IN-08
116465
P.96

NASA Contractor Report 4463

Engine Monitoring Display Study

Mary E. Hornsby

CONTRACT NAS1-18027
AUGUST 1992

NASA

NASA Contractor Report 4463

Engine Monitoring Display Study

Mary E. Hornsby
Boeing Commercial Airplane Group
The Boeing Company
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-18027

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1992

Table of Contents

Tables

No.

Figures

1. INTRODUCTION

1.1 Background

Monitoring the engines on today's commercial transport aircraft (either manually or electronically) is an extremely complex task. Even though the technology exists to provide detailed engine information, it is not often incorporated into today's transport aircraft, at least in a form that the crew can readily use. Because most engine parameters are graphically displayed near the pilot's primary field of view, they have not been included in the integrated crew alerting system. Furthermore, to evoke an alert in current cockpits, an abnormal event (e.g. engine fire) must occur or an instrument/sensor threshold must be exceeded. It is possible that many abnormal engine situations could be detected early or avoided altogether if the appropriate engine parameter information could be provided to the crew, correlated with information about other parameters. Finally, the presentation of most engine parameters does not vary based on the airplane state or take into account prior values. For example, although the red-line limit for engine temperature during engine start is different from the red-line limit for cruise operations, the red-line limit displayed for this parameter does not vary. In addition, the length of time that engine temperature or other parameter limits can be exceeded depends upon how much they are exceeded. Exceedance values differ for each engine and aircraft type, and are difficult to memorize and monitor. All these factors are made more difficult by the lack of a reference to help the pilot to determine what the expected range of values of a parameter is for specific conditions.

The system hardware and interfaces required to permit the crew to monitor the performance of their engines have been part of a continuously evolving technology. One of the first examples was the simple cycle counter that stored the number of engine start-ups and shut-downs. Today, a microprocessor-based "black box" records multiple engine parameters and warns of exceedances. Hardware and software are currently being developed (primarily for maintenance) that could develop into a third generation engine-monitoring system for the flight deck. One goal of this effort is to use engine modeling techniques which permit current parameter readings to be compared to expected, or "nominal," values. In developing the crew interfaces for such systems under a "human centered automation" philosophy, consideration must be given not only to the crew information requirements but also to the operational environment in which the system will be used. The amount and type of information presented to the crew should be situation dependent. Too much information, or information that is over- or under-processed, can cause degradation in crew decision making and problem solving as easily as too little information. At least three levels of information analysis can be identified for consideration: 1) system monitoring, which permits trend identification, anticipation of required actions, and planning; 2) alerting information, which gets the attention of the crew and provides identification of an out-of-tolerance condition; and 3) guidance information, which advises the crew of the actions appropriate for the situation. The focus of the current study is the display of information that can facilitate the monitoring and problem identification functions.

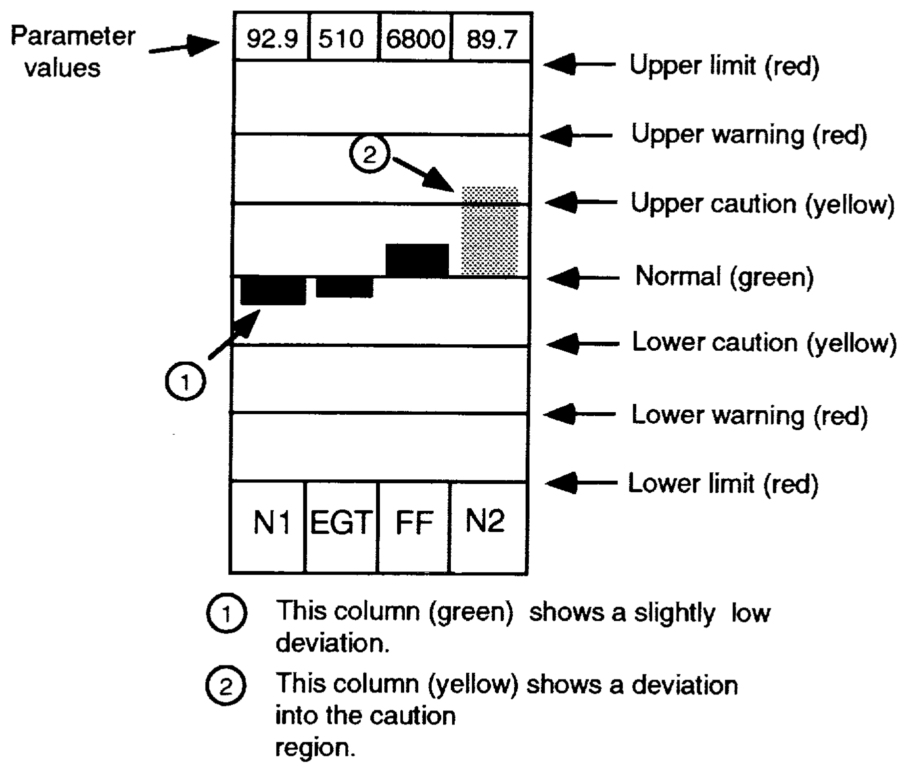


Figure 1. Example of Engine-Monitoring Display Element Derived from Task-oriented Design Process (from Abbott, 1989)

NASA has developed a "Task-Oriented Display Design" process (Abbott, 1989) which modifies the traditional design process by identifying and providing only relevant information in a form that is appropriate to the user's task. The application first chosen to demonstrate and evaluate this process was aircraft engine instruments because such instruments provide both a control task and a systems monitoring task. The result of the initial effort was an integrated engine parameter display that used bars that "grew" upward or downward from a horizontal line that represented "nominal" values to show engine parameter levels, and changed colors to show exceedances (Figure 1). One of the conclusions of this effort to compare traditional and task-oriented-designed displays was that "the overall results... showed a favorable increase of both the user's subjective assessment and failure detection rate (and therefore a reduction in what is typically termed 'operator error') for the task-oriented-design display." The results also confirmed the premise that "providing information that is tailored to the user's task, both in content and form, increases the user's ability to utilize that information" (Abbott, 1989). The goal of the current study was to modify the application of the NASA task-oriented design concept to incorporate it into currently operational "glass cockpit" engine displays, and to evaluate it using pilots in a full mission simulation.

1.2 Candidate Display Concepts

Five candidate engine-monitoring display formats were developed for this study using the Engine Indicating and Crew Alerting System (EICAS) displays currently used in Boeing advanced cockpits (757, 767, and 747-400) as a baseline. The five formats were designed to evaluate and compare the operational utility of adding three types of task-oriented information to the basic EICAS displays: engine parameter alert (caution and warning) messages, messages to "monitor" an engine parameter that deviates from expected values, and a graphic depiction of the range of nominal or expected values for the parameter for current conditions. The five display formats represent the major factor in the experimental design: Display Condition. Briefly, the five display formats are as follows:

Display Condition 1: Basic EICAS. Conventional EICAS engine displays; color changes occur when a parameter exceeds caution and/or warning limit(s); alphanumeric caution and warning messages appear for systems problems, but not for the graphically-displayed engine parameters.

Display Condition 2: Basic EICAS with engine parameter alert messages. Similar to Display Condition 1, except that alphanumeric alert messages are added if the value of any graphically-displayed engine parameters exceed caution and warning limits.

Display Condition 3: Augmented EICAS with green bands. Similar to Display Condition 1, except that an engine model augments the information available about engine performance and provides "nominal range" data for each engine parameter. The nominal range is shown by adding "green bands" to the graphical display. Color changes occur when the value of any parameter is outside the nominal range; no alphanumeric messages appear for the depicted engine parameters.

Display Condition 4: Augmented EICAS with engine parameter alert and "monitor parameter" messages. Similar to 3, except that the nominal ranges generated by the model are not depicted graphically. "Monitor parameter" messages and color changes occur when the value of engine parameters are outside the nominal range; engine parameter alert messages appear when parameter values exceed caution and warning limits.

Display Condition 5: Augmented EICAS with green bands, and engine parameter alert and "monitor parameter" messages. Combines features of Display Conditions 3 and 4; includes green "nominal range" bands, and both engine parameter alert and "monitor parameter" messages when appropriate.

The display conditions are described in more detail in section 5.2, and examples are shown in Figures 4 through 10. It should be noted that the display formats as implemented in this study are not necessarily sanctioned by Boeing.

2. STUDY OBJECTIVES

The overall objective of this effort was to develop operationally-viable display concepts for an engine monitoring system that would enable the crew not only to monitor engine trends more effectively but also to detect trends in multiple parameters. The specific objective for the current study was to evaluate the five EICAS display variants in a simulated operational environment under various non-normal conditions. In doing so, the goals were to:

a) Evaluate the concepts for performance differences.
b) Evaluate which, if any, of the features added to the basic EICAS format were useful or desirable.
c) Evaluate the perceived workload associated with each concept.
d) Determine what changes are recommended by the user community for engine monitoring displays and their implementation.

3. SUBJECTS

A total of 10 experienced transport pilots participated as subjects in the concept evaluation test. Because the test was to be conducted in a medium-fidelity research simulator equipped with a Pratt and Whitney 2037 two-engine model and EICAS, subject selection was restricted to pilots who were type-rated in the 757, which incorporates the EICAS displays and uses the Pratt and Whitney 2037 engine. It was hoped that this restriction would permit the subjects to make more meaningful judgements about the operational acceptability and perceived workload of the system. Three of the pilots who acted as subjects in the study were current line pilots with a major U.S. airline; the other seven were Boeing Flight Training pilots who could provide input from a training perspective. Data about the subjects and their experience is summarized in Table 1.

4. FACILITIES

A proper evaluation of any aircraft display or control system involves the problem of realistically duplicating the operational conditions (environment, workload, procedures, perception, etc.) under which the display or system is generally used. The amount of realism required to accomplish the evaluation is dependent on the objectives of the test. The environment created by the facility must be realistic enough to generate data which satisfy these objectives. In the current study, the technologies being evaluated required a facility capable of supporting advanced display concepts and providing a realistic environment for their operation. The following sections describe the test facility and the components that were used in the study

4.1 Engineering Flight Simulation Center

The Engineering Flight Simulation Center (EFSC) is a portion of the Flight Systems Laboratory which is the principal flight simulation and avionics test facility used in the design, development and certification of Boeing Commercial Air Transports. It is one of the foremost engineering simulation facilities available in the industry and can support all phases of avionics system development and testing. The laboratory contains all the components necessary to conduct a complete man-in-the-loop real-time aircraft simulation. It includes the Flight Deck Research Cab which provides a flexible tool for research and development efforts.

SUBJECT #	1	4	2	3	5	6	7	8	9	10		AVG. ALL	STD. DEV. ALL	AVG. BOEING	AVG. UNITED
TYPE(B=Boeing, U=United)	B	B	U	U	B	B	B	B	U	B					
Yrs. Employed by UAL/BCo	5	3	25	26	6.5	3	4	2.5	26.5	3		10.5	10.7	3.9	25.8
Present Status: (United)															
-Captain			yes	yes					yes						
Present Status: (Boeing)															
-Instructor pilot	Yes	Yes			Yes	Yes	Yes	Yes		Yes					
Age	46	45	48	55	54	42	47	51	51	46		48.5	4.1	47.3	51.3
Years served as pilot:															
-Military	20	0	0	5	21.5	17	20	0	8	22		11.4	9.6	14.4	4.3
-Airline	0	15	25	26	1	0	0	23	26	0		11.6	12.4	5.6	25.7
-General Aviation	0	6	10	20	34	0	0	4	2	0		7.6	11.2	6.3	10.7
-Other	0	0	0	0	4	0	0	0	0	0		0.4	1.3	0.6	0.0
-Boeing	5	3	0	0	6.5	3	4	2.5	0	3		2.7	2.2	3.9	0.0
Number of 757 hours:															
•Captain/Pilot															
-Aircraft	58	10	500	200	30	10	31	20	500	15		137.4	199.2	24.9	400.0
-Simulator	99	20	0	0	25	20	64	45	10	40		32.3	30.9	44.7	3.3
Number of 767 hours:															
•Captain/Pilot															
-Aircraft	0	0	1300	2700	45	20	80	5	400	100		465.0	881.7	35.7	1466.7
-Simulator	79	0	30	40	25	10	20	45	10	200		45.9	58.6	54.1	26.7
Number of 747-400 hours:															
•Captain/Pilot															
-Aircraft	38	0	0	0	0	0	0	0	400	0		43.8	125.7	5.4	133.3
-Simulator	70	0	0	0	0	0	0	0	25	0		9.5	22.7	10.0	8.3

Table 1. Summary of Subjects Experience

4.2 Flight Deck Research Laboratory and Cab

The Flight Deck Research Laboratory is a basic engineering laboratory that provides research and development capabilities to facilitate the progressive evolution of new display and control concepts. It was established to provide for systematic increases in simulation and technological capabilities; and to provide part-task demonstration and evaluation. This laboratory provides capabilities to support (1) early laboratory work requiring use of bench development and test facilities, (2) successive stages of partial simulation using simplified approximations of sensor and aircraft systems, and (3) concept implementation for full simulation to confirm the application.

Associated with this laboratory is the flexible all-electronic Research Cab (shown in Figure 2), which has been developed to fulfill a dual purpose. First, the cab provides a facility to appraise the requirements for an individual display or control, including both context (formats) and content (information requirements). It also permits the preliminary evaluation of dynamic display formats to ensure that the pilot receives the information quickly and accurately. Secondly, the cab provides the facility to initiate systems integration which is necessary in the development of new displays and controls. The cab facilitates evaluation of the degree to which new concepts meet flight deck system requirements. The cab also provides the facility to conduct architectural integration of new display/control concepts. As a system integration facility, the cab has become a concept demonstrator and the foundation for the development of advanced flight deck applications.

The cab instrumentation used in the current study is shown in Figure 2. The configuration included D-size display units (6.5" by 6.5" display area) for both the Electronic Flight Instrument System (EFIS) and the Engine Indicating and Crew Alerting System (EICAS) displays. These displays were driven by the Evans and Sutherland advanced Display Development System (DDS) which permits rapid prototyping of display formats, and provides flight-quality graphic formats that can be easily reconfigured for research and development testing. The flight control system used in the cab for this study was a wheel/column implementation with hydraulic "feel" system. This cab was provided with a switchable day/night Computer Generated Imagery (CGI) visual system for out-the-window displays. This is a two viewpoint CT-5 system manufactured by Rediffusion/Evans and Sutherland, and provided the pilot and co-pilot/observer with a front-window-collimated display. Each of these displays comprised a color TV monitor, beam splitter, and spherical mirror.

Figure 2. Research Cab and Instrumentation

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

5. METHODOLOGY

5.1 Design and Rationale

The test described in this section was designed to evaluate the effectiveness and viability of using engine models as a means of providing information to enable the pilot to monitor engine parameters more quickly and accurately in the operational environment, and to evaluate different formats for providing the information. The basic experimental design for the study is presented in Figure 3. The test compared the five EICAS display formats on the basis of both objective data (subject response time and accuracy) and subjective data (subject ratings). The test design was a 5 x 2 x 2 factorial within-subject design with repeated measures on all three independent variables. The "Display Condition" variable had five levels; the "Number of Engines" variable had two levels; and the "Problem Onset Time" variable had two levels.

5.2 Display Conditions

The Display Condition variable had five levels. The first level was the standard EICAS (with slight modifications) used on Boeing 757 aircraft equipped with Pratt and Whitney 2037 engines. Each of the other display conditions had one or more features added to the basic EICAS display format. Table 2 summarizes the characteristics of each display condition.

