnings are triggered. Each has an associated checklist for the pilots to complete using the ECL system. This was representative of industry standard operating procedures at the time of this evaluation in 2015. The remaining two non-normal events emulated a failure of the Inertial Reference System (IRS), the Inertial Reference Unit (IRU), and/or the Attitude Heading Reference Unit (AHRU) resulting in either unreliable position information or unreliable position/attitude information and invalid heading information. GPS position became the source for position information and the integrated standby flight display (iSFD) became the source for attitude information. Heading had to be manually set by the crews on the CDU.

2. AIME-2 Scenarios

Two off-nominal runs were flown to evaluate the eSyn/sECL technology [13]. The off-nominal runs involved either a left hydraulic systems failure or unreliable airspeed information due to a blocked pitot-static system. The runs ended once the non-normal checklists associated with the failures were completed.

Hydraulic Failure

The scenario was initialized at 18,000 ft Mean Sea Level (MSL) in cruise configuration (Landing Gear UP, Flaps UP) as the crew prepared for their initial descent for the RNAV RNP 31R approach at JFK. Seven minutes after run start, a hydraulic leak occurred that prevented the left engine and left electric hydraulic pumps to supply hydraulic pressure. In addition, the failure prevented the power transfer unit from providing system pressure as well. The left hydraulics system failure resulted in the following items inoperative: left autopilot, left thrust reverser, normal flap extension, and normal gear extension. The crew was required to complete the Hydraulic System Pressure (left only) non-normal checklist and to perform alternate flap extension and alternate gear extension.

Pitot-Static Failure

The scenario was initialized at 18,000 ft MSL in cruise configuration (Landing Gear UP, Flaps UP) as the crew prepared for their initial descent for the RNAV RNP 13L approach at JFK. At run startup, an EICAS message "HEAT PITOT L-C-R" was triggered for failure of the pitot heat system. The aircraft was in weather with precipitation at that time. At 10 mi from waypoint CAMRN, an ATC datalink message "HOLD AT CAMRN AS PUBLISHED, 2 MINUTE LEGS, MAINTAIN 210 KNOTS, EXPECT FURTHER CLEARANCE IN 30 MINUTES, DESCEND IN THE HOLD TO 6000" was issued. Descending through 9,000 ft MSL, a total failure of the pitot-static system occurred due to icing/blockage of the pitot and static ports as a result of the annunciated failure of the pitot heat system. This condition triggered an EICAS message "UNRELIABLE AIRSPEED", as airspeed and altitude information became unreliable and their sources switched to AOA airspeed and GPS altitude, respectively, for both Captain and First Officer PFDs. This failure also caused the autopilot, autothrottles, and flight directors to become inoperative. The crews had to manually fly the aircraft (without flight guidance or autothrottles) while they completed the six page Unreliable Airspeed ECL.

3. AIME 2.5 Scenario

One off-nominal run was flown to evaluate the SIS/sECL concept. The off-nominal run involved unreliable airspeed information due to a blocked pitot system [18]. The runs ended once the unreliable airspeed checklist was completed.

Pitot Failure

The scenario path and trigger point for the total pitot system blockage was identical as that employed in AIME 2 for the total pitot-static system blockage. Descending through 9,000 ft MSL, a total failure of the pitot system occurred due to icing/blockage of the pitot ports and failure of the pitot heat system. This condition triggered an EICAS message "UNRELIABLE AIRSPEED", as airspeed information became unreliable and its source switched to AOA airspeed for the Captain's PFD. This failure also caused the autopilot, autothrottles, and flight directors to become inoperative. The crews had to manually fly the aircraft (without flight guidance or autothrottles) while they completed the six page Unreliable Airspeed ECL. The runs ended once the crews completed the unreliable airspeed checklist.

C. Procedures

For the AIME experiments, commercial airline pilots flew scripted scenarios such as above in the RFD. Captains and First Officers from the same airline were paired to ensure crew coordination and cohesion with regard to airline standard operational procedures. The Captain flew in the left seat of the flight deck and the First Officer flew in the right for the duration of the test. Each crew began with a few runs for familiarization with the simulator and the new technologies. Data collection runs followed these training runs [5, 13, 18]. Data were collected individually from the pilot flying (PF) and the pilot monitoring (PM). The Captain and First Officer alternated PF/PM roles periodically so that each pilot assumed each role for about half the scenarios. Roles were not changed during flights, only between.

