Flightcrew Thrust Control and Engine Display Concepts for the Subsonic Single Aft Engine (SUSAN) Transport Aircraft

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NASA is developing a new hybrid-electric aircraft concept called the SUbsonic Single Aft eNgine (SUSAN) Electrofan. The SUSAN airplane is being designed as a 180-passenger commercial regional jet and is expected to fly in the 2040 time frame. The flight deck of the SUSAN airplane is expected to resemble a typical two person flightcrew transport. Research issues include pilot control and the display elements needed for the hybrid-electric propulsion system. The paper describes a research study conducted in a high-fidelity flight simulator where 18 commercial pilots (9 flightcrews) evaluated throttle controls and engine display concepts for a proposed SUSAN flight deck. The results showed that the number of throttle levers did not affect pilot's situation awareness, workload, or speed control.

I. Introduction

NASA is conducting trade studies for a new hybrid-electric aircraft concept called the SUbsonic Single Aft eNgine (SUSAN) Electrofan[1–3]. The SUSAN airplane (Fig. 1) is being designed to fly in the 2040 time frame and will use 20 Megawatt class Electrified Aircraft Propulsion (EAP) to enable advanced Propulsion Airframe Integration (PAI) in transport category aircraft. This aircraft will use alternative fuels to reduce the net emissions. Combining these features may reduce aircraft emissions by 50% per passenger/mile while retaining the capacity, speed, and range of narrow-body, single aisle jets (180 passengers).

NASA has been investigating the feasibility of electric engines for aircraft. NASA's X-57 airplane is an all-electric experimental aircraft developed to demonstrate the feasibility of electric powered aircraft[4]. Also, NASA has awarded contracts to General Electric (GE) Aviation and magniX to build electric aircraft demonstrators in 2026[5]. In addition to NASA's research efforts, aircraft manufacturers are beginning to work toward certification of the first all-electric aircraft. The Slovenian company Pipistrel received airworthiness certification from the Federal Aviation Administration (FAA) for its electric aircraft trainer called Alpha Electro[6]. It is a two-seat trainer that weighs 811 lbs and is powered by a 21kWh battery pack.

The Alice airplane, being built by the Israeli company Eviation, will be a two-pilot, 9 passenger all-electric aircraft that can fly for one hour on a 30-minute charge. It is currently in high-speed taxi testing as of early 2022[7]. The delivery courier DHL has an order for a cargo version of the Alice airplane that is expected to be delivered in 2024[8]. Delta Air Lines has announced a partnership with Joby to bring electric air taxi service to large metropolitan areas[9]. American Airlines is expecting the delivery of at least 50 electric aircraft from the British aerospace manufacturer

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Fig. 1 The SUSAN airplane concept rendering (Graphic Credit NASA / Eric S. Mindek).

Vertical Aerospace[10]. United has agreed to purchase one hundred ES-19 electric aircraft (19 passengers) from Heart Aerospace[11]. The commercial aircraft manufacturers Airbus and Boeing are conducting research for large commercial electric aircraft. Airbus has at least 3 research electric aircraft programs[12] (EcoPulse, CityAirbus, and E-Fan series), and Boeing is studying electric aircraft under project Subsonic Ultra Green Aircraft Research (SUGAR)[13].

NASA is exploring the electric engine technology for larger commercial transport aircraft as the electric aircraft market is expected to grow. As the SUSAN trade study has progressed, the proposed SUSAN propulsion system has become much more complex than the current small electric aircraft. SUSAN's propulsion system consists of a fuel burning engine, which will not only provide a component of thrust, but also power the 16 electric engines (8 engines each wing). The SUSAN propulsion system will also include a primary and secondary battery system, which will provide emergency power and power boosting, respectively. The SUSAN electrical system is described in Haglage [14].

In 2022, most domestic commercial transport aircraft propulsion systems consist of two wing-mounted engines and two throttle handles. The engine performance of modern commercial aircraft is completely managed by a Full Authority Digital Engine Control (FADEC) system[15]. The flightcrew modulates the aircraft's thrust either by engaging the auto-throttle system or manually moving the throttles. Asymmetric thrust in a multi-engine airplane is caused from either a failure or degraded/reduced thrust of an off-body axis engine. The auto-throttle system can handle small thrust asymmetry; but current auto-throttle systems will disengage if the asymmetric thrust becomes too large. For a SUSAN airplane with 17 engines (1 turbofan and 16 wing mounted electric engines), manually controlling 17 thrust levers will be too high of a workload for the flightcrew even under nominal flight conditions; thus, flight critical thrust automation will be required.

A. Flight Deck Research Goals

The research questions for this initial study were: 1) how many throttle handles are needed; and 2) how should the propulsion system state be displayed to the flight crew. Typical current day 180 passenger commercial aircraft have two wing mounted engines with two throttle levers for thrust control. With the proposed 17 engines of the SUSAN airplane, 17 throttle levers is widely considered as untenable; thus, some type of thrust automation is expected. The high-level design of the thrust automation is expected to include thrust differential to boost turning rate in nominal conditions; however, in this first study, there was no thrust automation implemented.

B. Flight Deck Design Philosophy

The SUSAN flight deck is being designed for two flightcrew members (14 CFR §121.385c), leveraging from current state-of-the-art commercial transport aircraft[16, 17]. The rationale for this evolutionary approach to the SUSAN flight deck design is to baseline from a proven concept and modify the flight deck to accommodate the unique hybrid-electric propulsion system. Therefore, the SUSAN flight deck is expected to be similar to modern commercial flight decks with modifications to the throttle levers and engine displays to account for hybrid-electric differences. This research paper focuses on the number of throttle levers and initial engine display concepts the flightcrew will need for the SUSAN flight deck.

The development of the SUSAN Engine Indicating and Crew Alerting System (EICAS) is dependent on the aircraft control laws and failure modes for the SUSAN airplane[18]. Typical commercial transport engine displays are being modified to show hybrid-electric engine state suitable for the flightcrew of the SUSAN aircraft.