5.2.1 Display Condition 1: Basic EICAS.

Features described in this section were common to all display conditions; each of the other conditions added one or more features to the Basic EICAS display format. In the basic (standard) EICAS display used in this study, information about engine parameters is shown in either round-dial or vertical-scale formats on two screens in the center front of the cockpit. Figure 4 shows the upper and lower EICAS screens when no engine problem exists. (All other figures in this section will show the display features present when an engine problem occurs, and include only the upper screen if appropriate.) In the case of round-dial indicators (EGT, for example), a pointer shows the current level of the parameter along the circumference of the dial. Red and amber tick marks along the circumference mark the upper and (if appropriate) lower caution and warning limits for the parameter. For vertical-scale parameters (oil temperature, for example), a caret-

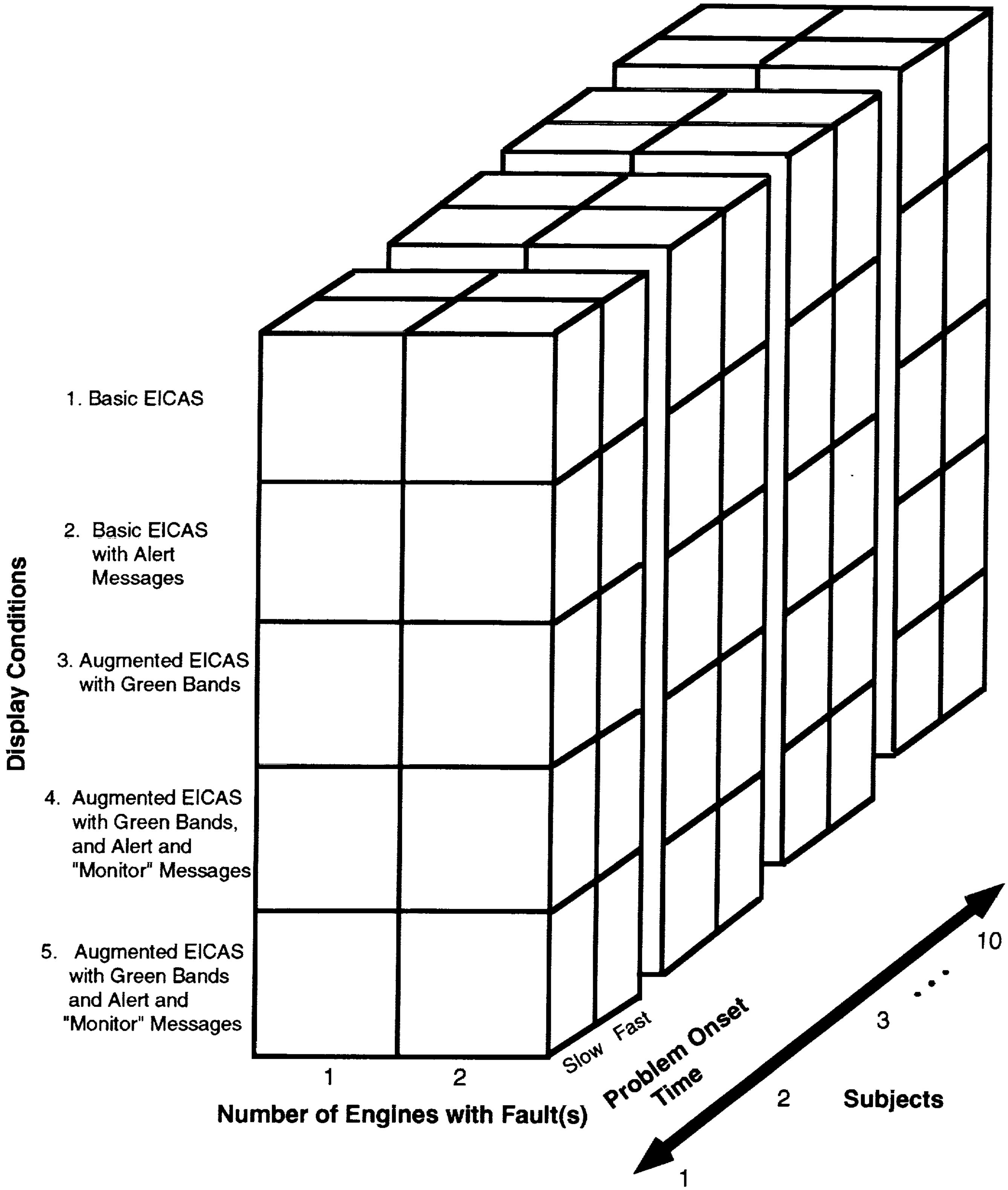


Figure 3. Basic Experimental Design

type pointer shows the current level of the parameter along the length of a vertical line; upper and lower caution and warning limits are shown, as appropriate, as tick marks at the top or bottom of the vertical scale.

DISPLAY CONDITION / FEATURES	1 Basic EICAS	2 Basic EICAS with Alert Messages	3 Augmented EICAS with Green Bands	4 Augmented EICAS with Alert and Monitor parameter Messages	5 Augmented EICAS with Green Bands and Alert and Monitor parameter Messages
Alphanumeric alerting messages for non-engine systems problems	X	X	X	X	X
Alphanumeric alerting messages (caution/ warning) for engine parameters		X		X	X
Alphanumeric "monitor parameter" messages for engine parameters				X	X
Green bands to depict "nominal range" for each engine parameter			X		X
Pointer and digital readout/box change color only when engine parameter exceeds caution/warning limits	X	X			
Pointer and digital readout/box change color when engine parameter value departs from "nominal range"			X	X	X

Table 2. Display Condition Features

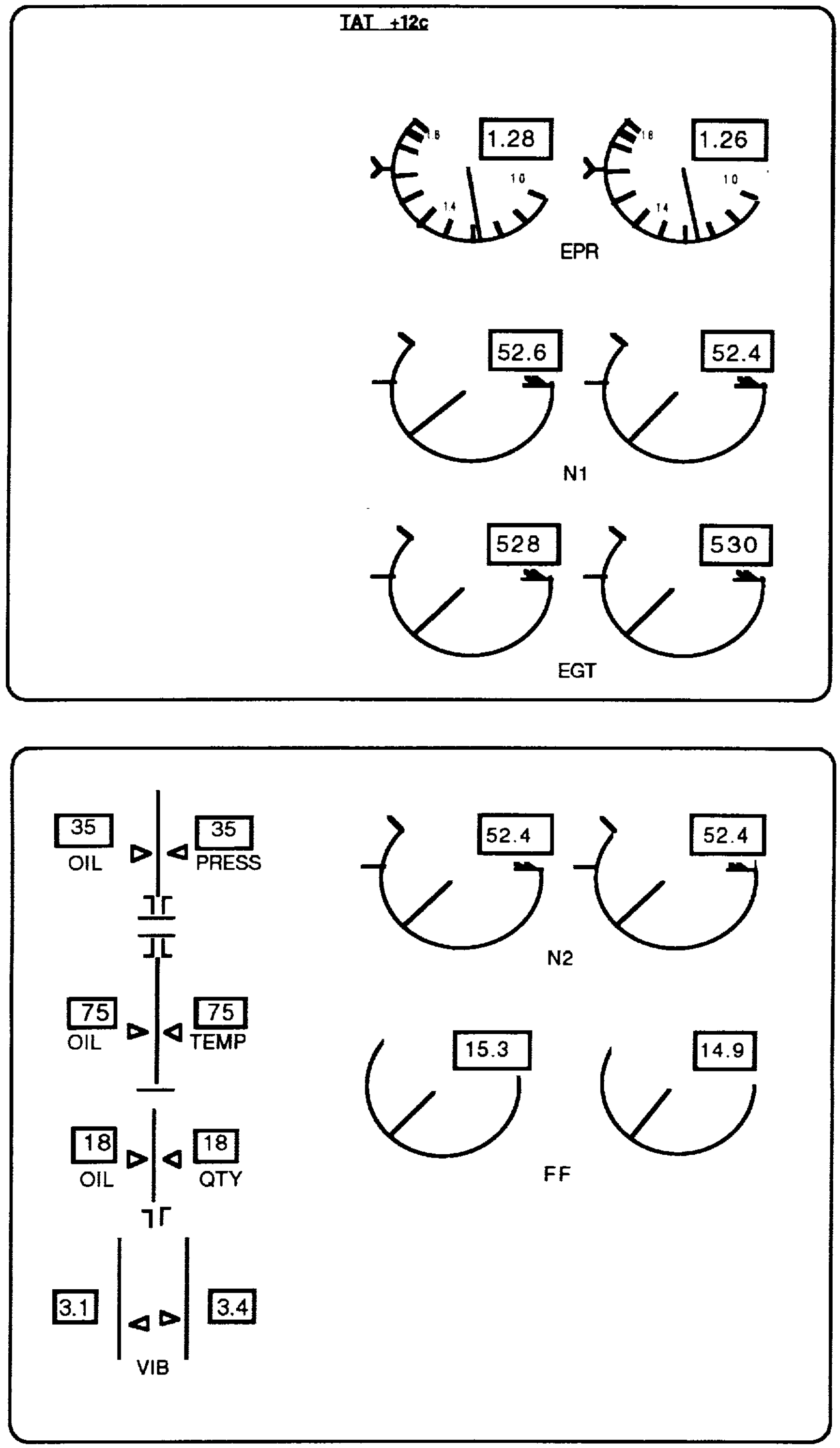


Figure 4. Example of Display Condition 1:
Basic EICAS, All Parameters Normal

For both round-dial and vertical-scale formats, these limits are normally "hard" limits; that is, they are set for the particular type of engine, and do not vary based on the current conditions or the operational history of the engine. A box with a digital readout also shows the current value of the parameter for each of the graphically-displayed engine parameters.

When the current value of the parameter exceeds caution (amber) or warning (red) limits, the pointer and the digital-readout box and number turn amber or red, respectively (see Figure 5). Information about non-engine systems status is presented in the form of color-coded alphanumeric caution, warning, and status messages in the top left corner of the upper display. These messages are listed in order of priority (first warning, then caution and status messages) and accumulate if necessary. No alphanumeric messages are presented in the basic EICAS system for the graphically-displayed engine-parameters.

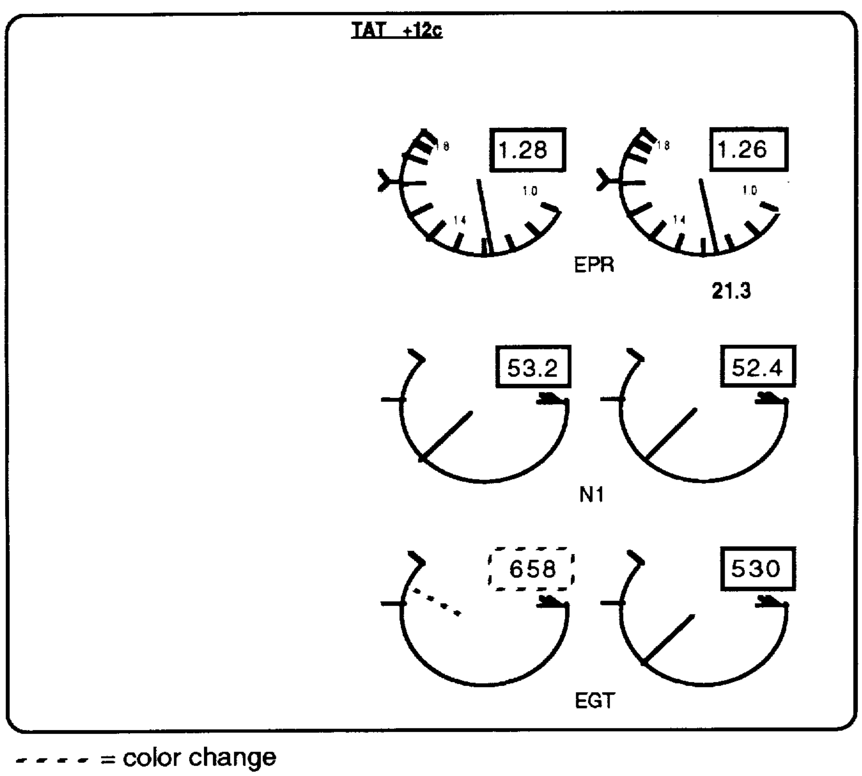


Figure 5. Example of Display Condition 1:
Basic EICAS, Left-Engine High EGT

The basic EICAS display format used in this study (Display Condition 1) differed from the standard EICAS presentation used on Boeing aircraft equipped with Pratt and Whitney 2037 engines only in the following ways. First, under most conditions, engine information is presented in a compact form only on the upper (of two) EICAS display screens in the aircraft, and the lower screen is blank. If a problem occurs that involves information normally presented in its full format on the lower screen, the lower screen information is automatically presented. During this study, however, EICAS information was always shown in full format on both screens. Second, in the standard EICAS format used on Boeing aircraft, the entire round-dial and vertical-tape scales that represent engine parameters are white. In this study, the portion of these scale that represented caution and warning conditions (above the upper, or below the lower, caution and warning limits) for engine parameters were colored amber and red, respectively. Finally, in the standard EICAS system, aural tones accompany the presentation of alphanumeric caution and warning alert messages. In the present study, aural alerts occurred only under the limited conditions described in section 5.3.2.

In this study, the EICAS display format for a Boeing 757 equipped with a Pratt and Whitney 2037 engine was used as the baseline. It is representative of current airline systems and was used so that realistic operational data could be obtained for comparison. As noted previously, this display was used in the expanded mode (two screens) so that all the parameters would be presented at all times. For the Pratt and Whitney 2037 engine, simulated in this study, the following parameters were presented. On the upper screen, Engine Pressure Ratio (EPR), N1, and Exhaust Gas Temperature (EGT) were shown in a round-dial format. On the lower screen, N2 and Fuel Flow (FF) were shown in a round-dial format, and the following parameters were shown in a vertical-scale format: oil temperature, oil pressure, oil quantity and engine vibration. For all parameters, the maximum/minimum caution and warning limits were marked on the scales with amber or red tick marks. When a specific parameter caution or warning limit was exceeded, the pointer (or caret), and the numeric readout and box changed to amber or red, as appropriate. No other alert indication was presented with the color change.

5.2.2 Display Condition 2: Basic EICAS with engine parameter alert messages.

The second display condition for this study integrated engine parameter information into the alert message system by adding alphanumeric messages about engine parameter exceedances. When a parameter limit (upper or lower) was exceeded, an appropriate caution or warning alert message (e.g. L ENG N1) appeared in the top left corner of the upper EICAS display, where caution, warning and status messages appear for other system alerts. This alert message was in addition to the standard change in color from white to amber or red for the pointer and the box with digital readout. An example of Display Condition 2 is shown in Figure 6. In this example, N1 is in the caution zone for the left engine.