D. Subjects

68 commercial airline pilots (34 crews), representing 4 U.S. airlines, participated in the AIME experiments. All subjects were Airline Transport Pilot-rated and currently qualified in wide body commercial aircraft. Captains had an average of 23,478 commercial flight hours with 20 having an average of 16.2 years military flight experience. First Officers had an average of 12,788 commercial flight hours with 22 having an average of 15.0 years military flight experience.

V. Summary Findings

Analyses of post-run usability ratings, acceptability ratings, and workload ratings as well as pilot feedback regarding the evolution of the eSyn/sECL technologies tested in the three AIME experiments are presented. Table 1 shows the type of synoptic tested, new SIS or enhanced existing synoptic pages, and the number of post-test ratings given for each during the AIME experiments. Additionally, post-test usability and acceptability ratings of the SIS/sECL technology tested in AIME 2.5 are presented. Interval plots of the usability, acceptability, and workload ratings with a 95% confidence interval of the mean are presented in Figures 9-13. eSyn/sECL performance was characterized by the time to complete the non-normal checklists (e.g., Unreliable Airspeed, Hydraulic Systems Pressure -Left Only) associated with a particular event (e.g., blocked pitot) or failure (e.g. left hydraulics system) and is also discussed.

Table 1. Number of post-run ratings for eSyn/sECL technology

AIME Experiment	*Enhanced Synoptics and Simplified Electronic Checklists (eSyn/sECL)*	*Number of Post-Run Ratings Collapsed across Crew Role*
1	SIS	41
2	SIS	14
2	Hydraulic and Flight Control Synoptics	12
2.5	SIS	20

A. Usability and Acceptability

The System Usability Scale (SUS) [25] was used to gauge how pilots assessed the usability of the eSyn/sECL technologies tested over the AIME series of experiments. Using the method described in [26], SUS scores were calculated based on ten sub-scores and fell in a range from 0 to 100, but these are not percentile ranks. SUS scores can be associated with specific letter grades and adjective ratings [26]. A SUS score between 68 and 80.3 is considered a “good” design and a score above 80.3 is considered an “excellent” design. SUS ratings were taken after each eSyn/sECL run for AIME 1, 2, and 2.5 experiments. In AIME 2.5, post-test SUS ratings were also taken to evaluate the most current SIS format and sECL.

Across all AIME experiments, the eSyn/sECL interface was considered a good design for handling both the SIS and hydraulic failure runs as all PF and PM mean scores were above 68 (see Fig. 9). However, there was a decrease in both PF and PM post-run usability scores for the SIS with sECL between AIME 1 and AIME 2 experiments. This decrease may be due to two experiment differences: (1) the unreliable airspeed checklist was revised after AIME-1 testing to reflect the current industry standard at the time of AIME-2 testing; and, (2) in AIME 2 the crews received in-classroom training of the SIS with sECL but not in-simulator training. Post-test, some pilots commented that they felt they did not have enough training on the use of the new synoptic page with simplified electronic checklists, and this may be indicative of the lower scores. The principal investigators took that as a lesson-learned and in AIME 2.5 testing provided both in-class and in-simulator training of the new SIS page and sECL. A different flight critical data failure was used for AIME 2.5 in-simulator training than what was used in data collection so that the failure was a “surprise” to the flight crews. AIME 2.5 SIS usability scores were comparable to AIME 1 scores in that PF ratings indicated a good design for the SIS/sECL and the PM ratings indicated an excellent design.

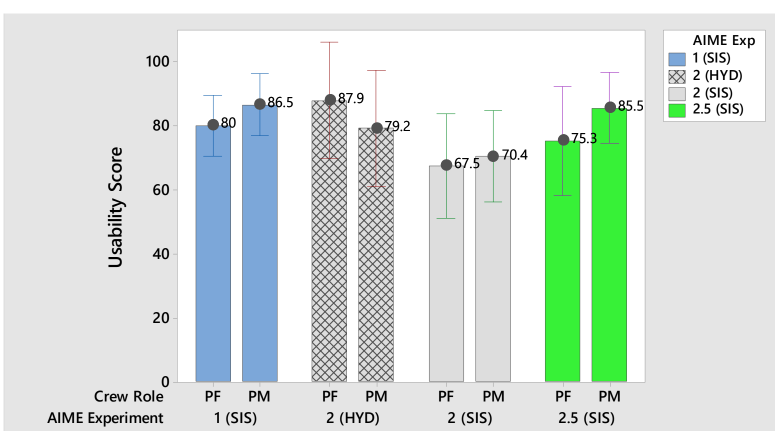

Fig. 9. Post-run usability scores for pilot flying and pilot monitoring across AIME experiment series.