C. Pilot Controls

The thrust of a SUSAN airplane will be highly optimized by the engine control system; therefore, the flightcrew will not need differential throttle control. However, the flightcrew may need to manually shutdown any of the 17 engines. As the SUSAN airplane design is in the early stages, many control laws, automation decisions, and fail modes are not yet known. For the purposes of this study, several assumptions were made about the SUSAN airplane:

- Electric engines were managed automatically and did not require pilot control of individual engines. This is an extension of fly-by-wire with envelope protections into electric thrust management.
- There was no thrust reverser on the turbine engine.
- The pilot controlled the switch to using primary (emergency) batteries in the event of a turbine engine failure.
- There are four main generators that provide electric power.
- Each motor generator has four outputs (each three phase AC with for a total of 12 windings) where each three-phase bus drives four electric engine pairs on each wing.
- Each main generator output (each circuit interrupter) bus drives one electric engine (2 counter-rotating fans); therefore, each main generator drives four electric engines in pairs on each wing.
- The motor/generator has four windings (three-phase power so 12 windings) that connect to four of the main generator buses and balance the load on the turbine engine.
- Aircraft electric power avionics/hydraulics/actuators comes from combined power of main generators and motor/generator.
- Modern generator and bus controllers allow reset but no other pilot control options. Circuit interrupters can be reset. The generator can be reset and generator drive can be disconnected. As most circuit interrupters only affect one electric engine, automated control is assumed.
- Electric engines can be enabled/disabled individually with menu control.

Another consideration is the control of switching to emergency use batteries. During nominal operations, the current SUSAN design uses batteries that are recharged by the turbine engine; however, if the turbine engine fails, single use batteries will used to power the electric engines. As of this writing, the current design is sized to have a 30-minute battery life at a 100% power setting at 35,000 ft. Automation of the switch from rechargeable to primary (emergency) batteries is not yet determined.

II. Simulation Experiment

Flightcrews flew 11 scenarios using various throttle lever configurations. At the completion of each scenario, flightcrews completed a situation awareness questionnaire[19] (Situational Awareness Rating Technique (SART)), a workload questionnaire[20] (NASA-TLX), a usability questionnaire[21] focused on the number of throttle levers and engine state display, and an acceptability rating of the propulsion system. Airplane state data (including pilot control inputs) was recorded for each data collection run.

A. Evaluation Pilots

Nine flightcrews (18 pilots) from 3 different US airlines participated in the simulator study. Each flightcrew was from the same airline. Captains had a mean of 16,600 flight hours (median of 6,800 flight hours), and first officers had a mean of 9,300 flight hours (median of 7,000 flight hours).

B. Langley Flight Simulation Facility

The NASA Langley Research Center (LaRC) Research Flight Deck (RFD) simulator is a high-fidelity simulator that was configured to simulate the SUSAN aircraft (Fig. 2). The RFD instrument panel had four color displays typical of a modern commercial transport aircraft. Also, the RFD had a mode control panel, Flight Management System (FMS), control display units, and hydraulic-actuated side-stick control inceptors. A collimated Out-The-Window (OTW) scene provides approximately 200° horizontal by 40° vertical Field-Of-View (FOV).

Fig. 2 The Research Flight Deck simulator at NASA Langley Research Center (Photo Credit NASA).

C. Training

Each flightcrew viewed a 50-minute recorded brief that described the SUSAN aircraft and the purpose of the simulator study. Following the briefing, flightcrews received 60-minutes of familiarization training in the RFD simulator. As the RFD does not represent any particular commercial aircraft, guidance was provided throughout the experiment to help the flightcrew with the location and/or function of unfamiliar items.

D. Throttle Evaluation

Single and dual throttles were easily implemented in RFD by disabling one throttle for single throttle operations. Adding a third throttle was prohibitively expensive due to the mechanical complexity in the center aisle stand. Therefore, a compromise was to have the third throttle be a simple mechanical attachment that moves coincident with electric engine throttle (see Fig. 3). A guided discussion via a post-test semi-structured interview was used to further explore with the evaluation pilots the need/desire for the number of throttle levers for thrust control.

Below is a description of the various throttle configurations and functions used in the study.

1) One throttle lever controlled total aircraft thrust. To facilitate turbine engine troubleshooting and the requirement to shut-down the engine for certain failures like engine fire, additional controls were used to either maintain automated control of electric engine thrust while troubleshooting the turbine engine or vice versa. For this study, separate turbine and electric control was achieved by turning off the auto-throttle arm switch and using the auto-throttle disconnect on the throttle levers to toggle between turbine and electric engine thrust control. The annunciation of which engine was being controlled by the single throttle lever was shown on the thrust mode line

of the engine display as a ‘T’ for turbine engine or a ‘E’ for all electric engines.

2) Two throttle levers were used to control the electric engine thrust separately from the turbine engine thrust. The left throttle lever controlled the turbine engine thrust and the right throttle lever controlled the total electric engine thrust.
3) Three throttle levers were used to control the left-wing electric engines, turbine engine, and right-wing electric engines respectively (Fig. 3).

Fig. 3 The three throttle concept in the RFD. Throttles #1 (left lever) and #3 (right lever) were physically linked and controlled the electric engines. Throttle #2 (middle lever) controlled the turbine engine. The physical link was installed only for the 3 throttle concept (Photo Credit NASA).

Checklist usage is a significant part of operating procedures and where control of autothrottle and ‘land as soon as possible’ decisions are made. Electronic checklist usage is a normal procedure for modern commercial aircraft operations and were utilized for this pilot study. Typical commercial transport (e.g., B777, B787) electronic checklists were changed to accommodate electric engine considerations.

E. Engine Displays

There are significant interactions between thrust, turbine engine control, and electric power control and distribution. Many of the SUSAN design details are still being considered and evaluated through trade studies. The entry into service date of 2040 further complicates what information should be displayed to the pilots for an electrified aircraft. Trends toward simplified presentations and increasingly autonomous systems with automated reconfiguration and control are just a few examples that might indicate a very simplified system diagram for a display concept and only one or possibly no round dial (even for the turbine engine). Health of the turbine engine is critical to safe continued flight and use of emergency resources (e.g., the single-use batteries and automated reduction of thrust) for critical phases of flight (takeoff and climb) still indicate a need for some turbine display and overall total thrust (turbine and electric engines). The minimum requirement then is for a simple standard turbine engine display and display of overall total thrust.

Two engine display concepts were used in this initial pilot study (see Fig. 4). The ‘Bars’ engine display showed typical engine display for the turbine with added thrust output for each electric engine shown as a moving bar. For this study, all of the electric bars moved together (i.e., no differential thrust of individual electric engines) unless, of course, an electric engine had failed. The total percentage thrust for all electric engines for each wing was displayed below the thrust bars. If the electric engines were working normally, the thrust bars were displayed in green. For electric engine faults/failures, the thrust bars and the digital readout were shown in yellow.

The ‘Dials’ engine display showed the left and right wing electric engine thrust as a thrust percentage for all 8 electric engines. The center dials and digital readouts showed typical turbine engine status. For the Dials engine display, a fault/failure of an electric engine would result in the percentage thrust numeric readout displayed in yellow.