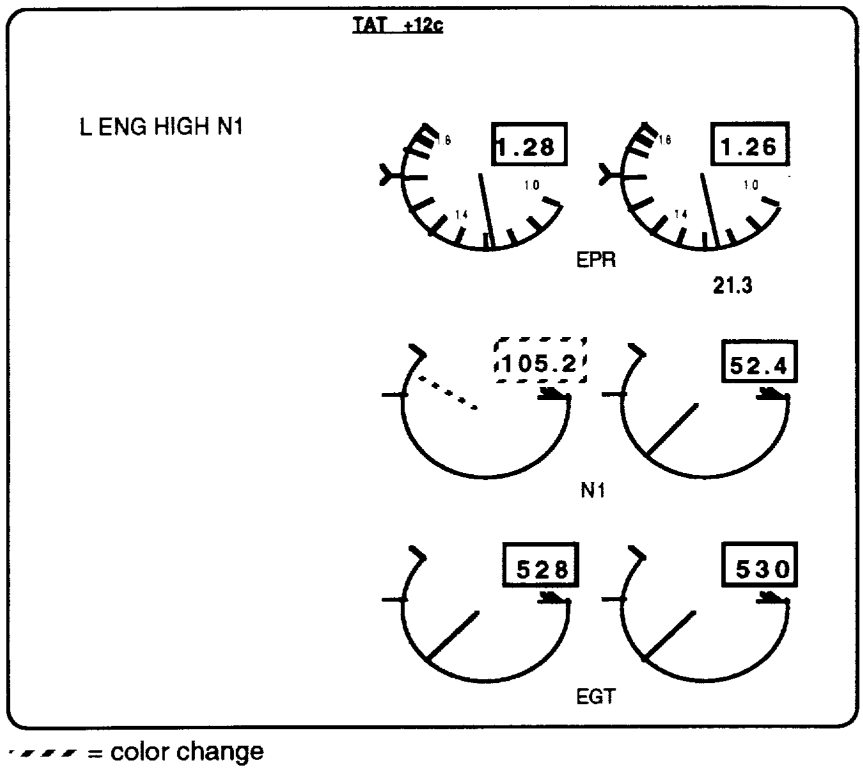


Figure 6. Example of Display Condition 2:
Basic EICAS with Engine Parameter Alert
Messages, Left-Engine High N1

One hypothesis of the study was that under high workload conditions, the addition of an alphanumeric engine parameter caution or alert message would benefit the detection of, and identification of, engine faults. This could result partially from the salient location of the message, which is in the top left corner of the upper EICAS display, closest to the primary flight displays. Additionally, placement of the message in the top left corner would make the display conditions associated with engine problems more similar to that of problems with other systems. If subjects are accustomed to seeing most caution- and warning-level problems identified by alert messages displayed in a consistent color- and spatially-coded alphanumeric form in a specific location, it may take longer to detect and respond to problems not identified in that manner.

5.2.3 Display Condition 3: Augmented EICAS with green "nominal range" bands

In the third display condition, a graphic display of the range of acceptable nominal engine values for the current conditions for each parameter was added to the basic EICAS display to allow the user to compare the current value of the parameter with the nominal, or expected, range. This range was generated by an engine model running as a background routine of the simulation software. This engine model was a simplified Pratt and Whitney 2037 engine, developed by Boeing with data provided by Pratt and Whitney. The model incorporated effects of airspeed, altitude, air temperature, air pressure, and throttle position. It was used to predict a range of values of each parameter that was expected ("nominal") for a given flight phase or operating condition. A more sophisticated model could also take into account, for example, the operational history of a given engine. Comparing current parameter values to those generated by the model permitted the system to detect not only when parameter caution and warning limits were exceeded, but also when parameter values deviated significantly from nominal range values. A dynamic "green band" along the inside of the round-dial format, or along the sides of the vertical-scale format, showed the extent of the nominal range. In this study, the dynamics of the green band were simplified. The bands moved as appropriate around the circumference of the round-dial indicators, or up and down the side of the vertical-scale indicators. However, the green bands for a particular parameter did not vary in their extent (arc or vertical length) as would be expected in a fully dynamic model.

In this display condition, the location of the current value of the parameter relative to the nominal range could be determined by comparing the location of the pointer (for round-dial indicators) or the caret (for vertical-scale indicators) to that of the green band. It was assumed that the graphic display of the nominal range would make it easier and quicker to determine if a parameter was starting to deviate from normal, and whether that deviation was high or low for the current conditions. The pointer or caret, and the numeric readout and box, changed color to amber whenever the value of the parameter went outside the nominal range; when this happened, the position of the pointer was also outside area indicated by the green band. The pointer, box, and readout also changed to amber or red, as appropriate, if a caution or warning limit was exceeded (if it had not already done so). In this display condition, no alphanumeric alert message appeared if an engine-parameter limit was exceeded. By comparing performance using Display Condition 3 to the performance using either Display Condition 1 (basic EICAS) or Display Condition 2 (basic EICAS with engine parameter alert messages), the hypothesis that the green "nominal range" bands aid in detecting or identifying the direction of engine parameter deviations can be tested. Figure 7 shows a representation of Display Condition 3. In this example, left-engine N1 is outside the nominal range, but not yet in the caution range.

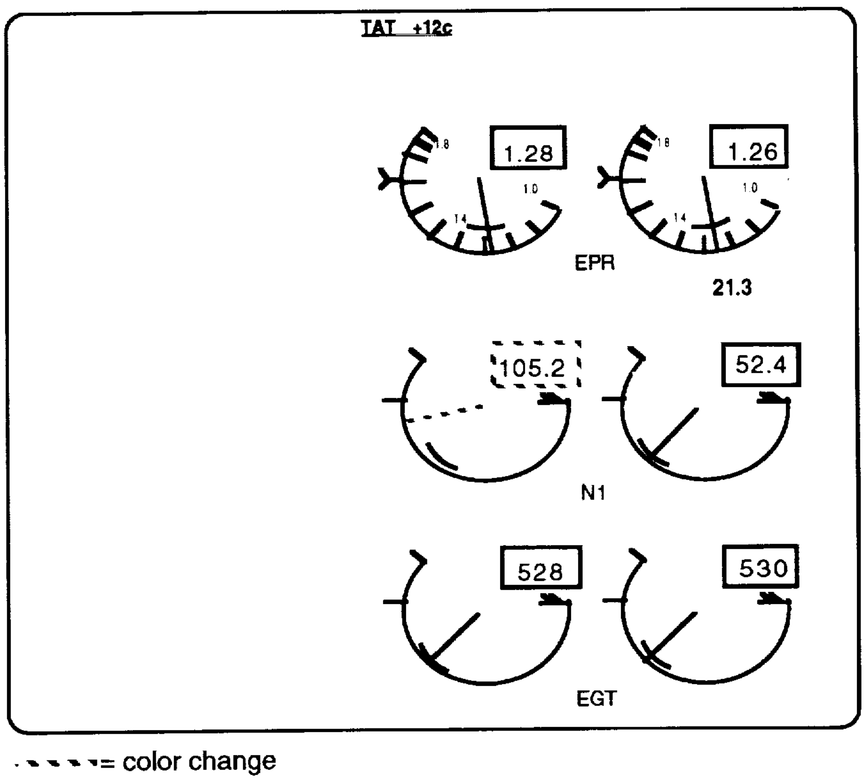


Figure 7. Example of Display Condition 3: Augmented EICAS with Green Bands, Left-Engine N1 Outside Nominal Range

5.2.4 Display Condition 4: Augmented EICAS with engine parameter alert and "monitor parameter" messages.

As in Display Condition 3, an engine model was incorporated into Display Condition 4, and a process compared the values generated by the model with current values. In this display condition, however, the range of the nominal values was not displayed graphically. Instead, if the value of one of the engine parameters went outside the nominal range, an appropriate "monitor parameter" message was generated, e.g. "MONITOR L ENG N1," and the pointer and the box with digital readout changed from white to amber. If the value of the parameter continued to deviate and exceeded caution or warning limits, an appropriate engine-parameter alert message appeared in addition to the "monitor parameter" message. This display condition, without the green bands to graphically indicate the range of nominal values, might not permit subjects to identify easily the direction of the fault (i.e. high or low values) but it could draw attention to the problem parameter and engine. An example of Display Condition 4 is shown in Figure 8. In this example, N1 is outside the nominal range (not depicted), but not yet in the caution range.

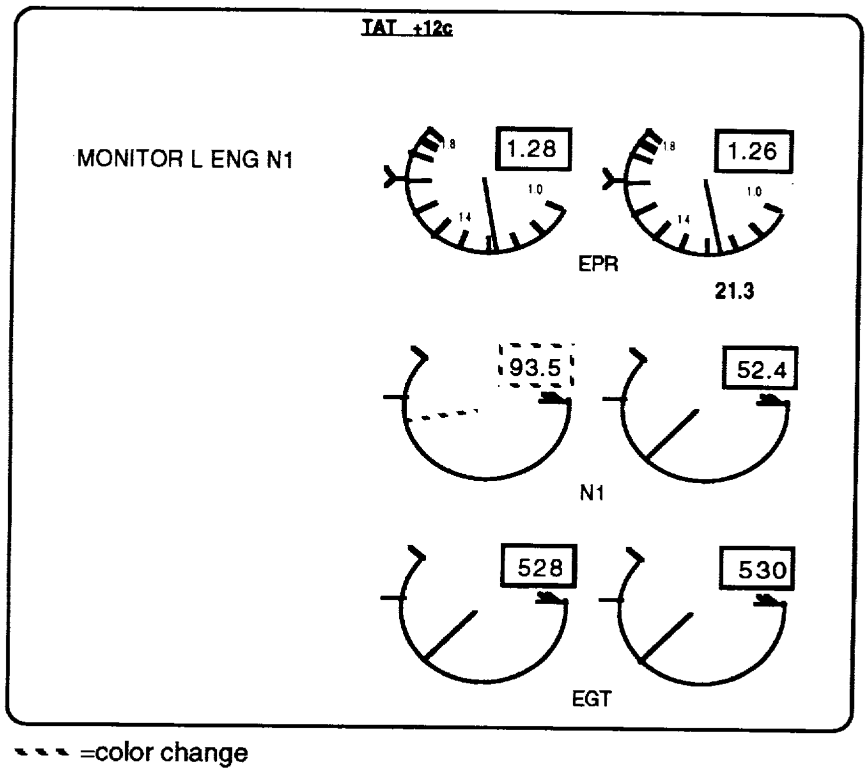


Figure 8. Example of Display Condition 4:
Augmented EICAS with Alert and "Monitor Parameter"
Messages, Left-Engine N1 Outside Nominal Range

5.2.5 Display Condition 5: Augmented EICAS with green bands, and engine parameter alert and "monitor parameter" messages.

The final display condition combined features from Display Conditions 3 and 4. The display of nominal ranges was the same as in Display Condition 3: nominal ranges were shown as green bands along the circumference of the round-dial parameters, and along the sides of the vertical-scale parameters. The form and timing for alphanumeric "monitor engine parameter" and caution and warning alert engine parameter messages were identical to that in Display Condition 4. Figure 9 shows a photo of Display Condition 5 in the Research Cab with right-engine N1 in the caution range. Figure 10 shows a line-drawing example of Display Condition 5 with right engine oil pressure (on the lower screen) outside the normal range but not yet in the caution range.

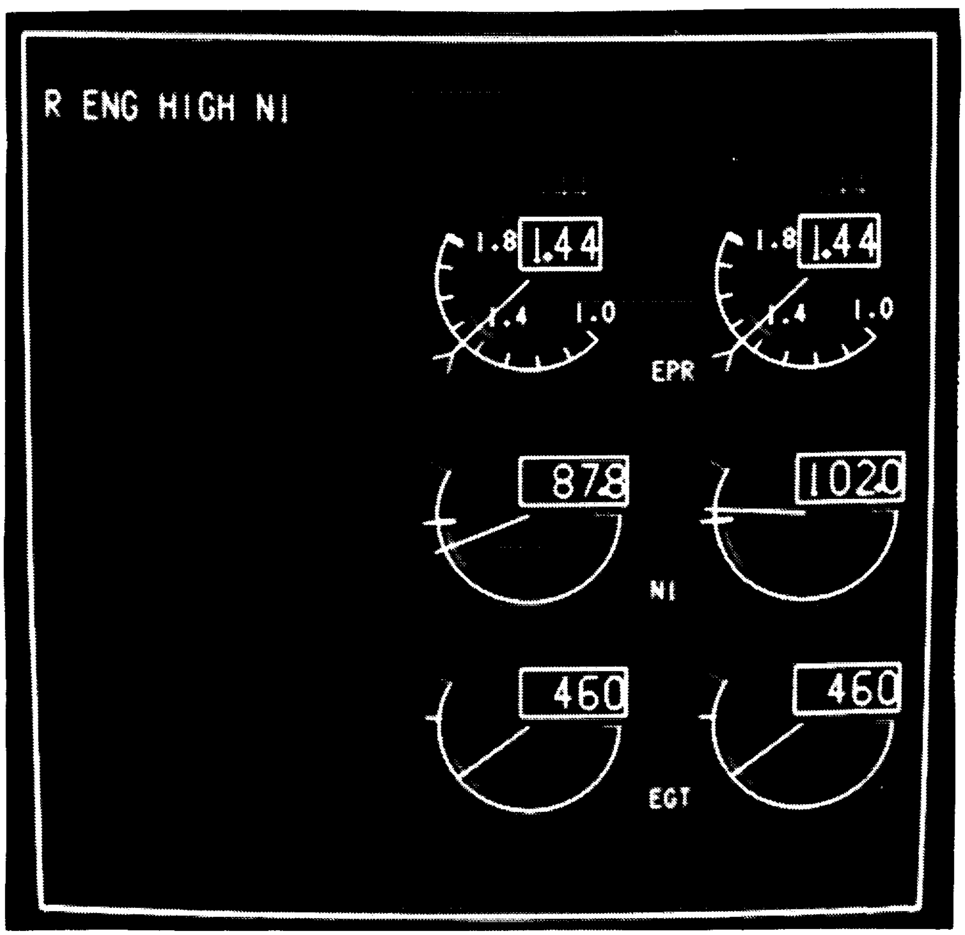
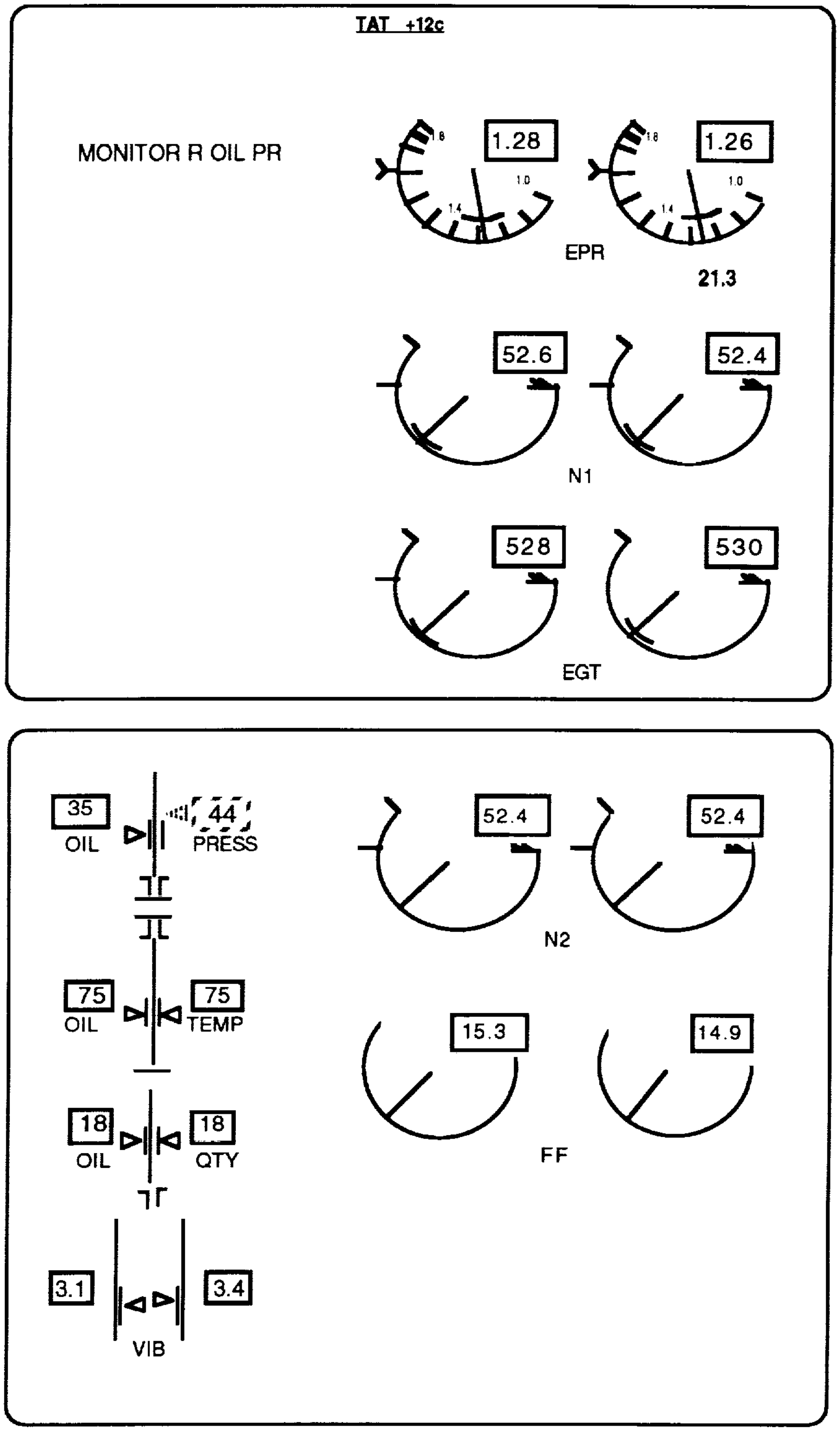


Figure 9. Example of Display Condition 5 in Research Cab: Augmented EICAS with Green Bands, Engine Parameter Alert and "Monitor Parameter" Messages, Right-Engine N1 in Caution Range



= color change

Figure 10. Example of Display Condition 5: Augmented EICAS with Green Bands, Alert and "Monitor Parameter" Messages, Right-Engine Oil Pressure Outside Nominal Range

Research has shown that a significant portion of response time variance is generated by the time it takes to detect the problem (Boucek et al., 1980). In normal operation, an aural warning accompanies the presentation of any alphanumeric caution or warning message on the basic EICAS display and aids in detecting the problem. However, a decision was made to eliminate the aural warning in this study for all the caution and warning alert messages (both engine and non-engine) in all display conditions. Aural warnings were eliminated because they could act as a consistent cue that a non-normal event had occurred and invalidate the use of the response-time dependent variable.