Acceptability of the eSyn/sECL technology was self-assessed after each run using a seven point Likert scale with a rating of 1 being "very unacceptable," a rating of 7 being "very acceptable," and a rating of 4 being "average." In AIME 2.5, post-test acceptability ratings were also taken for the most current SIS format and sECL.

Self-reported post-run acceptability ratings revealed both the PF (mean value of 5.5) and PM (mean value of 5.8) found the eSyn/sECL to be highly acceptable for dealing with the hydraulic failure event and unreliable flight critical data events tested over the AIME experiment series (see Fig. 10). As was noted for the usability scores, there was a decrease in the acceptability ratings for the SIS/sECL technology from AIME 1 to AIME 2 experiments. However, increased training on the SIS format in AIME 2.5 testing appears to have brought the acceptability ratings back up to AIME 1 levels for both the PF and PM.

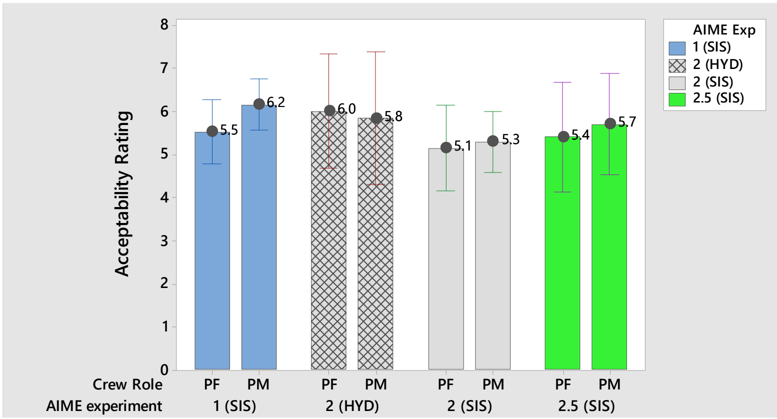

Fig. 10. Post-run acceptability ratings for pilot flying and pilot monitoring across AIME experiment series.

AIME 2.5 crews were asked to provide SUS ratings and acceptability ratings for the SIS/sECL after they had completed all data collection runs for the day. As shown in Fig. 11, crews rated the current SIS format and sECL as a good design for the PF (mean = 79.5) and an excellent design for PM (mean = 90.5). Both PF and PM rated the SIS/sECL as being highly acceptable for dealing with unreliable airspeed information (Fig. 12).

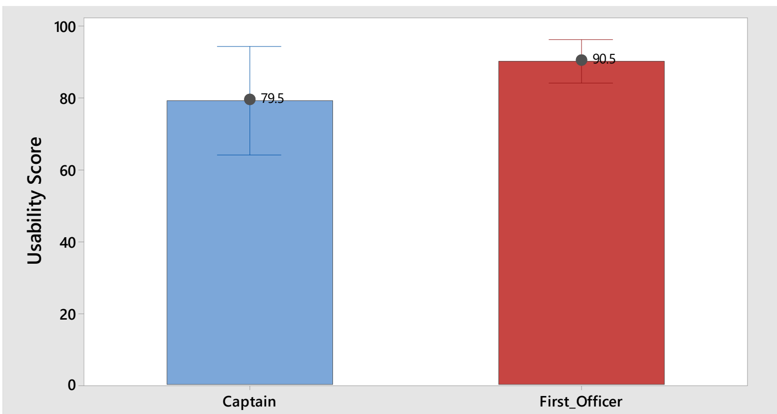

Fig. 11. Post-test usability scores for captain and first officer for AIME 2.5 experiment.

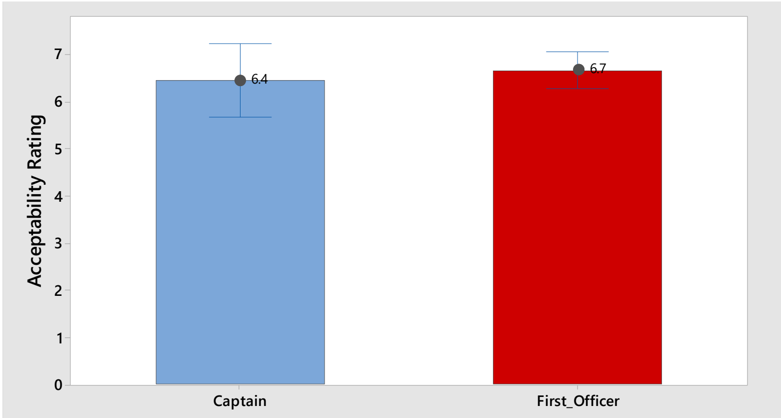

Fig. 12. Post-test acceptability ratings for captain and first officer for AIME 2.5 experiment.