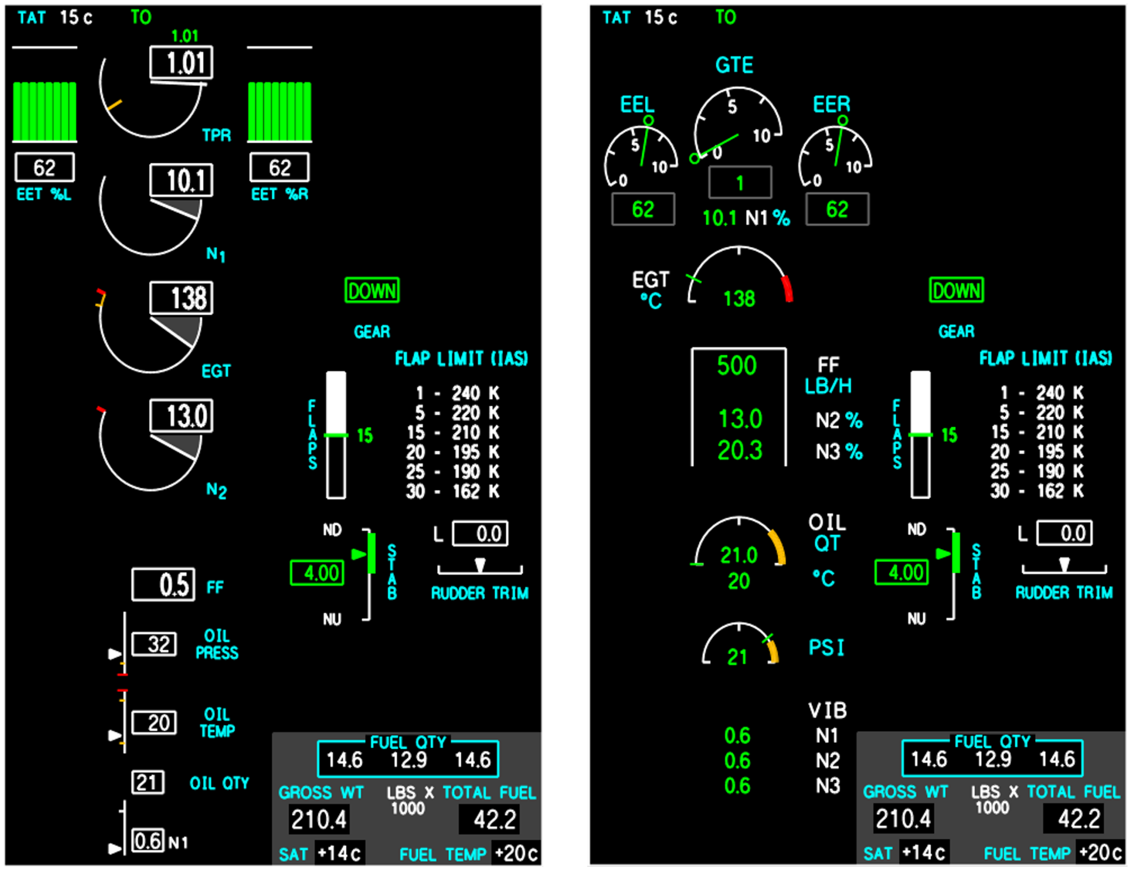

Fig. 4 The two engine display concepts: the Bars display (left) and the Dials display (right).

F. Evaluation Task

1. Normal Operations

Normal procedures in the study included taxi, takeoff, climb profiles, cruise, descent profiles, visual approach procedures, landing, and taxi-in which required manual and automated throttle manipulations. Some drag-required operations and idle-descent throttle operations were flown.

Event 1: Normal Flight Profile Takeoff with Cruise Portion

Event 1 was a normal departure from John F. Kennedy (KJFK) International Airport. The simulation started at hold short position for runway 4L on taxiway K2 and flightcrews were cleared for the DEEZ4 departure. After takeoff, flightcrews were instructed to engage the LNAV, VNAV and the autopilot. The FMS was programmed with a flight plan from KJFK to Denver International Airport (KDEN) with a cost index of 100. The cruise altitude was 31,000 feet and the aircraft was loaded near maximum gross weight with a full fuel load. The simulated weather was clear with daytime Visual Meteorological Conditions (VMC). The data run ended 5 minutes after cruise altitude was reached.

Event 2: Normal Flight Profile with Descent and Landing

Event 2 was a normal landing with a short taxi segment. The arrival was conducted from cruise altitude of 31,000 feet with 5-10 minutes of time to top of descent. Denver Airport-Terminal Information Service (ATIS) reported weather with thunderstorms in the vicinity and the active runway for landing was 35R. Clearance was given for an Instrument

Landing System (ILS) 35R landing on the WOLLF.TELLR2 arrival. An unforecasted tailwind of 150 knots was not loaded into the FMS. This required manual intervention by the flightcrew to maintain descent restrictions keeping the throttles at idle and using speed brakes. The simultated weather was moderate turbulence in the daytime with light winds on landing.

2. Abnormal Operations

Abnormal operations were evaluated using existing EICAS failures for typical twin turbine commercial airplanes that triggered the message and associated electronic checklist as a starting point. Abnormal operations included full and partial failures of the turbine engine, various number of electric engine failures, and an unannounciated fuel leak condition. Overheat/thermal faults provided more critical failure modes than bus faults. For instance, faults/fires can take out multiple electric engines on one wing.

Event 3: Single Electric Engine Failure

Single electric engine failures are non-critical events and were evaluated at the worst possible conditions (outboard electric engine fail). This Event was included for completeness and to create a discussion about any perceived need for throttle control of electric engines separate from turbine engine control. Although not realistic, they were evaluated with no compensation from the other engines and during the most stressful flight condition for the pilot and thrust standpoint, with a failure after V1 speed. (The V1 speed is maximum speed on takeoff for which a rejected takeoff can safely occur). The initial conditions were the same as Event 1 except it was flown at nighttime. The EICAS message was suppressed until after 400 feet of altitude gain in accordance with current flight deck philosophies of deferred alerting during takeoff roll. The data run ended at the completion of the electronic checklist for this bus failure.

Event 4: Failure of Four Electric Engines

Loss of one main generator or an associated fault of a main generator bus controller will result in the failure of four engines for the current SUSAN design. The FMS was programmed with a flight plan from KDEN to Albuquerque International (KABQ) airport. The cruise altitude was 31,000 feet with a cost index 100. The aircraft was loaded near maximum gross weight with a full fuel load. ATIS indicated Instrument Flight Rules (IFR) weather with thunderstorms in and around the airport. The weather at KABQ was 1000 feet overcast. The aircraft was positioned at hold line for runway 35R and cleared for takeoff. At 400 feet Above Ground Level (AGL), one of the electric generators was failed resulting in the failure of 4 electric engines. The data run ended at the completion of the electronic checklist for the main generator failure.