5.3 Number of Engines with Faults

The second variable that was manipulated in the study was the number of engines that exhibited an engine parameter fault. Half the engine-related problems that occurred affected only one engine, and half affected two engines. Whenever a two-engine problem occurred, the parameter affected and the extent of the problem was identical for both engines. If the subject performed a normal cross-check between engines, it was hypothesized that it should have been easier to detect an out-of-tolerance parameter in one engine than in two engines because the displayed indications (location of the pointers or carets, level and rate of change of the numeric readout) would differ for the engines for that parameter. However, the benefit (if any) of adding the green "nominal range" bands (Display Conditions 3 and 5) might not be as great when a fault in a given parameter occurs in a single engine as when the fault occurs simultaneously in both engines. This could result because visually comparing the position of the pointer or caret to the position of the green band for a given parameter may provide a more useful reference for the expected range of a parameter than cross-checking the value of that parameter on the second engine.

5.4 Problem Onset Time

The third variable manipulated in this study was Problem Onset Time: the amount of time it took for an engine problem to develop and manifest itself on the EICAS display(s). After a parameter value (or values) began to change when an engine problem was triggered, it could go outside the "nominal range" (if appropriate for the display condition), or exceed caution and warning limits, more or less rapidly. Problem Onset Time was defined as the amount of time from the problem trigger point to the time that the pointer and digital readout and box changed color and/or an alphanumeric alert message appeared, depending on the display condition. "Fast-onset" times were programmed to be between five and nine seconds; "slow-onset" times were between 20 and 25 seconds. Problem Onset Time was not independent of Display Condition, because the display changes that defined the end of the problem onset time (color changes and/or alphanumeric messages) appeared sooner for some display conditions than for others. For example, in the augmented EICAS conditions (Display Conditions 3, 4, and 5), a comparison of the current engine parameter values to the "nominal" values for those parameters provided by the engine model triggered color changes in the pointer and digital readouts whenever an engine parameter value departed from the "nominal range." For Display Conditions 1 and 2, these same color changes did not occur until the parameter value exceeded caution and warning limits. This meant that the pointer would have to travel farther from the baseline value in the latter display conditions before highly salient changes in the display would indicate a problem. For engine problems that develop very quickly, the addition of graphic information about normal parameter ranges may not be as useful in predicting engine problems, although it may be useful for overall problem monitoring. This problem and its implications are further discussed in the Data Analysis and Results sections (7 and 8).

For the primary independent variable, Display Condition, the order of training and test trials was completely counterbalanced to avoid or minimize training effects. The order of display conditions was counterbalanced by randomizing them, with the constraint that each of the five display conditions occur an equal number of times in the first, second, third, fourth, and fifth order of presentation for the ten subjects (twice in each ordinal position). A second constraint was that the sequential order of any two display conditions occur equally often. After constructing the order of display conditions for each subject, the display conditions were then paired with the five full-flight and ten take-off-only scenarios developed for the study (discussed below). For each subject, each display condition was paired with one of the full-flight scenarios (numbers 1 through 5) and two of the take-off-only scenarios (numbers 6 through 15); these pairings determined the three-flight trial blocks for each display condition for subject. Each display condition was paired equally often with each of the 15 scenarios, with the additional constraint that, for each three-flight trial block, each of the full-flight scenarios was paired with one of the take-off-only scenarios numbered 6-10 and one numbered 11-15. Furthermore, scenarios 6-10 and scenarios 11-15 occurred equally often in the second and third position in the three-flight block.

Scenarios 6-11 included engine problems, while scenarios 12-15 included non-engine problems, and this procedure roughly equalized the pairings of engine-problem and non-engine-problem take-off-only scenarios with full flight scenarios. Table 3 gives the order of display conditions and scenarios paired with them for each of the ten subjects.

Sub #	Display Condition	Display Condition Order	Full Flight Scenario #	Take-off Scenario #
1	Basic EICAS	1	1	10,12
	Basic EICAS with alert messages	2	2	13,9
	Augmented EICAS with green bands	3	4	8,15
	Augmented EICAS with alert and "monitor parameter" messages	4	3	6,14
	Augmented EICAS with green bands & alert, monitor messages	5	5	11,7
2	Basic EICAS with alert messages	2	3	11,10
	Basic EICAS	3	5	12,9
	Augmented EICAS with alert and "monitor parameter" messages	1	2	15,8
	Augmented EICAS with green bands & alert, monitor messages	5	4	6,13
	Augmented EICAS with green bands	4	1	14,7
3	Augmented EICAS with alert and "monitor parameter" messages	3	4	12,6
	Augmented EICAS with green bands & alert, monitor messages	1	3	14,10
	Basic EICAS	5	2	8,11
	Augmented EICAS with green bands	4	5	13,7
	Basic EICAS with alert messages	2	1	15,9
4	Augmented EICAS with green bands	4	2	9,11
	Augmented EICAS with green bands & alert, monitor messages	3	3	12,10
	Basic EICAS with alert messages	2	5	14,8
	Basic EICAS	1	4	6,15
	Augmented EICAS with alert and "monitor parameter" messages	5	1	13,7
5	Augmented EICAS with green bands & alert, monitor messages	4	1	14,8
	Augmented EICAS with green bands	5	3	7,11
	Augmented EICAS with alert and "monitor parameter" messages	3	2	15,9
	Basic EICAS with alert messages	2	4	10,12
	Basic EICAS	1	5	6,13
6	Basic EICAS	1	5	8,11
	Augmented EICAS with green bands	4	4	7,15
	Augmented EICAS with green bands & alert, monitor messages	5	3	12,6
	Augmented EICAS with alert and "monitor parameter" messages	2	1	9,13
	Basic EICAS with alert messages	3	2	10,14
7	Basic EICAS with alert messages	2	3	7,15
	Basic EICAS	1	4	11,10
	Augmented EICAS with green bands	5	1	12,8
	Augmented EICAS with green bands & alert, monitor messages	4	5	9,13
	Augmented EICAS with alert and "monitor parameter" messages	3	2	6,14
8	Augmented EICAS with alert and "monitor parameter" messages	3	3	15,9
	Augmented EICAS with green bands & alert, monitor messages	5	2	6,13
	Basic EICAS	1	1	10,14
	Basic EICAS with alert messages	2	4	7,11
	Augmented EICAS with green bands	4	5	8,12
9	Augmented EICAS with green bands	4	2	13,10
	Basic EICAS with alert messages	2	5	14,7
	Augmented EICAS with alert and "monitor parameter" messages	3	4	8,11
	Basic EICAS	1	3	15,6
	Augmented EICAS with green bands & alert, monitor messages	5	1	9,12
10	Augmented EICAS with green bands & alert, monitor messages	5	4	13,10
	Augmented EICAS with alert and "monitor parameter" messages	3	5	6,12
	Basic EICAS with alert messages	2	1	7,15
	Augmented EICAS with green bands	4	3	11,9
	Basic EICAS	1	2	14,8

Table 3. Display Condition and Scenario Order

Each of the three independent variables was counterbalanced with the others. Each full-flight scenarios included six non-normal events: four engine-related problems, and two non-engine problems. Each of the ten take-off-only scenarios included one non-normal event; six included an engine problem, and four included a non-engine problem. For each subject, there were a total of 26 engine-related problems: 20 during the five full-flight scenarios, and 6 during the take-off-only scenarios. Of the 20 engine problems in the full-flight scenarios, ten were one-engine problems and ten were two-engine problems. Although the total number of engine problems were equally divided between one and two engine problems, and between slow- and fast-onset problems, this was not the case within a single full-flight scenario. At least one problem of each type (one versus two engine, slow- versus fast-onset) occurred in each scenario. Half of the one-engine problems overall and half of the two-engine problems overall had fast-onset times, and the other half had slow-onset times. Similar counterbalancing was carried out in the take-off only scenarios. Because there were only six problems per subject in these scenarios, the Number of Engines and Problem Onset Time variables could not be completely counterbalanced within a subject, but they were counterbalanced across subjects. Table 4 gives a list of all the engine problems (in chronological order) for each scenario. Table 4 also includes the alphanumeric alert and "monitor parameter" messages associated with the problem, the time into the scenario that triggered the problem, the number of engines affected by the problem, the engine(s) affected, and the problem onset time.

Because there were unequal numbers of one-engine versus two-engine problems, and slow-onset versus fast-onset problems in a given scenario, and scenarios were randomly paired with display conditions for different subjects, the result was an unequal number of data points per subject within a Display Condition level for one versus two engines, and for slow- versus fast-onset times. This was true even though the number of data points for these conditions were equal over all subjects combined.

5.5 Simulation Methodology

In the basic test paradigm, each subject flew a specified flight plan, and was asked to detect and identify non-normal events (engine and non-engine problems) as they occurred during the flight. During the test trials, both engine-related and non-engine-related conditions were presented. This was done in an attempt to keep the subject from focusing entirely on the graphical display of engine parameters and spending an inordinate amount of time scanning that portion of the display. Non-engine related problems were chosen from the Boeing 767 alert message set and are shown in Table 5.

Scenario #,Type	Engine Problem(s)	EICAS Message(s) (Alerts)	EICAS Message(s) (Monitor)	Level	Onset Time	Onset Class	# of Eng	Which Eng	Problem Trigger
1 - FF **	1. Low oil pressure	R LOW OIL PRESS	MONITOR R OIL PR	Red	8 sec	Fast	1	R	120 sec. after start
	2. High vibration	L, R ENG VIBRATION*	MONITOR ENG VIB	Red	25 sec	Slow	2	L, R	240 sec. after start
	3. Low N1, Low N2	L, R ENG LOW N1* L, R ENG LOW N2*	MONITOR L, R N1* MONITOR L, R N2*	Amber	22 sec	Slow	2	L, R	440 sec. after start
	4. High N1	R ENG HIGH N1	MONITOR R N1	Red	23 sec	Slow	1	R	600 sec. after start
2 - FF	1. High EGT	L, R HIGH EGT*	MONITOR L, R EGT*	Amber	20 sec	Slow	2	L, R	300 sec. after start
	2. Low N2	L, R ENG LOW N2*	MONITOR L, R N2*	Amber	9 sec	Fast	2	L, R	380 sec. after start
	3. Low N1	L ENG LOW N1	MONITOR L N1	Red	8 sec	Fast	1	L	500 sec. after start
	4. Low oil pressure	L, R LOW OIL PRESS*	MONITOR L, R OIL PR*	Red	24 sec	Slow	2	L, R	580 sec. after start
3 - FF	1. High EGT	R ENG HIGH EGT	MONITOR R EGT	Red	6 sec	Fast	1	R	220 sec. after start
	2. Low EGT	L ENG LOW EGT	MONITOR L EGT	Red	7 sec	Fast	2	L, R	310 sec. after start
	3. High N1	L, R ENG HIGH N1*	MONITOR L, R N1*	Amber	9 sec	Fast	2	L, R	420 sec. after start
	4. High oil temperature	R HIGH OIL TEMP	MONITOR OIL TEMP	Amber	22 sec	Slow	1	R	690 sec. after start
4 - FF	1. High oil temperature	L, R HIGH OIL TEMP*	MONITOR OIL TEMP	Red	6 sec	Fast	2	L, R	140 sec. after start
	2. High vibration	L ENG VIBRATION	MONITOR ENG VIB	Red	8 sec	Fast	1	L	420 sec. after start
	3. Low N2	R ENG LOW N2	MONITOR R N2	Red	7 sec	Fast	1	R	500 sec. after start
	4. High N2	L ENG HIGH N2	MONITOR L N2	Amber	23 sec	Slow	1	L	620 sec. after start
5 - FF	1. High N2	L, R ENG HIGH N2	MONITOR L, R N2*	Red	25 sec	Slow	2	L, R	145 sec. after start
	2. Low N1 , Low N2	L ENG LOW N1 L ENG LOW N2	MONITOR L N1 MONITOR L N2	Red	8 sec	Fast	1	L	310 sec. after start
	3. Low N1	L, R ENG LOW N1	MONITOR L, R N1*	Amber	24 sec	Slow	2	L, R	400 sec. after start
	4. Low EGT	L ENG LOW EGT	MONITOR L EGT	Amber	22 sec	Slow	1	L	500 sec. after start
6 - T/O **	High N2	R ENG HIGH N2	MONITOR R N2	Amber	25 sec	Slow	1	R	V1***+15 kts
7 - T/O	High oil temperature	L, R HIGH OIL TEMP*	MONITOR OIL TEMP	Red	24 sec	Slow	1	L	V1***+15 kts
8 - T/O	Low oil pressure	R LOW OIL PRESS*	MONITOR R OIL PR	Red	7 sec	Fast	1	R	V1***-25 kts
9 - T/O	High EGT	L, R HIGH EGT*	MONITOR L, R EGT*	Amber	9 sec	Fast	2	L, R	V1***-40 kts
10 - T/O	High vibration	L, R ENG VIBRATION	MONITOR ENG VIB	Amber	24 sec	Slow	2	L, R	V1***-5 kts
11 - T/O	Low N2	L, R ENG LOW N2	MONITOR L,R N2*	Red	8 sec	Fast	2	L, R	V1***-30 kts
12 - T/O	-	-	-	-	-	-	-	-	-
13 - T/O	-	-	-	-	-	-	-	-	-
14 - T/O	-	-	-	-	-	-	-	-	-
15 - T/O	-	-	-	-	-	-	-	-	-