B. Workload

The NASA Task Load Index (TLX) [27] method captures 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. Overall workload was calculated as the unweighted average of the ratings of the six subscales for both the PF and PM and was used to examine task load variation for the SIS/sECL and enhancements to existing synoptic pages/sECL.

Based on the questionnaire responses using TLX over the series of AIME experiment, the resulting PF and PM workload ratings are shown in Fig. for the two types of enhanced synoptic pages, new SIS and on existing synoptic pages, tested.

For the hydraulic failure runs where crews used the simplified electronic checklists and enhanced hydraulic and flight control synoptic pages, pilots rated their overall workload (Fig. 13) as being moderate as reflected in the PF (mean rating of 46) and PM (mean rating of 58) TLX ratings. Similarly, crews rated their overall workload as moderate for both the PF (mean rating of 56) and PM (mean rating of 55) when using the SIS with sECL to troubleshoot and manage unreliable flight critical data during flight. There were no significant PF or PM workload differences for the eSyn/sECL in the off-nominal flight conditions tested (left hydraulic failure or unreliable flight critical data information).

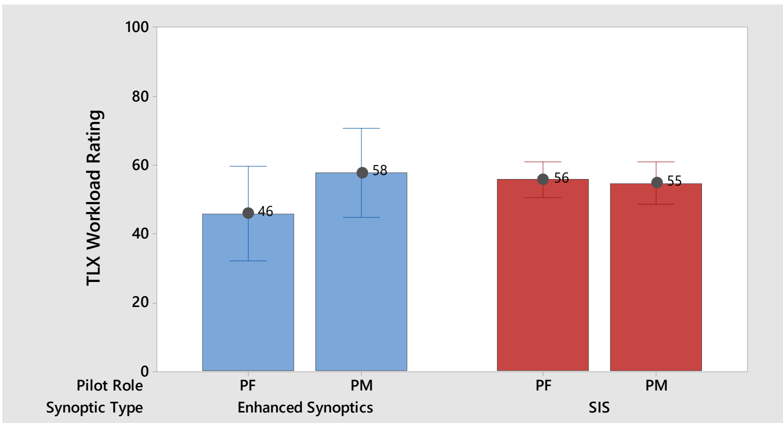

Fig. 13 Pilot flying and pilot monitoring TLX ratings for enhanced synoptics/SIS with sECL.

C. Pilot Comments

Crews provided comments on the eSyn/sECL technology during the post-run ratings. Each crew also participated in a post-test interview and debriefing where they also completed a short questionnaire asking them to provide comments regarding their overall satisfaction with the Enhanced Synoptics (SIS or on existing synoptic pages) and simplified electronic checklists technology concept. Discussion and selected observations from these are provided below for the two types of enhanced synoptics with simplified electronic checklists tested over the series of AIME experiments.

1. SIS and Simplified Electronic Checklist

Pilot comments supported the favorable usability and acceptability ratings and moderate workload scores provided by the SIS with sECL technology during the AIME series of experiments [6, 13, 18]. Example comments include:

> *"The synoptics make it so much better, gives the big picture of the situation at a glance."*
>
> *"Increases SA significantly, and avoids PM becoming buried in long checklists."*
>
> *"Expedites working through otherwise lengthy checklists. Allows both pilots to stay in the flight."*
>
> *"Backed up the EICAS message for 100% understanding of the malfunction. EICAS only gives a title to the problem. This was like opening a book and immediately being given the rest of the story to understand what exactly the effects were."*
>
> *"The notes on the SIS page were very helpful and flight critical data computations would vastly improve mental models of required system state. These computations free up time for stick and rudder monitoring and flying."*
>
> *"I am extremely satisfied with the information provided by the SIS and simplified electronic checklist. Knowing exactly what systems one has lost is key to solving the problem or deciding whether to land immediately or fly with the malfunction until destination. If it is possible to further shorten the ECL, I would recommend it. All items listed must be read and it takes too much time. OBJECTIVES are not always needed and notes referring to go to a synoptic are not required. We will do that without direction."*
>
> *"Very helpful in seeing what the problem is. Having pitch and power information available is a huge timesaver. This enhances flight safety by not wasting lot of time. Knowing what PFD is malfunctioning adds a lot of confidence as well as the source of the data. You can evaluate the situation quickly. Overall, very satisfied with the display and checklist."*
>
> *"Great device, collects all data into one convenient display. Timely data for unreliable airspeed/NAV AIR and DAT SYS. Pitch and power data display invaluable."*