Event 5: Immediate Total Loss of the Turbine Engine

The initial conditions for this Event were the same as Event 4. At 130 knots on the takeoff roll, an immediate failure of the turbine engine was triggered. In addition, after 5 minutes, the rechargeable batteries would be totally discharged resulting in the complete loss of thrust (unless the flightcrew switch to primary (emergency) battery). The run ended when the flightcrew handled the emergency and completed the loss of engine checklist.

So that each flightcrew could experience all 3 throttle concepts and both engine display concepts, Event 5 was repeated 2 more times for each flightcrew.

Event 6: Thermal Failure

At the time of this writing, thermal failures are currently not well understood as the thermal system is still being designed. For the purpose of this initial evaluation, it was assumed to be a critical failure. Even though the failure of full thrust for all electric engines will be designed to be improbable, this critical failure was considered a fail test case. For this initial study, this thermal failure resulted in the loss of full thrust capability in all the electric engines.

The aircraft began at cruise altitude (31,000 feet), directly west of KDEN enroute to KABQ to runway 8 via the SANDIA3 arrival. ATIS indicated IFR weather with thunderstorms in and around the airport. The weather at KABQ was 1000 feet overcast. After 5 minutes from the start of the data run, all 16 electric engines were immediately failed. The data run ended when a divert decision was made by the flightcrew and the checklist was completed.

Event 7: Birdstrike

For this event, a flock of birds were encountered on climb-out at 1,000 feet of altitude causing the immediate failure of the 8 electric engines on right wing. The initial conditions for this Event were the same as Event 4. The data run ended once the aircraft was stabilized and the flightcrew requested to return to KDEN.

Event 8: Partial Loss of Turbine Engine

This is a set of failures that requires the flightcrew to reduce thrust of the turbine engine. Almost all the failures result in similar throttle actions: Reduce thrust until condition clears or throttle is at idle. If at idle and condition persists, shutdown the affected engine.

Event 8 was a failure of the turbine engine that resulted in an ENG EXCEED message being displayed on the EICAS that could not be cleared with the engine at idle and required the flightcrew to shutdown the turbine engine in-flight. The initial conditions for this Event were the same as Event 6. The data run ended when the flightcrew finished the engine checklist and made a divert decision.

Event 9: Fuel Leak

The fuel leak provided an interesting scenario as it is an unannunciated failure. As the fuel totalizer begins to disagree with the computed fuel required in the FMS, a fuel disagree message appeared on the Control Display Unit (CDU). The initial conditions for this Event were the same as Event 6. The data run ended when the flightcrew finished the fuel leak checklist and made a divert decision.

Table 1 Summary of Events.

Event	Description
1	Normal takeoff and departure
2	Normal arrival and landing (150 knot tailwind and moderate turbulence)
3	Single electric engine fail
4	Single main generator fail (4 electric engines fail)
5	Turbine engine fail on takeoff after 130 knots
6	Thermal system failure (all 16 electric engines fail)
7	Birdstrike on right side: all 8 right wind electric engines fail
8	Turbine engine limit exceedance resulting in an in-flight shutdown of the turbine engine
9	Fuel leak resulting in an in-flight shutdown of the turbine engine

3. Experiment Matrix

All flightcrews experienced all of the nominal and fail events described in Table 1. Events 1 and 2 were always the first and second runs, respectively. Throttles and engine displays were varied across flightcrews and Events 3 - 9 were randomized for each flightcrew. All flightcrews flew Event 5 (turbine engine failed on takeoff) with all three throttle configurations. Also for one of the Event 5 scenarios, the other engine display concept was flown by the flightcrew. This other engine display was always shown in the later half of the day to reduce training effects. Table 2 shows the experiment design matrix for each flightcrew.

Table 2 Flightcrew run matrix. B1 = Bars display and 1 throttle, D3 = Dials display and 3 throttles. Underlined Events denote a different throttle concept and/or engine display concept.

	Flightcrew								
Event	1	2	3	4	5	6	7	8	9
1	B1	D2	B3	D1	B2	D3	B1	D2	B3
2	B1	D2	B3	D1	B2	D3	B1	D2	B3
3	B1	D2	B3	D1	B2	D3	B1	D2	B3
4	B1	D2	B3	D1	B2	D3	B1	D2	B3
5_1	B1	D1	D1	D1	B1	B1	B1	D1	D1
5_2	D2	D2	B2	B2	B2	D2	D2	D2	B2
5_3	B3	B3	B3	D3	D3	D3	B3	B3	B3
6	B1	D2	B3	D1	B2	D3	B1	D2	B3
7	B1	D2	B3	D1	B2	D3	B1	D2	B3
8	B1	D2	B3	D1	B2	D3	B1	D2	B3
9	B1	D2	B3	D1	B2	D3	B1	D2	B3

III. Results

Quantitative (i.e., aircraft state) data as well as qualitative (i.e., questionnaires, workload and situation awareness metrics, pilot opinion) responses were recorded and used in a detailed data analysis to provide recommendations for the number of throttle levers for a hybrid-electric aircraft. The legend for the box and whisker plot data which follows is shown in Fig. 5. Data that are greater than 1.5 times the InterQuartile Range (IQR) from the 25% quartile (Q1) or the 75% quartile (Q3) are considered outliers.

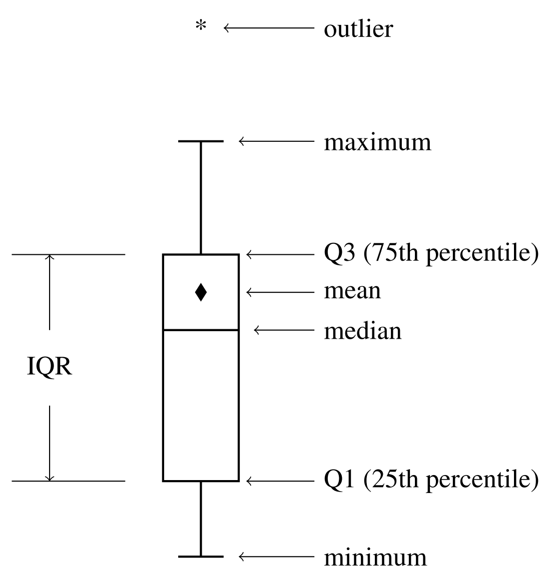

Fig. 5 Legend for box plots (not to scale). Data that are greater than 1.5 times the InterQuartile Range (IQR) from the 25% quartile (Q1) or the 75% quartile (Q3) are considered outliers.