*separate messages for left and right engines **FF=Full flight; T/O =Takeoff only ***assumes V1=130 kts

Table 4. Engine Problem Description By Scenario

Scenario #,Type	Non-engine Problem(s)	EICAS Message(s)	Level	Onset Time	Problem Trigger
1 - FF*	Cargo door	FWD CARGO DOOR	Amber	0 sec	320 sec
	Left IRS failure	L IRS FAIL	Amber	0 sec	700 sec
2 - FF	Aft cargo fire	AFT CARGO FIRE	Red	0 sec	210 sec
	Air conditioning pack failure	R PACK OFF	Amber	0 sec	680 sec
3 - FF	Leading edge slat asymmetry	LE SLAT ASYM	Amber	0 sec	500 sec
	Low center hydraulic quantity	C HYD QTY	Amber	0 sec	600 sec
4 - FF	Antiskid off	ANTISKID OFF	Amber	0 sec	220 sec
	Right generator off	R GEN OFF	Amber	0 sec	350 sec
5 - FF	Cabin Altitude above 10,000 ft.	CABIN ALTITUDE	Red	0 sec	220 sec
	Left hydraulic pressure low	L HYD SYS PRESS	Amber	0 sec	600 sec
6 - T/O*	-	-	-	-	-
7 - T/O	-	-	-	-	-
8 - T/O	-	-	-	-	-
9 - T/O	-	-	-	-	-
10 - T/O	-	-	-	-	-
11 - T/O	-	-	-	-	-
12 - T/O	Stabilizer trim	STAB TRIM	Red	0 sec	V1** plus 25 kts
13 - T/O	Wheel well fire	WHEEL WELL FIRE	Red	0 sec	V1**plus 15 kts
14 - T/O	L AC bus off	L AC BUS OFF	Amber	0 sec	V1** plus 20 kts
15 - T/O	Right IRS failure	R IRS FAIL	Amber	0 sec	V1** plus 30 kts

* FF=Full flight; T/O =Takeoff only
** assumes V1=130 kts

Table 5. Non-Engine Problem Description by Scenario

5.5.1 Flight Task

In order to make the simulation as realistic as possible, the crews flew operational flight legs. The Research Flight Simulator (Research Cab) was used to create the flight deck environment and work patterns. A set of flight scenarios was developed for the study, using various airfields in Washington state. A total of 15 scenarios were generated. Five of these (scenarios 1-5) were extended "full flight" scenarios, approximately 10 to 12 minutes in length, with a planned route from one airfield to another. Figure 11 shows the flight route for "full flight" scenario 1; the flight routes for the other four full-flight scenarios are given in Appendix A. The other ten scenarios (6-15) were "take-off-only;" they lasted less than two minutes. All take-off-only scenarios used Boeing Field in Seattle as the take-off field.

For each of the five extended scenarios, six points were selected during the scenario at which non-normal events were triggered. These points were defined by time into the scenario, in seconds, and varied from scenario to scenario. The first non-normal event in each scenario occurred no sooner than 120 seconds into the scenario; the other events

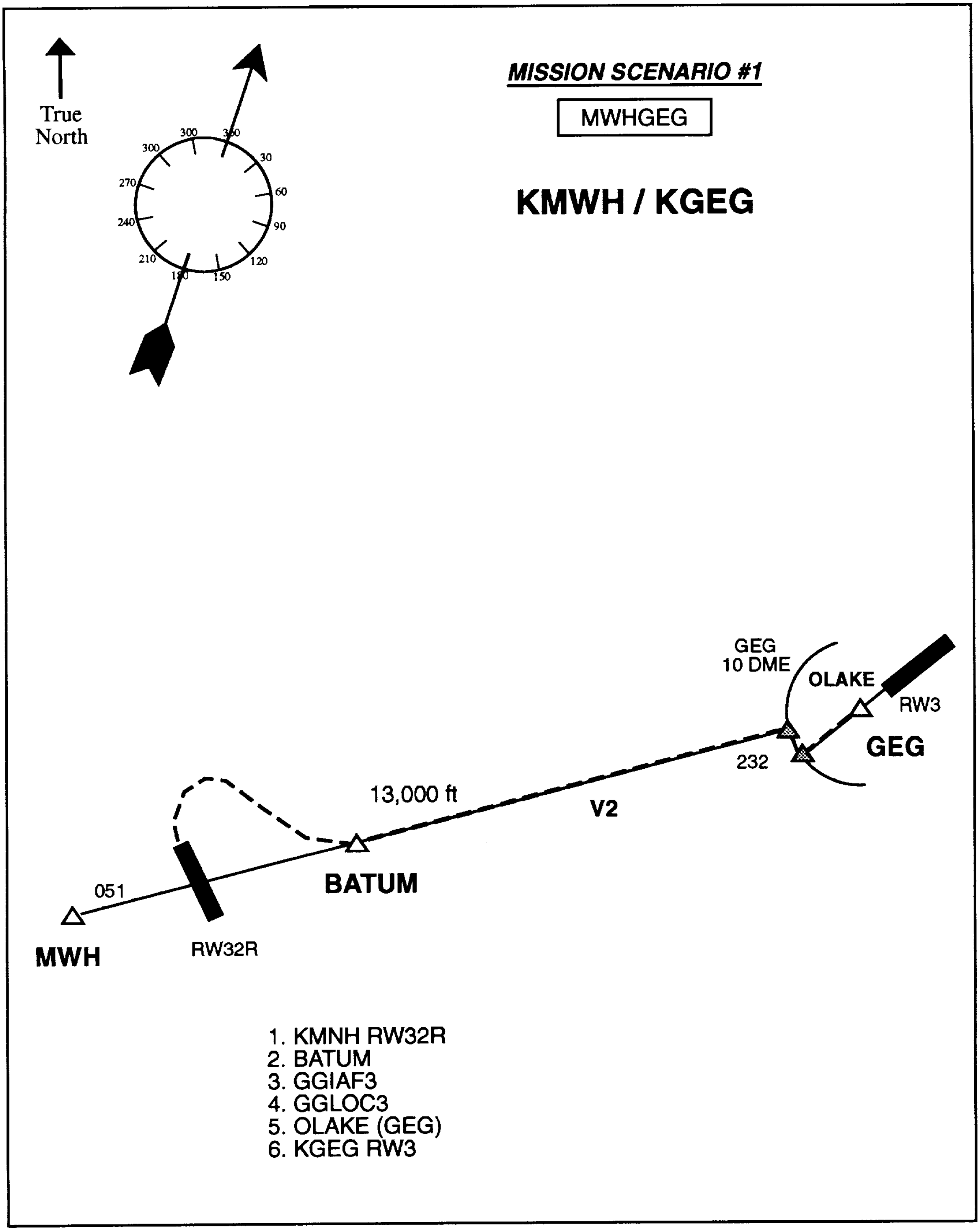


Figure 11. Scenario 1 Flight Route

followed at intervals that varied from 75 to 120 seconds. Four of the non-normal events in each scenario were engine-related and two were non-engine-related. For the ten take-off-only scenarios, a single trigger point for the non-normal event was defined by air-speed (in knots) relative to V_1 (plus or minus up to 40 knots). Table 6 shows the trial order/data sheet for subject 1. It includes the time- and V_1-based trigger points for all the non-normal events in all scenarios. Each full-flight scenario had an associated Air Traffic Control (ATC) script that provided a basic structure for a live controller who was permitted to improvise as the scenarios proceeded. The basic ATC script for full-flight Scenario 1 is given in Table 7; the scripts for the other full flight scenarios are in Appendix A. In order to provide a realistically high workload, the scenarios included a number of flight route changes, intervening waypoints, and other attention-demanding maneuvers.

During each flight trial the subject was required to manually fly the prescribed flight plan, respond to ATC communications, and respond to alerts.

5.5.2 Response Task

When a subject detected a non-normal condition, he was requested to depress a switch located on the left side of the control wheel (the lower microphone switch). This action was used to record the response time to detect the occurrence of a non-normal condition. Even though the switch press was artificial in relation to operational flight tasks, training trials showed that the subjects did not have significant difficulty learning to respond in that manner. In addition, past test programs have shown that the subjects quickly learn to perform it and that it does not significantly affect flight task performance.

After pressing the switch to indicate detection of a non-normal event, the subject was required to verbally identify the problem. For engine-related problems, three types of information were required as part of the identification: the parameter involved (e.g., N1), the engine exhibiting the problem (left, right or both), and the direction of the problem (high or low). Subjects were told that they could give this information in any order. The experimenter recorded the verbal response verbatim on the trial order/data sheet. If the subject provided some but not all of the required information, the experimenter would prompt the subject for the information that had been omitted and record it verbatim if it was added. A response was counted as accurate only if all three types of information were given (with or without a prompt).

Subject #1 Date________

Data	Scen.	Disp. Cond	Problem	Time (sec)	Eng.	Response	Bedford Rating	Comments
	3	2	1. High EGT	220	R			
			2. Low EGT	310	L, R			
			5. High N1	420	L, R		-	
			3. Leading edge slat asymmetry	500	-		-	
			4. Low center hydraulic quantity	600	-		-	
			6. High oil temperature	690	R		-	
	11	3	Low N2	V1-30	L, R		-	
	9	1	High EGT	V1-40	L, R		-	
	8	5	Low Oil Pressure	V1 -25	R		-	
	6	4	High N2	V1+15	R		-	
D	1	1	1. Low oil pressure	120	R			
			2. High vibration	240	L, R			
			3. Cargo door	320	-		-	
			5. Low N1, Low N2	440	L, R		-	
			6. High N1	600	R		-	
			4. Left IRS failure	700	-		-	
D	10	1	High vibration	V1-5	L, R		-	
D	12	1	Stabilizer trim	V1+25	-		-	
Ques							-	
D	2	2	3. Aft cargo fire	210	-			
			1. High EGT	300	L, R			
			2. Low N2	380	L, R		-	
			5. Low N1	500	L		-	
			6. Low oil pressure	580	L, R		-	
			4. Air conditioning pack failure	680	-		-	
D	13	2	Wheel well fire	V1+15	-		-	
D	9	2	High EGT	V1-40	L, R		-	
Ques							-	

Table 6. Trial Order/Data Sheet (1 of 2)

Data	Scen.	Disp. Cond	Problem	Time (sec)	Eng.	Response	Bedford Rating	Comment
D	4	3	1. High oil temperature	140	L, R			
			3. Antiskid off	220	-			
			4. Right generator off	350	-		-	
			2. High vibration	420	L		-	
			5. Low N2	500	R		-	
			6. High N2	620	L		-	
D	8	3	Low Oil Pressure	V1-25	R		-	
D	15	3	Right IRS failure	V1+30	-		-	
Ques								
D	3	4	1. High EGT	220	R			
			2. Low EGT	310	L, R			
			5. High N1	420	L, R		-	
			3. Leading edge slat asymmetry	500	-		-	
			4. Low center hydraulic quantity	600	-		-	
			6. High oil temperature	690	R		-	
D	6	4	High N2	V1+15	R		-	
D	14	4	L AC bus off	V1+20	-		-	
Ques							-	
D	5	5	1. High N2	145	L, R			
			4. Cabin altitude above 10000 ft.	220	-			
			2. Low N1, Low N2	310	L		-	
			5. Low N1	400	L, R		-	
			6. Low EGT	500	L		-	
			3. Left hydraulic pressure low	600	-		-	
D	11	5	Low N2	V1-30	L, R		-	
D	7	5	High oil temperature	V1-25	L		-	
Ques							-	

Table 6. Trial Order/Data Sheet (2 of 2)

Mission Scenario 1
KMWH/KGEG

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Spokane International Airport as filed. Climb and Maintain 8,000. Expect 13,000 five minutes after departure. Leaving 3,000 turn right to heading 100 to intercept V2. Squawk 7571. Departure Control frequency will be120.85
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 32R at Taxiway A.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 32R.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 126.1
One minute after level at 8,000 ft. MSL	Boeing 757, radar contact, climb and maintain 13,000.
One minute after level at 13,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
Aircraft passes D40/GEG	Boeing 757, contact Spokane Approach Control on 124.3.
Crew contacts Spokane Approach Control	Boeing 757, for traffic ahead, reduce speed to 210, then descend and maintain 5,000. Plan an ILS Runway 03 approach. Intercept the ILS Runway 03 localizer via the 10 DME Arc. Report crossing the 216^{o} radial of the Spokane VOR.
Crew reports crossing GEG 216^{o} radial	Boeing 757, cleared for an ILS Runway 03 approach to the Spokane International Airport. Contact the Spokane tower 118.3 at OLAKE.
Crew reports OLAKE	Boeing 757, cleared to land, Runway 03. Wind 340 at 25 with gusts to 35. RVR Runway 03 2,4000. Runway 03 braking action reported poor by a 737.
Aircraft slows to 60 knots	Boeing 757, clear the runway at taxiway C, if able, then contact Ground Control on 121.9.
Crew calls ground control	Boeing 757, taxi to the terminal via taxiways M and H.

Table 7. Air Traffic Control (ATC) Script for Flight Scenario 1

It was anticipated that the subject pilots would have diverse backgrounds, and have experience with different response procedures for the various non-normal situations. In order to reduce the effect of this variation and to reduce the amount of time required to train the subjects in the simulator, the only response required for each of the non-normals events was to push the "event recognized" switch and verbally identify the problem. Five seconds after the "event recognized" switch was pressed, the non-normal event was corrected without any further action on the part of the subject. If the problem was not detected within 15 seconds after it appeared in the EICAS display (as indicated by an alphanumeric message or change in color of the pointer/caret and digital readout), a "beep" sounded. Subjects had previously been instructed that if they heard the beep to press the lower microphone switch and verbally identify the engine problem type, engine(s) involved and direction of the problem. Those problems were also corrected within five seconds of the "beep" without any further action on the part of the subject.

Each full-flight scenario included four engine problems and two non-engine problems. Six non-normal events in a 12-minute flight is greater than the number of problems expected in normal flight operations. This number was selected in order to provide the subject with a sufficient quantity of engine-related non-normal events while maintaining a realistic minimum time period between occurrences. It was believed that the subjective data (ratings of the display conditions) would not be negatively affected by the event rate as long as enough time was available between the events for the subject to return to normal operation. However, the higher rate of occurrence, and the fact that subjects knew that non-normal events would occur, could have affected the objective data. Previous research (Boucek, 1980) has shown that these factors can reduce the surprise and uncertainty factors and result in shorter response times than would be expected in operational situations. However, this should not have affected the validity of the results since only the relative differences between display concepts were of interest.

5.5.3 Workload Measure

In order to get an approximate measure of the workload involved in the test flights, the subjects were required to give a subjective workload rating twice during each of the extended flight scenarios. At 180 and 540 seconds into each of the five full-flight scenarios, four "beeps" sounded and the experimenter announced "workload." Subjects had been instructed that when this occurred, they should respond with a workload rating by giving a number from one to ten, based on the Bedford workload rating scale. The Bedford workload rating scale is shown in Figure 12. Subjects received verbal instructions on how to use the Bedford scale before beginning the practice flights, and had a copy of the scale in the cab that they could refer to any time they wished. The experimenter recorded the workload ratings when they were given.