As indicated above, the majority of pilots were satisfied with the content and presentation on the SIS, but a few provided suggested improvements as shown by these comments.

> *"Very satisfied. . . But I wonder if it can be simplified even more. Synoptics are still very busy....maybe highlight in red or bold the "big ticket" items to a safe landing."*
>
> *"Would like to see all "do not use" or failed items on synoptic page - if possible."*
>
> *"Good system. However the items on the SIS page that lists APP/LDG LIMITATIONS could stand out a little more. Also the bottom left/right area of screen could stand out a little more."*

2. Enhancements to Existing Synoptic Pages and Simplified Electronic Checklists

In general, pilots favored using the enhanced flight control and hydraulic synoptic pages in concert with a simplified electronic checklist for the left hydraulic failure employed in AIME 2. Pilot comments supported the SUS ratings that found the technology to be a good system design for understanding the effects of such a failure on the aircraft and aircraft systems. Example written comments include:

> *"This very much improves understanding of the state of the aircraft system, both the malfunction and how it affects aircraft control. Having it graphically displayed and with short phrases ("do not autoland") right on the display in amber made it easy to understand what we were dealing with and how to proceed. Even as PF, I could glance over and see it."*

"Excellent improvement. Really like the landing distance calculations."

"Overall, satisfied with the concept and the display and I did feel it increased my SA concerning the energy state."

"It is a nice enhancement with ever increasing system complexity. Quick access to important flight information."

"Better than standard. The pictorials are easier to understand then written word. Especially performance numbers."

"Highly beneficial in visualizing and understanding certain system malfunctions!"

"This is great and should be implemented ASAP. Everything that you've lost is condensed on one page with landing distances, so you don't have to search through QRHs to find numbers."

One pilot commented that additional training may be needed in order to fully comprehend the information on the enhanced synoptic pages.

""I think there is a lot of information available and perhaps with more training it would be less cumbersome to see all the info it's presenting."

D. eSyn/sECL Checklist Completion Time

Time-to-complete relevant checklist(s) can be an indicator for effectively handling failures and understanding their effects.

In AIME 1, the SIS allowed for a reduction of the original four checklists associated with the loss of air data test condition by a total of 432 lines of text. Individual checklists were reduced by as much as 50% and sometimes able to fit on one page [6]. The combination of the pictorial information on the SIS, indicating what systems were working and what had failed, combined with the shortened checklists significantly reduced time to complete the procedure compared to when crews had to complete it using the original length checklists without the SIS (i.e., the baseline condition). When using the SIS, there was much less confusion among the crews as to the effects of these types of failures and much more effective discussion and decision-making with respect to appropriate actions to take (e.g., frequent pointing to the SIS graphic versus reading aloud lines of text on the ECL).

In AIME 2, the SIS with sECL allowed for a 25% reduction in checklist completion time (mean time of 9 min 21 sec with SIS) compared to the baseline condition (mean time of 12 min 25 sec) for the blocked pitot-static system which resulted in unreliable airspeed information. On average, crews were able to complete the non-normal checklist three minutes sooner using the eSyn/sECL technology as compared to using the standard ECL. The maximum time savings across all runs for the blocked pitot-static system was 58% (9 min and 29 sec).

Similarly in AIME 2, the crews were able to complete the non-normal checklist for the left hydraulic systems failure significantly faster when using the enhanced hydraulic and flight control synoptic pages with the sECL (mean time of 8 min 57 sec) versus when only using the baseline checklist (mean time of 12 min 54 sec). On average, crews were able to complete the non-normal checklist almost four minutes sooner using the eSyn/sECL technology as compared to using the baseline Synoptics/ECL [18]. This is a time reduction of ~30%. The maximum time savings across all runs for the left hydraulic systems failure was 42% (6 min and 10 sec).