A. Quantitative

1. Airspeed Error

For each of the turbine engine failures, the thermal failure (all electric engines overheat), and the fuel leak, speed error was calculated as the difference between airspeed and the commanded airspeed. Figure 6 shows that for all fail events and throttle cases, the mean speed error was below 10 knots which is considered operationally adequate.

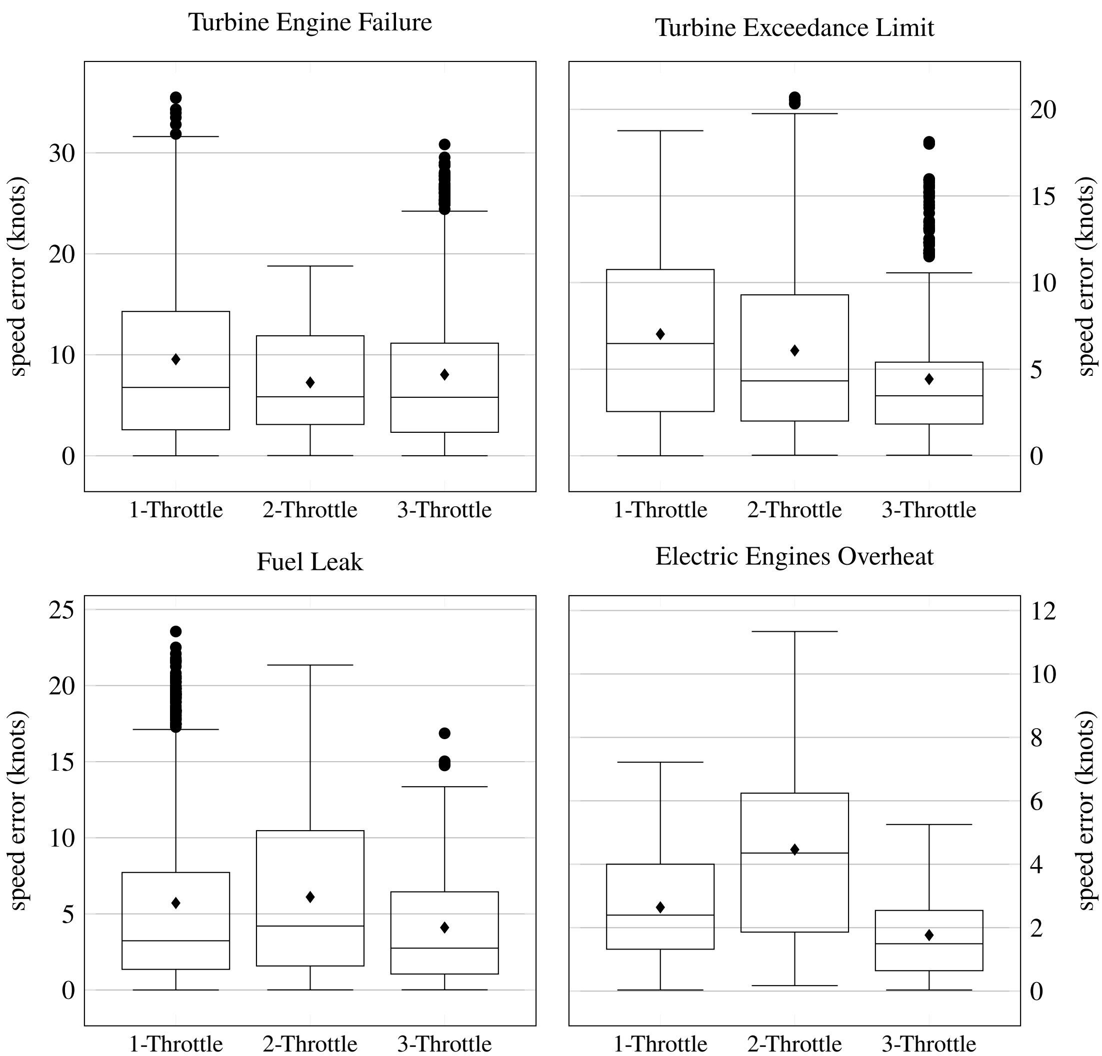

Fig. 6 Speed error versus failure event.

2. Electronic Checklist Completion Time

For each failure case with an electronic checklist, time was recorded to complete the associated checklist (Fig. 7). These times were plotted for each of the throttle lever conditions across all flightcrews. A mean value line shows the general trend across each throttle lever condition. The data shows 1) the time to complete a checklist was not operationally significant for the 3 throttle lever conditions; and 2) a trend towards shorter checklist completion times for the 3 throttle lever case.