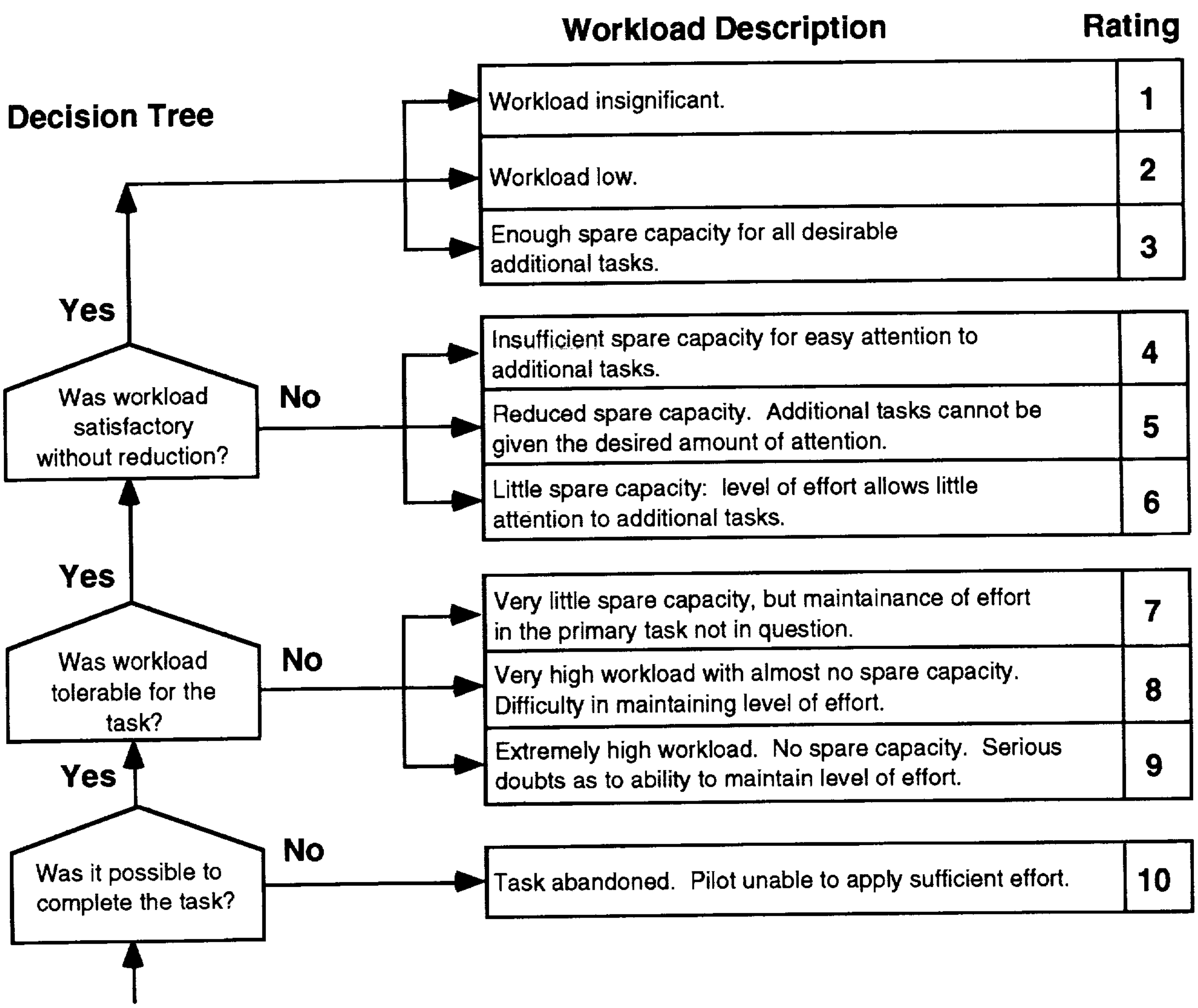


Figure 12. Bedford Workload Rating Scale

5.6 Experiment Schedule and Procedures

Each subject was run individually, and was scheduled for a five-hour block of time for the experiment. Table 8 presents an approximate schedule for a morning test session. Training, described in more detail below, consisted of a briefing on the study; an explanation of the display conditions, the required responses, and the Bedford workload rating scale; a study period and a quiz on the values of engine parameters used in the study; and an explanation of the subjective rating questionnaires to be filled out after each trial block. This was followed by a familiarization period in the simulator. The subject was then introduced to the engine monitoring concepts and given hands-on response practice to non-normal conditions (including practice with the detection switch).

TIME	ACTIVITY
7:00-8:00	Simulator Checkout
7:30-7:45	Introduction to the Simulation Center
7:45-8:45	Briefing
8:45-9:30	Familiarization and Practice Trials
9:30-9:45	Break
9:45-11:30	Test Trials
11:30-12:00	Debriefing

Table 8. Sample Subject Test Schedule

Each subject then performed at least one full-flight practice flight, followed by four take-off-only practice flights. The test flights consisted of a total of ten take-off-only flights and five full-flight scenarios. Five blocks of test flights followed; each block included one full flight and two take-off-only flights.

5.6.1 Briefing

The experimental session for each subject began with an introduction to the Flight Simulation Center. This introduction included a brief description and walk through the facility. Following this introduction, the subject was briefed in a room adjacent to the simulator. Each subject was given a brief summary of the background and purpose of the study, and why his input was sought. For each display condition, a series of line drawings was used to show what the upper and (if appropriate) lower EICAS screen would look like for each of several circumstances: all parameters normal; one parameter in the caution or warning range; and one parameter outside the nominal value range, but not yet into the caution or warning range. The drawings included examples of both round-dial and vertical-scale parameters. Each line drawing was appropriately colored to show the changes in coding that would occur, and labelled to indicate the specific condition that the drawing represented.

The subject was then briefed on the operation of the simulator, including its instrumentation and how it differed from a standard 757 flight deck. He was then given a list of "Critical Engine Parameters," shown in Table 9. This list included the normal, caution, and warning (both high and low) ranges for all the engine parameters shown on the EICAS displays. The subject was asked to memorize the list and told that he would be given a quiz on the information. The subject was allowed to take as much time as he wanted to study the list, after which he completed a fill-in-the-blank quiz. Each subject completed the quiz with a minimum of 96 percent accuracy.

N1 Limits:	Caution (low)	-	0 to 20%
	Normal	-	20 to 100%
	Caution (high)	-	100 to 110%
	Warning (high)	-	above 110%
EGT Limits:	Caution (low)	-	below 250°C
	Normal	-	250 to 600°C
	Caution (high)	-	600 to 800°C
	Warning (high)	-	above 800°C
N2 Limits:	Caution (low)	-	0 to 60%
	Normal	-	60 to 100%
	Caution (high)	-	100 to 110%
	Warning (high)	-	above 100%
Oil Pressure:	Warning (low)	-	at or below 70 PSI
	Caution (low)	-	70 to 75 PSI
	Normal	-	75 to 160 PSI
	Caution (high)	-	above 160 PSI
Oil Temperature:	Caution (low)	-	below 40°C
	Normal	-	40 to 163°C
	Caution (high)	-	163 to 177°C
	Warning (high)	-	above 177°C
Oil Quantity:	Warning (low)	-	below 4.0 qts
	Normal	-	above 4.0 qts

Table 9. Critical Engine Parameter List

The Bedford workload rating scale (shown earlier in Figure 12) was then explained to the subject, and he was given an opportunity to study the scale and ask any questions about it. Each subject had a copy of the rating scale with him for reference throughout the practice and test trials.

The objective response measures were then explained to the subject. Both speed and accuracy of responses were emphasized. Because response time was recorded when the lower microphone switch was pressed, each subject was instructed to press that switch as soon as he detected a non-normal event (either engine or non-engine), and then to give the verbal description of the problem. As noted earlier, each subject was instructed to give three pieces of information about each engine problem: the parameter involved, which engine(s) exhibited the problem, and the direction (high or low) of the problem. The subject was told that he could give the information in any order. For non-engine problems, he was told to identify the nature of the problem; in essence, this meant reading the caution or alert message on the upper EICAS screen. Each subject was then shown samples of the subjective rating questionnaires to be filled out for each display condition. Finally, each subject was given a questionnaire to fill out about his background and flight experience. The questionnaire is shown in Appendix B, and the data from this questionnaire is summarized in Table 1. Each subject was encouraged to ask questions during all parts of the briefing. The subject then moved to the simulator, where he had hands-on practice with the alerting system, engine displays, response switch, and data collection procedures.

5.6.2 Familiarization and Practice Trials

Each subject flew at least five familiarization/practice flights in the simulator before test trials began. The first flight was a 10 to 12 minute "full flight" using one of the five display conditions. The features associated with the given display condition were explained at the beginning of the flight. The subject was instructed to make all required responses, and any mistakes or omissions were corrected. The copilot/observer in the right seat provided instruction about flying the simulator, demonstrated response procedures, and noted any difficulties that the subject had in adjusting to the flight characteristics of the simulator. Most subjects showed adequate flight proficiency at the end of the full-flight scenario; those who did not were allowed to fly another complete or partial full-flight scenario with the same display condition. Then each subject flew four additional take-off-only scenarios, each with one of the four remaining display conditions not used in the initial full-flight scenario. At the beginning of each take-off-only flight the features of the display condition specific to that practice trial were reviewed, and the subject was asked if he had any questions. There were few questions during the practice trials, and they were all answered completely. Objective data collection procedures were carried out during all practice trials, and workload ratings were also recorded to familiarize the subjects with making those responses. Subjective questionnaires, however, were not filled out during the practice period. The order of the practice-trial scenarios and the order of the display conditions paired with those scenarios was randomized and completely counterbalanced across subjects.

5.6.3 Test Trials

After all practice trials were completed, test (data collection) trials blocks began. Subjects first flew a full-flight scenario, followed by two take-off-only scenarios; the same display condition was used in all three scenarios. The specific features of the appropriate display condition were reviewed at the beginning of the three-scenario trial block. At the completion of each block of test flights, each subject filled out a questionnaire to provide a subjective evaluation of the display condition used in that block.

5.6.4 Debriefing

At the end of the full test session, each subject filled out a final questionnaire to provide comparisons among the display conditions, and to allow the subjects to make more open ended comments. The experimenter conducted a debriefing and answered any questions.

6. DATA COLLECTION

The variables that were not being tested were held constant or controlled so that they would not bias or confound the results. During the flight task, aircraft noise of approximately 75 db was used to mask the uncontrolled noise that might occur around the cab. The ambient lighting was kept relatively low to permit the use of the outside visual scene. ATC communication and aural alerts were presented approximately 8 db above the ambient noise and held constant for all trials. The ATC messages were approximately the same for each subject. All subjects received the same instructions and training to avoid experimental bias.

Whenever the performance of the same task is measured under several different treatment conditions, as in the present experiment, learning and/or fatigue effects from earlier trials may influence the performance on later trials. Care was taken to prevent these carry-over effects from differentially affecting the performance measures for the different treatment conditions. This was accomplished by counterbalancing the order which the subjects received the treatment conditions. The subjects were informed before each flight which display condition would be used for that flight.

The data that was collected during the display evaluations fell into two categories: objective data (response time to detect non-normal events and accuracy of identifying them) and subjective data (rating and comment questionnaires and subjective workload measures).

6.1 Objective Data

The objective measures that were used during the study concerned the subjects' recognition of non-normal events and the acquisition of relevant information from the EICAS displays.

The measures that were used to provide insight into the issues of information transfer and the display effectiveness were detection time (response time) and identification accuracy (response accuracy). Detection time was defined as the time between the trigger time for a non-normal event (engine or non-engine problem) and the time that the subject pressed the lower microphone switch to indicate that the event had been detected. Response time was automatically recorded when the switch was pressed. As noted earlier, however, this definition included an unequal amount of time between the problem trigger and the full problem onset (the point in time when a color change or alphanumeric message appeared on the display) for the different display conditions. A color change (in the pointer and digital readout and box) occurred in Display Conditions 3, 4, and 5 (augmented EICAS conditions) when the value of a displayed parameter went outside the nominal range, whether or not that range was graphically depicted by green bands. The same color changes did not occur in Display Conditions 1 and 2 (basic EICAS) until the value of the parameter exceeded caution and warning limits. Similarly, alphanumeric engine parameter alert messages first appeared in Display Conditions 4 and 5 when the value of the parameter went outside the nominal range, but did not appear in Display Condition 2 until the value of the parameter exceeded caution and warning limits. Alphanumeric messages did not occur for engine problems in Display Conditions 1 and 3. Therefore, if color changes were a critical cue for detecting an engine parameter problem on the EICAS displays, then the average response times for the five display conditions should have been, in increasing order, for Display Conditions 3, 4, and 5, followed by Display Conditions 1 and 2. If the appearance of an alphanumeric engine parameter message (alert or "monitor parameter") was a critical cue, then the response times in increasing order should have been for Display Conditions 4 and 5 followed by Display Conditions 2, and then by Display Conditions 1 and 3.

As indicated earlier, a limit was put on the amount of time for the subject to respond to a non-normal event (engine or non-engine). If the subject did not respond within 15 seconds after a color change or alphanumeric engine parameter alert or "monitor parameter" message was presented, then a beep sounded and the subject was instructed to verbally identify the problem. In that case, the problem onset time plus 15 seconds was recorded as the response time for that non-normal event.

Flight task performance was not assessed during this study. Because data was collected in both full-flight and take-off only scenarios, there was only one traditional flight performance variable that could have been measured across all data trials: heading accuracy. Because the take-off only scenarios were of such short duration, however, it was decided that data about heading accuracy would not provide much useful information.

6.2 Subjective Data

Subjective data was gathered throughout the experiment in order to assess the subjects' judgements of the usefulness and interpretability of the engine monitoring display concepts. There were three formal methods of gathering subject opinion concerning the monitoring display. Following the block of three flights for each display condition, each subject was given a short questionnaire to evaluate that display condition while the experience with it was fresh. Subjects rated the ease and speed of interpreting engine parameter information (overall, and in both the round-dial and vertical-scale formats) on the EICAS displays. At the end of the test session each subject filled out a questionnaire to rank order the five display conditions according to ease of use. They also rated the overall usefulness and ease of interpreting the three features added to the basic EICAS display and examined in this study: alphanumeric alert (caution and warning) messages for engine parameters, alphanumeric "monitor parameter" messages, and green "nominal range" bands. Three open-ended questions were also included to elicit any positive and negative opinions about the display features, and any other comments.

The questionnaires used to evaluate each of the display conditions with a summary of the responses are given in Appendix C. The final questionnaire used to rank them and evaluate the features and a summary of responses are also given in Appendix C.

6.3 Workload Data

In addition to the opinion data about the display formats and features, the subjects were asked to provide subjective ratings of their workload during each of the full flights. The Bedford workload-rating scale was used because of its non-intrusive nature. A replica of the Bedford rating scale was available to them for reference during the practice and experimental sessions.

7. DATA ANALYSIS AND RESULTS

7.1 Objective Data

The objective data were analyzed using an analysis of variance program designed for repeated measures. Experimental errors and problems in data recording resulted in missing data for three full-flights and one take-off-only flight across all subjects for the response time dependent variable. In the sections that follow, data will be reported as means across subjects. Means reported in the text and shown in the figures represent all data points, uncorrected for missing data or unequal number of observations.

In order to perform statistical analyses for the repeated measures design used in this study, equal numbers of data points were required for each level of each independent variable, and each combination of independent variables. There were equal numbers of data points per subject for the Number of Engines and Problem Onset Time variables. However, because the Number of Engines and Problem Onset Times were unevenly distributed within scenarios, which were then randomly paired with Display Conditions, there were not equal numbers of observations in all Number of Engines/Problem Onset Time/Display Condition cells. Because of these problems with missing and unequal observations, the analyses were done separately for the Number of Engines/ Problem Onset Time and the Display Condition variables.