In AIME 2.5, the crews (on average) completed the unreliable airspeed in 6 min and 18 sec using the SIS/sECL technology for the blocked pitot system.

VI. Conclusions

Two types of eSyn/sECL concepts were evaluated - a new synoptic page (i.e., SIS) as well as enhancements to existing synoptic pages. Both were evaluated when used in conjunction with simplified electronic checklists and were deemed usable and acceptable by the participating flight crews. Further, evaluations were conducted in a relevant environment and spanned a set of complex situations such as encountered by crews in previous incidents/ accidents. Demonstrations raised the TRL of these concepts to five (or higher) and achieved the CAST goal for relevant research outputs.

For enhanced synoptic pages where simplified checklists are used with information elements designed into the synoptic pages, crew workload was reduced and time-to-complete procedures was reduced by as much as 30 percent. Minutes saved can often make the difference between safe completion of the flight and an accident or incident. The time saved helps manage the overall workload of dealing with real emergencies like handling communications with ATC and dispatch and making good continue or divert decisions. When crews are pressed for time they tend not to gather other critical information. In addition to time savings, it was clear that the crews had a better understanding of the situation by having access to a graphical display coupled to the checklist. This better understanding makes it less likely an inadvertent error will be made while handling an off-nominal situation.

The SIS was designed to meet the need for an information graphic to augment pilot understanding of the information processing of the automation in a form that was familiar, like the mechanical aircraft systems schematics. At a high level it shows in simple form which aircraft state information elements are correct, how those elements are presented to the flight deck displays, and what information is currently used for the automation and envelope protection systems. The additional information provided for aircraft control including pitch and power settings consistent with current aircraft environmental conditions and aircraft state like gross weight, flaps, and gear configuration allows for immediate safe operation of the aircraft and faster decision making for determining reliable versus unreliable information. The status information provides immediate and persistent indications of the result of any failures on continued safe flight and if landing data and configuration needs to be adjusted.

Distractions are one of the largest variables in the time-to-complete procedures. Most often, these distractions occur from ATC or operations center communications or from assistance requested from other crew members. One of the things we have observed conducting studies in relevant environments is that emergency procedures conducted in actual flying conditions are different than airline simulator training. Crews are told to declare an emergency and to contact dispatch for help, but it is very different when you actually communicate with real people instead of verbalizing the step. In realistic environments and real life, ATC will attempt to help. They will ask for critical information they need in trying to decide how to handle the flight and they often contact the crew multiple times. Crews feel the need to provide the information and that contributes to increased time-to-complete the checklist and significantly increases the risk of missed checklist steps.

Although the time-to-complete relevant checklists was substantial and provided a significant safety benefit and a margin for handling other time critical tasks, time-to-complete checklists in the study had significant variance. Some of those factors were illuminated here but the variability highlights the relative importance of getting critical steps as early in the procedure as possible. Often critical checklist steps can be elevated to the first page of a complex checklist. Items can be evaluated before other distractions take place. In actual flight conditions, it is likely the reduction of checklist completion time with eSyn and sECL will be greater than shown in these studies, which can further increase the safety margin.

The test scenarios were designed to stress crews and provide discrimination in the data analysis. Crews had to be trained on new systems without providing an indication to the actual failures being tested so they would be truly surprised as in an actual emergency. The scenario conditions were chosen with actual distractions like runway changes or spurious traffic calls at precise times. When airspeed failures occur near maximum or minimum operating speeds, the aircraft quickly enters actual overspeed or near stall conditions. These events were used as well in the design of the scenarios.

Pilots were unanimous in feeling the enhanced synoptic display and the associated reduced checklists make relevant tasks much less demanding. Most pilots commented that providing the big picture of the situation at a glance allowed for quickly realizing what systems are still available versus those that are inoperative. Several appreciated its role in providing a backup to the EICAS messages for better understanding of malfunctions.

One negative aspect with respect to synoptics is that current non-normal procedures do not require reference to synoptic pages, even in aircraft where these displays are part of the type certificate. If, as suggested in this paper, references to synoptic pages replace more detailed prose on checklists, the synoptic display may call for additional certification costs (i.e., the synoptic becomes essential equipment to complete a non-normal checklist). A risk-based approach for certification is now in place for Part 23 aircraft, perhaps the same approach can be applied to Part 121 aircraft for secondary information like synoptic displays allowing reductions in certification costs for technology that has a clear and proven safety benefit. This may allow cost-effective retrofit of such technology.

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