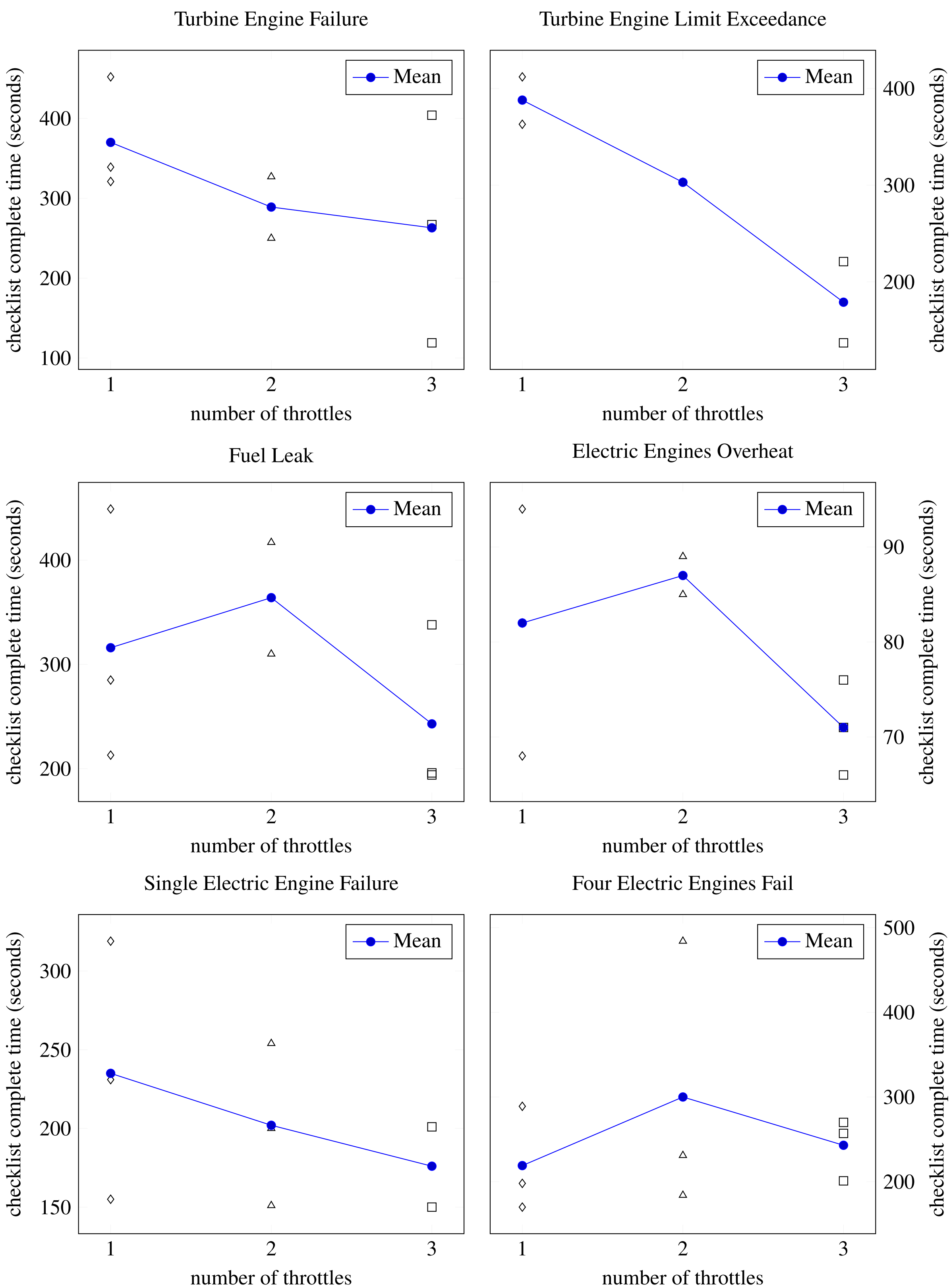

Fig. 7 Time to complete checklist for each failure event.

B. Qualitative

1. Situation Awareness and Workload

A three dimensional (Demand, Supply, and Understanding) SART[19] questionnaire and the NASA Task Load Index (TLX)[20] was administered to both pilots after each data run. An Analysis of Variance (ANOVA) revealed no statistically significant effects ($p < 0.05$) for the number of throttle levers for either SART or workload measures (Fig. 8).

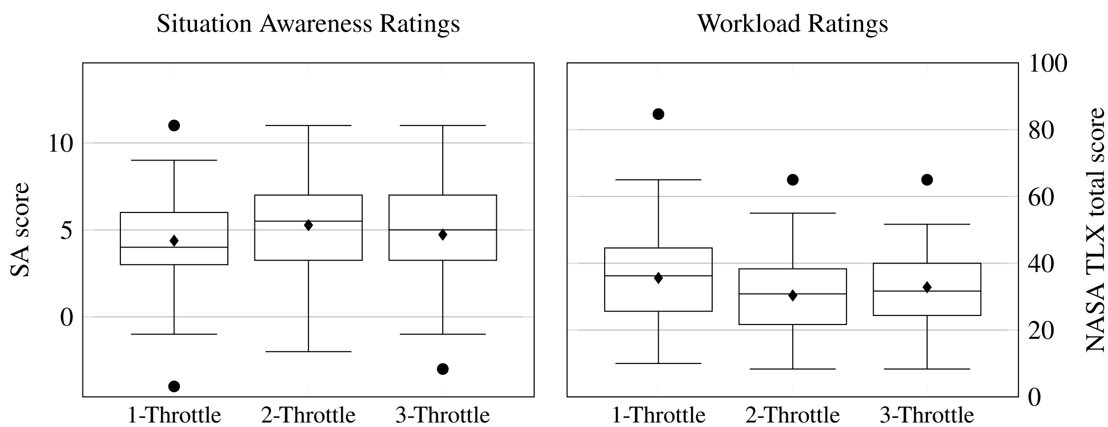

Fig. 8 Situation Awareness and Workload ratings are not statistically significantly (p>0.05).

2. Usability

After each data run, a usability questionnaire[21] was administered to each pilot. The usability questionnaire consists of 10 questions where pilots provide their level of agreement with statements about the usability of the thrust system (throttle levers and engine display). The responses to the 10 questions are used to calculate a single usability score for the thrust system. A score of 68.0 (dashed blue horizontal line in Fig. 9) and above is considered a good design and a score of 80.3 (solid green horizontal line in Fig. 9) and above is considered an excellent design. Figure 9 shows the usability scores for the throttles and the engine displays. All means and medians for each concept were in the "good" design range. The 2-Throttle, 3-Throttle and the Dials engine display concepts means and median were in the excellent design range.

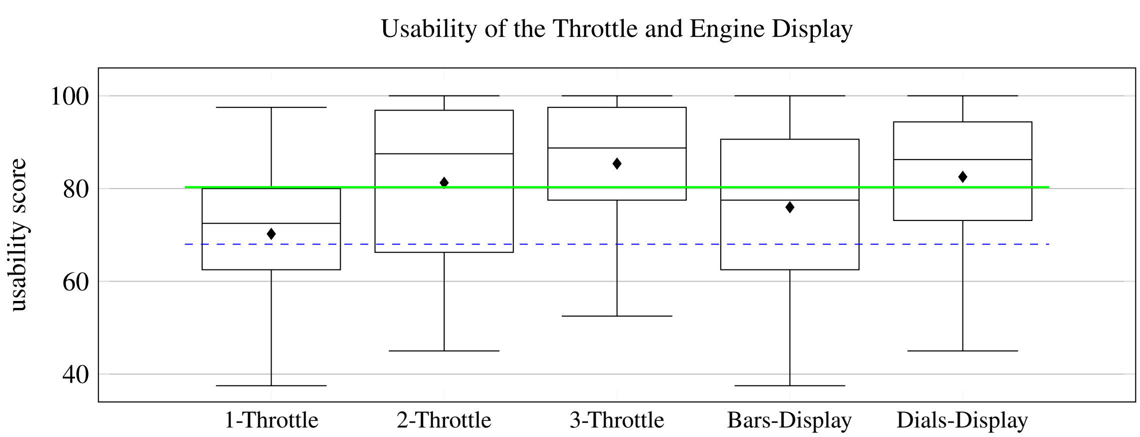

Fig. 9 Usability Score for the Thrust System.

3. Acceptability

At the end of each data run, pilots were asked to rate the acceptability of the thrust system (number of throttle levers and engine display). The rating scale was from 1 - 7, where 1 was defined as very unacceptable, 4 was defined as average acceptability, and 7 was defined as very acceptable. Figure 10 shows that both the means and median values were rated above average acceptability.