There were 26 possible data points per subject for each of the dependent variables: response time to detect a non-normal engine event (in seconds) and identification accuracy. Thirteen of these data points were for single engine problems, and 13 were for two-engine problems. Similarly, 13 of the data points were for fast-onset problems, and 13 were for slow-onset problems. Missing observations (a total of 9 data points across all subjects) were replaced by the appropriate cell mean for the subject and a repeated-measures ANOVA was then performed on these data.

Figures 13 and 14 show the average response times for Number of Engines and Problem Onset Time. Significant effects were found for Problem Onset ($F=19.25$, $df=1,9$, $p<.005$) and for Trials ($F=16.51$, $df=6,54$, $p<.001$). Responses were faster for "fast-onset problems" (9.0 sec) than for "slow-onset problems" (14.59 sec), and there was a significant amount of variability in responding to different problems within different scenarios. There was no effect for Number of Engines. Average response times for engine versus non-engine problems are shown in Figure 15. The average response time for non-engine problems was much faster then for engine problems because the only requirement for non-engine problems was that the subjects read the caution or warning message.

Figures 16 and 17 show the average identification accuracy for Number of Engines and Problem Onset Time. No significant effects were found. For Number of Engines, the accuracy of problem identification was slightly higher for two-engine problems (91%) than for one-engine problems (87%). Accuracy was virtually identical for slow-onset (89%) versus fast onset (88%) problems. Figure 18 shows that identification accuracy was 100% for non-engine problems.

A one-way analysis of variance for Display Condition was carried out with the response time and identification accuracy data for each subject. For response time, the main effect of Display Condition was highly significant ($F=24.38$, $df=4,36$, $p<.0001$). Figure 19 shows that average response times decreased in order from Display Condition 1 to Display Condition 5 (18.56, 13.51, 12.19, 7.75, and 6.73 sec, respectively). But recall that response time was confounded with the amount of time that it took for a an engine problem to trigger a color change or message in the display. For color changes, this time decreased from Display Condition 1 to Display Conditions 2, 3, 4 and 5; for messages, it decreased from Display Condition 1 to Display Condition 2, and from Display Condition 3 to Display Conditions 4 and 5.

No effects were significant for identification accuracy. Identification accuracy is shown in Figure 20. Accuracy was highest for Display Condition 2 (98%), followed by Display Conditions 1 and 3 (both 92%), and then by Display Conditions 4 and 5 (82% and 80%, respectively).