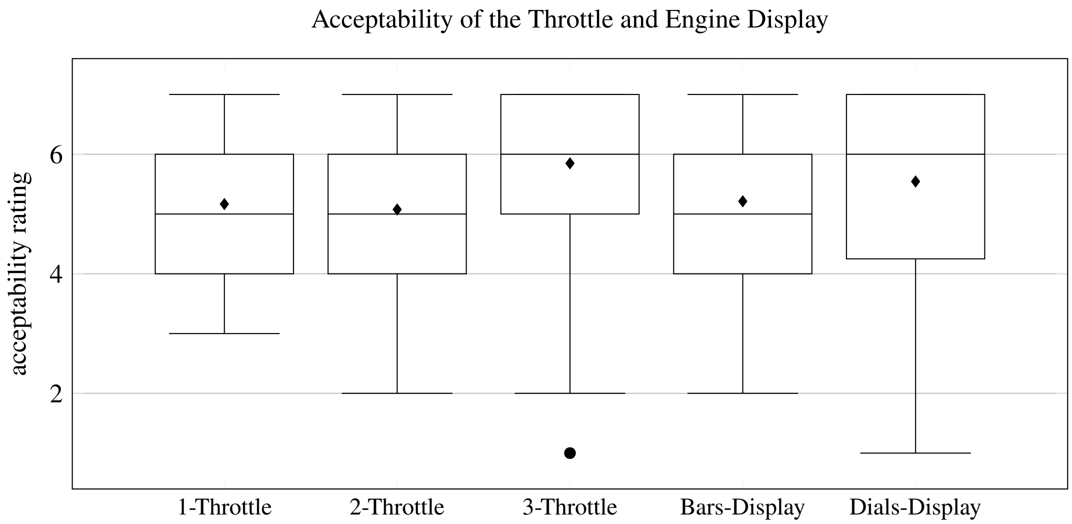

Fig. 10 Acceptability Ratings by Pilots. A rating of 1 was defined as very unacceptable and a rating of 7 was defined as very acceptable.

4. Pilot Rank Order for Throttle Levers

At the completion of all data runs, a semi-structured interview was conducted with the flightcrew. Pilots were asked to rank order their preference for the number of throttle levers during non-normal conditions. Ten pilots ranked the preference for the number of throttle levers as 3, followed by 1 with 2 being the least desired. Five pilots chose 3 as their top preference; however, their second choice was 2 followed by 1. Three pilots chose having 2 throttle levers as their top choice. The pilots' throttle lever preference is shown in Figure 11.

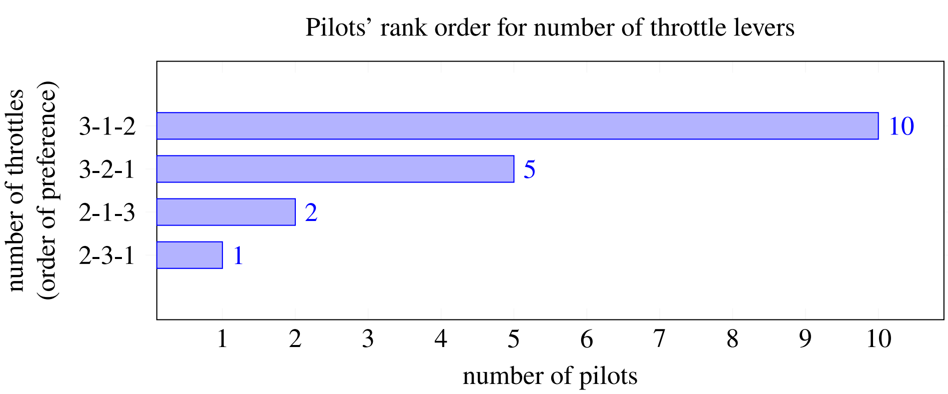

Fig. 11 Pilot preference for number of throttles.

IV. Discussion

A. Throttle Discussion

A single throttle lever was found acceptable for use in a commercial passenger aircraft. From the Acceptability questionnaire which has a range of 1 to 7, the median value for single throttle lever was 5.2, slightly higher than dual at 5.0 and lower than triple at 5.9. This data matches post-test pilot preference where 10 of 18 pilots ranked the number of preferred throttle levers as 3-1-2. Only 8 of 18 pilots preferred the dual throttle configuration as their first or second choice. Only three selected dual as their first choice. The most consistent comment during post-test debrief was the potential for confusion in a dual throttle configuration. Even though we used a tactile reminder during the study, some pilots commented that a significant difference in the feel of the throttle was needed between the turbine and electric engine throttle levers if a dual throttle configuration was used. Sixteen of 18 pilots preferred the triple throttle configuration either as first choice or second choice. Post-test debrief comments indicated this is the most consistent memory map between throttle levers and engine clusters and the one that would lead to the least confusion during failures without additional automated support. Twelve of 18 pilots preferred the single throttle configuration as their second choice. Although no pilots selected single as their top choice, many pilots indicated post-test that if automation support and additional controls were used for engine failures, they would prefer the single throttle configuration. Further design considerations are discussed in the usability scores discussion section below. When looking at acceptability scores for normal operations only, pilots rated the single throttle configuration above dual or triple.

There is no statistically significant difference between any of the throttle configurations when comparing situation awareness ratings using SART or workload ratings using NASA TLX. For the single throttle configuration, crews needed to toggle between engine control during non-normal operations. This may be reflected in the slight increase in workload for the single throttle configuration.

Median usability ratings indicate that any of the throttle configurations represent a good design with scores greater than 68. There is no operationally significant difference between either of the throttle configurations. Not surprisingly, dual and triple throttle quadrant designs are prevalent in the industry and pilots rated them an excellent design with scores greater than 80.3. There are currently no certified multi-engine, single throttle designs, for FAR Part 25 aircraft. Significant automation support of electric engine control is expected in the final design. Coupling of the flight controls is expected to be operational in the final design for directional control and stability. Pilot control of individual electric engines or the ability for pilot control of asymmetric thrust is not envisioned. Future designs of thrust control systems will likely be engaged full time and be equivalent to fly-by-wire. Dassault Aviation envisions this single throttle design in their next production aircraft, the Falcon 10X[22]. The control design for the SUSAN electric engine control is not yet finalized, so those aspects were not implemented in this study. Even with the novel single throttle design used in the study, where use of the auto-throttle disconnect was used to toggle between turbine and electric engine control while the auto-throttle arm was off, the design was still rated a good design. During the post-test interview, when a single throttle design was described where the single lever represented aircraft thrust with an auto-throttle capable of remaining engaged even during engine failures, pilots indicated that design would be significantly better than the one used in the study. When asked for improvements to the current designs, one pilot indicated maybe zero throttles, but this is clearly a minority opinion. Pilots suggested texturing or even different shapes of the throttle handles to differentiate turbine engine control and electric engine control. Some pilots even suggested using this difference even if a triple throttle configuration was used. One pilot suggested using a mechanical clutch with a nested throttle. The throttles would operate as a single throttle for normal operations and could be split for non-normals. One pilot suggested five throttles, one for each of the four motor-generators that control four electric engines and one for the turbine engine.

Another indication of usability is control of thrust during manual operations. This was measured by the median airspeed error as indicated by the difference between selected airspeed from the mode control panel and the indicated airspeed of the aircraft. For each of the failures, the time spent manually flying was when the auto-throttle was disconnected until the associated electronic checklist was complete. Errors during operation with the turbine engine failure include more configuration changes due to the transition from climb and stabilization of the aircraft for the return to the field for landing. Each time selected airspeed is changed, the mean error increases until the indicated airspeed is stabilized. Airspeed tracking within 10 knots is considered acceptable for enroute operations. There is little difference between throttle configurations with average values ranging from 3 to 9. There is the greatest error for the turbine engine failure during takeoff as expected. At no time did any of the flightcrews mis-manage airspeed and approach stall limits.

Time to complete the associated checklists was measured (Fig. 7). The checklists reported are the ones where auto-throttle arm was turned off which required some throttle manipulation to maintain aircraft control. There is little difference between the throttle configurations in the study. The time to complete the engine fail checklist using the single throttle configuration took one third more time than the other two throttle configurations. No real conclusion can be drawn from the checklist completion data as the sample size is small and many crews did not complete the required checklists before deciding to divert, which was the end-run criteria.

B. Engine Display

At the time of the study, detailed design for the electrical components that would be under direct pilot control, if any, was still being discussed. A full electrical schematic was provided during training and available during simulation runs but no system pages were created for use on the flight deck. Two different engine displays were modeled. One using a Boeing representation for the turbine engine display and an electric engine display using bars to represent thrust provided by each of the 16 electric engines. The second engine display concept used an Airbus representation for the turbine engine display and a round dial indication of aggregate thrust from each of the wing-mounted electric engines. There was no operationally significant difference in usability or acceptability scores reported during the study. A majority of the pilots are currently flying Airbus aircraft so there is a slight preference for the Airbus-like turbine display but pilot comments during and post-test interview indicate a strong preference for the bars display for the electric engine information. All 18 pilots indicated they preferred the bars displays over the dial representation for the electric engines. The following comments (see below) collected post-test support this preference. Some pilots commented on additional information they would like to see added as well.

- "Liked bars because the dials were confusing."
- "Prefer a little more information like engine limits."
- "Like the thermometer for the electric engines but prefer the dial from the other for the turbine engine."
- "Bars have more information and easier to read."
- "Want better bars."
- "Want color amber and red when below certain %."
- "5-minute countdown timer should be automatically displayed (for rechargeable batteries)."

C. Battery Control

The rechargeable batteries allow for 1) electric-only taxi; 2) balancing the electric load on the turbine during changing thrust; and 3) boost during climb power to allow for a smaller turbine engine. In addition, they are used to provide electric power to individual engines during some bus failures. Primary (single use/emergency) batteries are provided for backup power in the event of a turbine engine failure, or for use during generator failures if full thrust is needed from engine pairs after the rechargeable batteries have depleted their charge. Control of when rechargeable and primary (single use) batteries are connected to the respective electric engine bus is controlled by contactors and, for the final design, may be under: 1) manual control, 2) automated control, 3) manual with automated override, or 4) automated with manual override. During testing, automated control of the rechargeable batteries was implemented since this is the anticipated nominal operation. Manual control was chosen for the primary, single use battery as it was anticipated that pilots would like control over a resource that is essentially a reserve fuel supply. During the post-test interview, pilots were questioned if they preferred the method implemented for the test. Thirteen of eighteen pilots preferred to be in control of using the single use batteries and provided the following comments as justification.

- "Want to know when you are getting into reserves."
- "If there is a maintenance action, I want control."
- "You know when selected and use time hack."
- "Want manual to know the state, I would be concerned that auto mode would switch at an inappropriate time."
- "Manual, especially if irreversible."
- "Want to be in charge of that resource."
- "I would like to use rechargeable first but want to be in charge of that resource."
- "Always need manual way but should be automated."

Five of eighteen pilots indicated they would like to have the single use battery automated and provided the following comments to support their opinion.

- "Like automatic as long as there is a reference to time."
- "Automatic if automation let's the pilot know."
- "Drain as much as practical from rechargeable and start a timer on the EICAS. Automatic with manual override."

All but one pilot preferred automatic control of the rechargeable batteries as implemented in the study. Some pilots commented on the need for manual control to override the automation for the following reasons.

- "Would like manual control for thermal runaway."
- "Manual Override."
- "Manual only if you have to isolate a bad battery."

The pilot that preferred manual control made the following comment when presented with that scenario.

- "Manual but probably automatic if it happens on climb."

The following pilot comments indicate concerns, preference for additional controls, or additional messages than what was provide during testing.

- "Would like control over individual battery/engine."
- "If there is a way to select single use on selected engine, I would like to select that."
- "Concern over no APU (Auxiliary Power Unit)."
- "Want warning for potential loss of power."
- "5-minute timer on rechargeable battery needed."
- "Time on rechargeable batteries needs to be 10 minutes."

D. Pilots' Concerns for Hybrid Aircraft

Pilots were questioned during the post-test interview what their top concerns were for a hybrid aircraft in revenue service. The pilots provided the following concerns.

- Heat dissipation.
- How long do you actually have with backup batteries.
- Thrust reversing or drag from dead electric engine if not freewheeling.
- Lightning strikes
- Degraded battery performance over time
- Loss of all electric power.
- Time to charge or turnaround time on the ground.
- Rechargeable batteries need to be 10 minutes

V. Conclusions

An initial pilot study of the SUSAN airplane flight deck was conducted to determine the number of throttle handles for the thrust system. The data showed that one, two, or three throttle levers did not affect the pilot's situation awareness, workload, or speed control. Further, questionnaires and pilot interviews showed a preference towards having three throttle levers; but, post-test interviews indicated with better implementation and automation, a single throttle lever would be preferred. In addition, pilots preferred the individual thrust display of each electric engine rather than an aggregate of all the thrust on a wing. In post-test interviews, pilots expressed they wanted a simplified engine display tailored to the phase of flight. Future work will include exploring hybrid-electric propulsion engine displays using the results from this study as a starting point and improving the simulation of the hybrid-electric propulsion system.

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