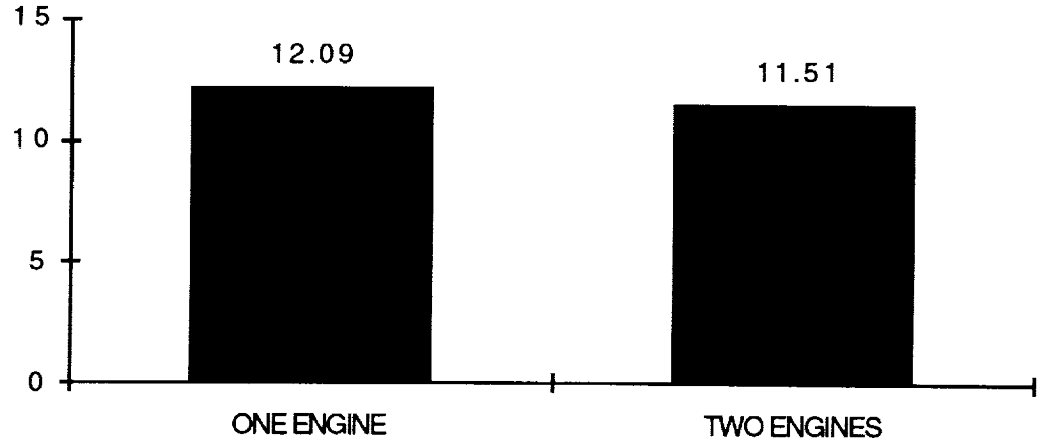


Figure 13. Average Response Time (sec) by Number of Engines

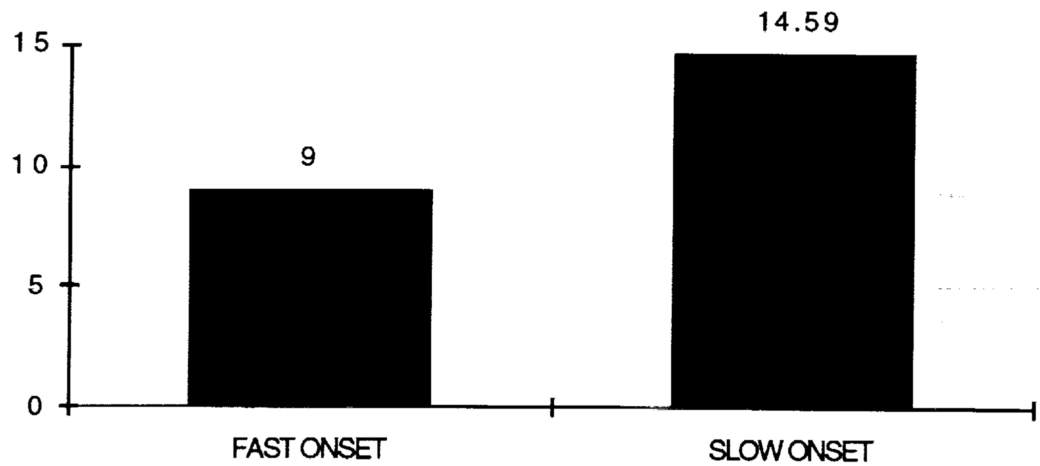


Figure 14. Average Response Time (sec) by Problem Onset Time

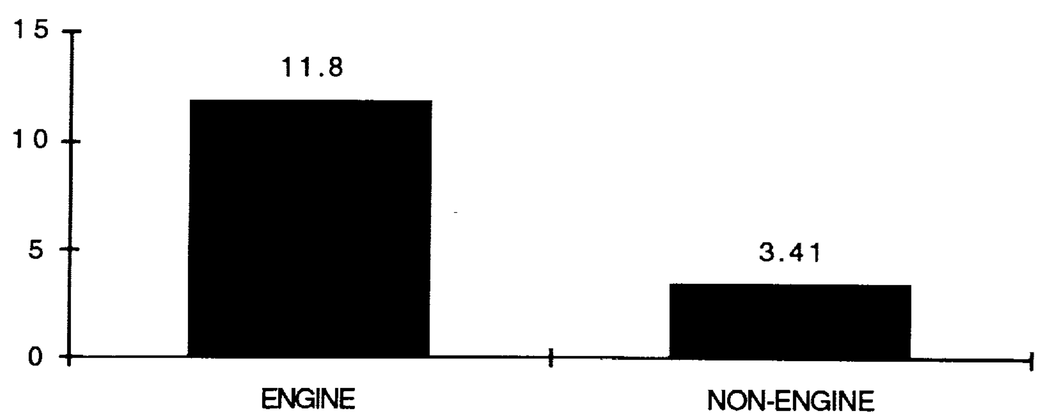


Figure 15. Average Response Time (sec) for Engine and Non-Engine Problems

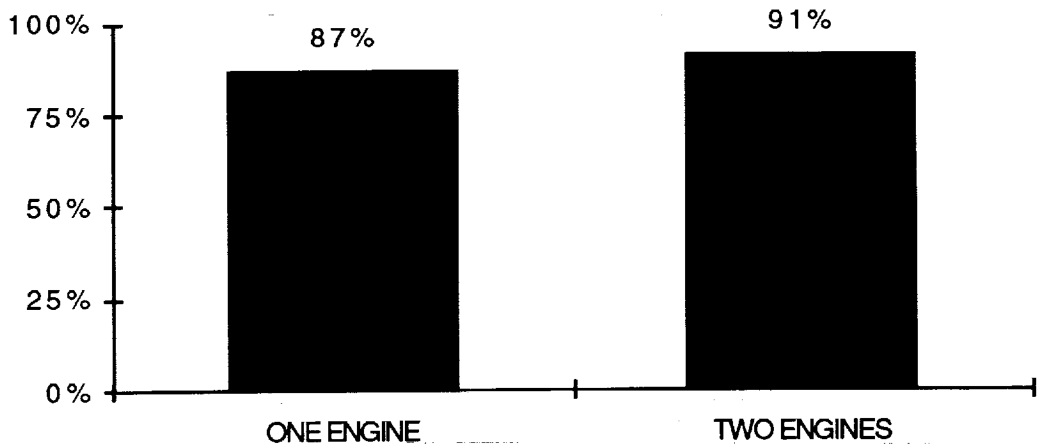


Figure 16. Average Identification Accuracy by Number of Engines

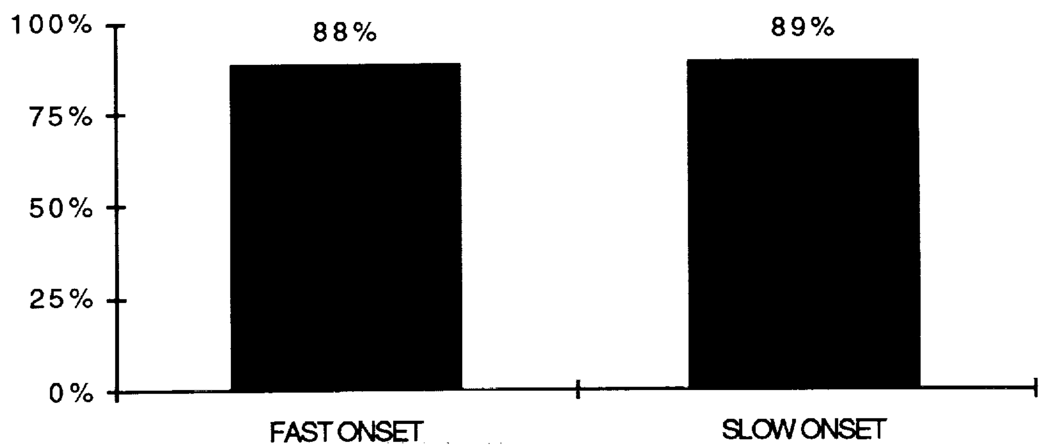


Figure 17. Average Identification Accuracy by Problem Onset Time

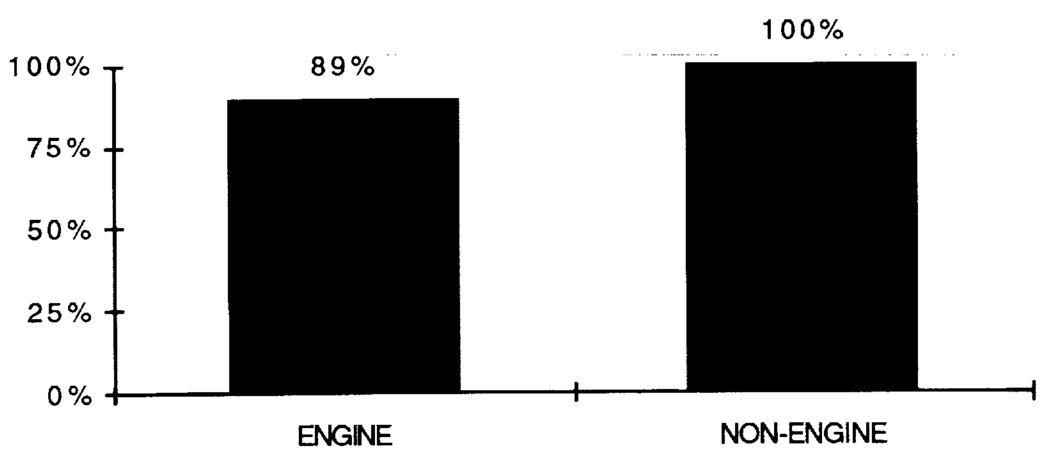


Figure 18. Average Identification Accuracy for Engine and Non-Engine Problems

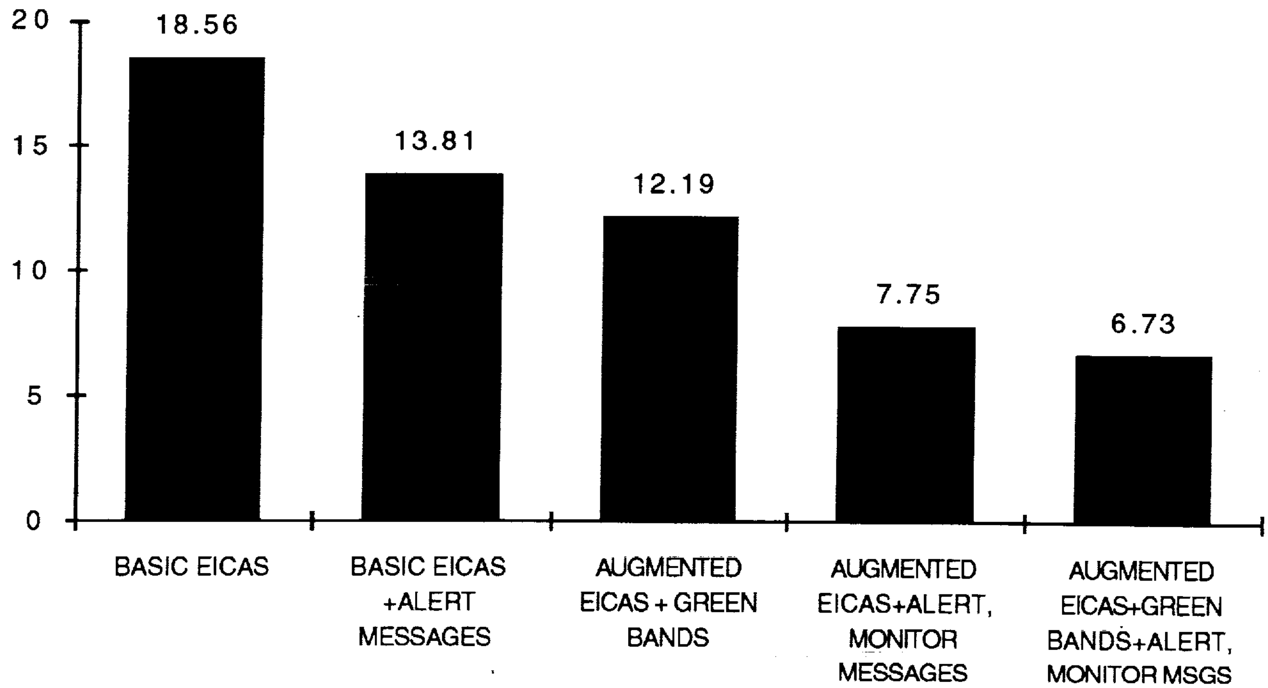


Figure 19. Average Response Time (sec) by Display Condition

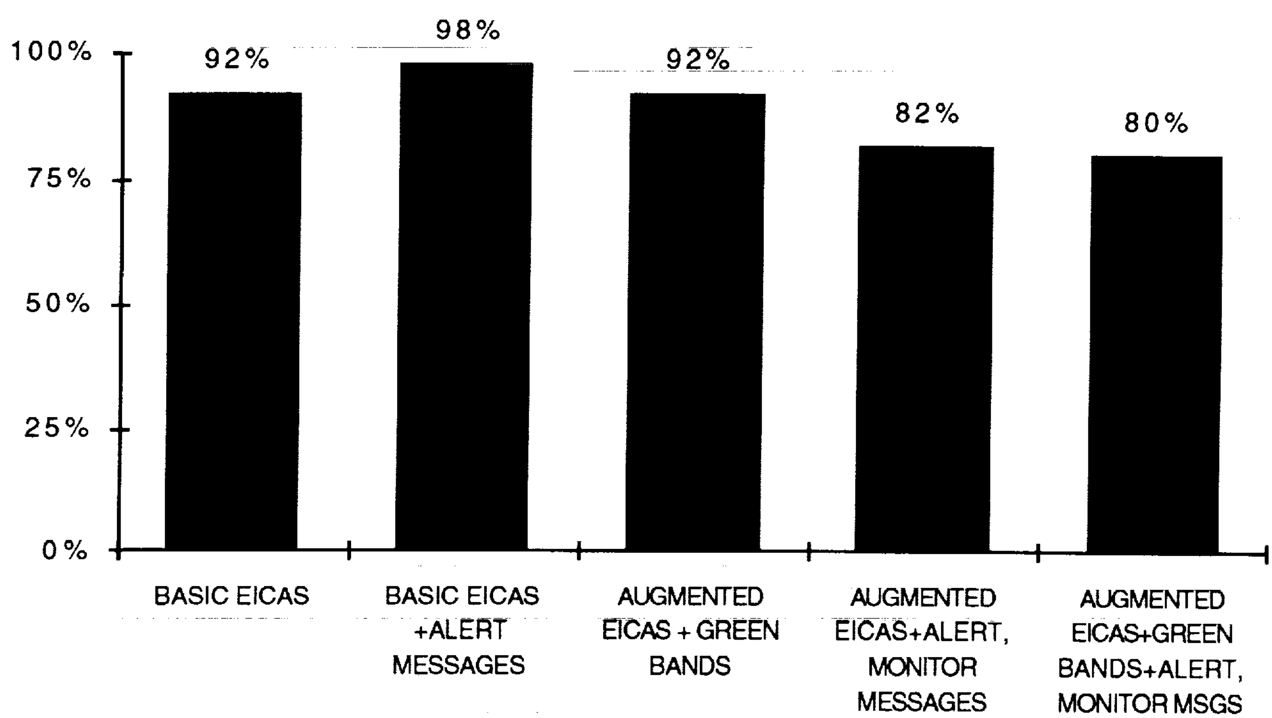


Figure 20. Average Identification Accuracy by Display Condition

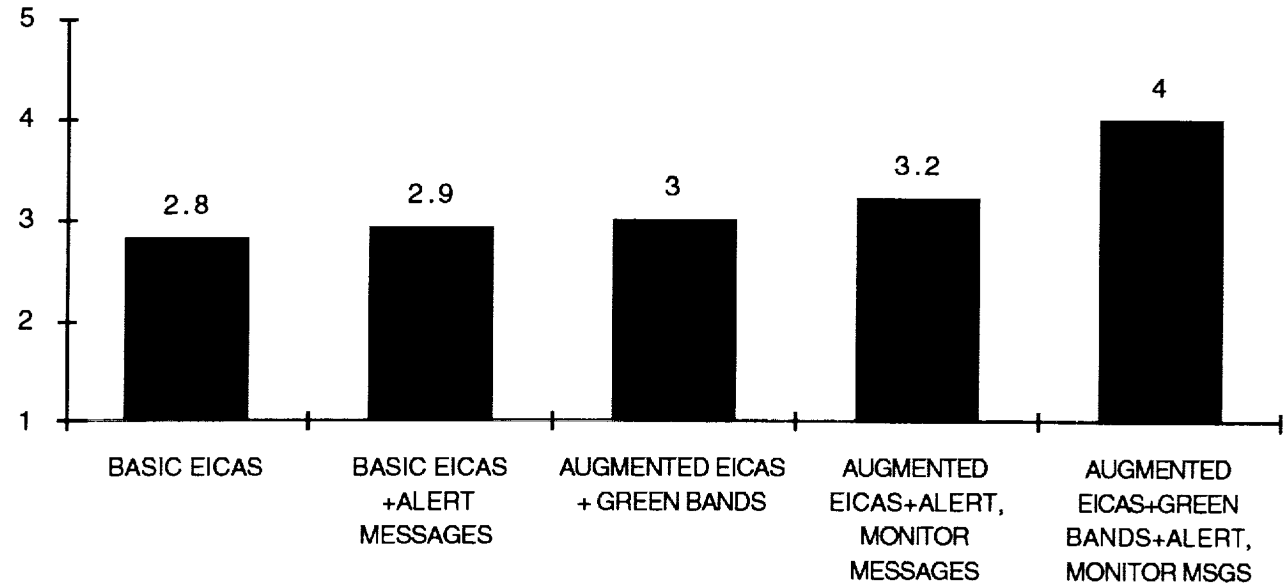
7.2 Subjective data

Ratings collected about each of the display conditions at the end of each trial block were analyzed separately from the overall ratings and ranking of display conditions. A one-way analysis of variance for repeated measures was applied to all the subjective rating and ranking data. There were no missing subjective data.

At the end of each data collection block, subjects rated the overall ease of interpretation, the ease and speed of interpreting round-dial format information, and the ease and speed of interpreting vertical-scale information for the display condition used in that block. All ratings were on a scale of 1 (extremely easy) to 5 (moderately easy). For purposes of analyzing and graphing the results, these ratings were transformed so that higher numbers represented more preferred conditions (5 = extremely easy and 1 = moderately easy). All means reported in the text and figures represent the transformed ratings.

Figure 21 shows the average ratings for overall ease of interpretation for each display condition. Subjects rated Display Condition 5 easiest, followed by Display Conditions 4, 3, 2, and 1 (ratings of 4.0, 3.2, 3.0, 2.9, and 2.8, respectively). A one-way analysis of variance showed that the overall effect of Display Condition was significant ($F=3.68$, $df=4,36$, $p<.05$). Tukey test comparisons were then made between pairs of individual means. The only paired comparison that showed a significant difference was between Display Condition 5, which included engine parameter alert messages, "monitor parameter" messages and green bands; and Display Condition 1 (basic EICAS). There were no pair-wise comparisons that showed a significant difference on the ratings of ease or speed of interpretation of round-dial or vertical-scale information.

After all trial blocks were completed, subjects also rank-ordered the Display Conditions for ease of use. Figure 22 shows the average rankings for each of the display conditions. In order of preference, the rankings were Display Conditions 2, 4, 5, 3, and 1. A one-way analysis of variance on the rankings showed a significant difference for Display Condition ($F=5.29$, $df=4,36$, $p<.005$). Subsequent Tukey tests for pair-wise comparisons showed that the rankings for Display Conditions 2, 4, and 5 were each significantly greater than the rankings for Display Conditions 1 and 3. After all



1= Very Difficult; 5= Very Easy

Figure 21. Average Ratings of Overall Ease of Interpreting Display Conditions

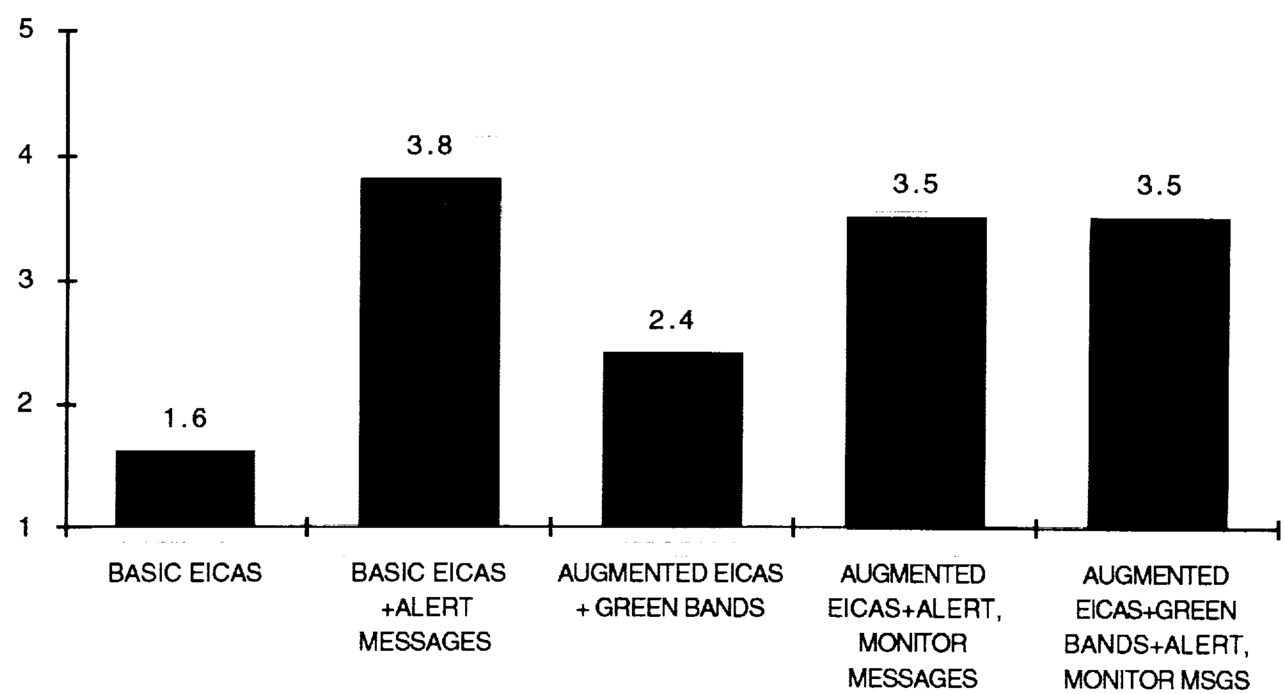


Figure 22. Average Rankings of Display Conditions for Ease of Use

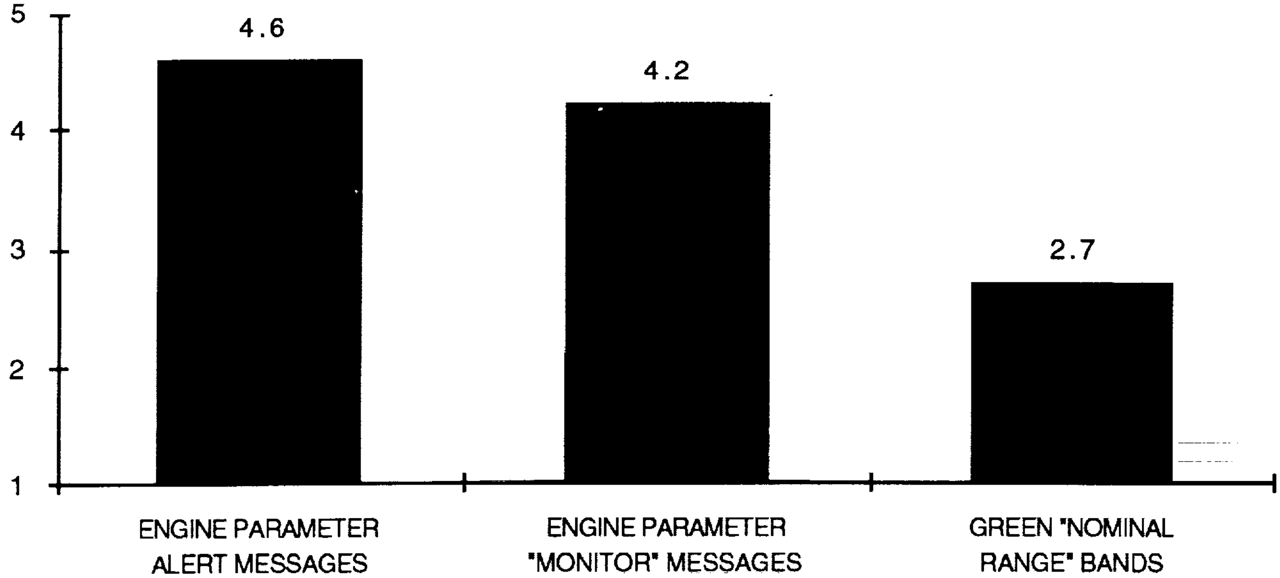
trial blocks were completed, subjects also rated the usefulness and ease of interpretation of the three features added to the displays (alphanumeric engine parameter alert messages, alphanumeric "monitor parameter" messages, and green "nominal range" bands).

These ratings were on a scale of 1 to 5 for usefulness (not at all useful to very useful) or and interpretability (very difficult to interpret to very easy to interpret). Figure 23 shows the average ratings of "usefulness" for the three features. Alphanumeric alert messages were rated most useful (4.6), followed by the "monitor parameter" messages (4.2), and then by the green bands (2.7). The ratings were analyzed using the BMDP 2V one-way analysis of variance program. There was a significant effect of feature type ($F=12.37$, $df=2,18$, $p<.001$). Tukey test comparisons between means showed that the rated usefulness of both types of alphanumeric messages (engine parameter alert (caution/warning) messages and "monitor parameter" messages) was significantly higher than the rated usefulness of the green "nominal range" bands; no other paired comparisons were significant.

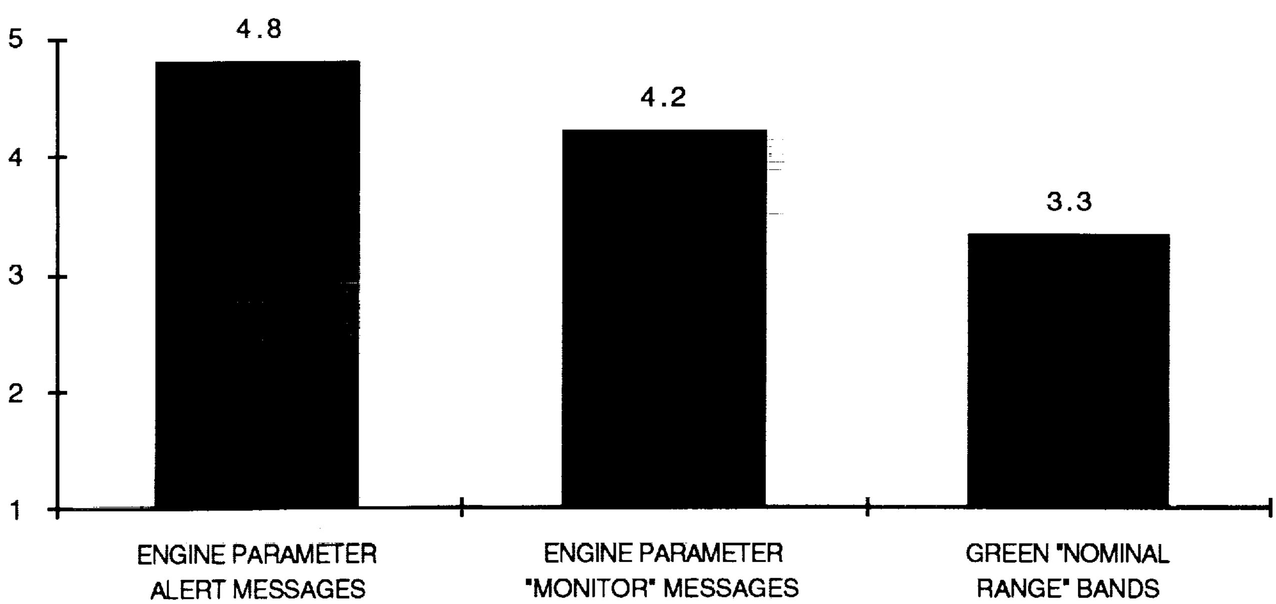
Figure 24 shows the average ratings of "ease of interpretation" for the three features. The alphanumeric alert messages were rated easiest to interpret (4.8), followed by the "monitor parameter" messages (4.2), and then by the green bands (3.3). There was again a significant effect of feature type ($F=5.94$, $df=2,18$, $p=.01$). Tukey tests showed that the rated ease of interpretation of the caution/warning alert messages was significantly higher than the rated ease of interpretation of the green bands; no other paired comparisons were significant. Subjects made a variety of responses to the open-ended questions; their responses are summarized in Table 10.

7.3 Workload Data

The average Bedford Scale workload ratings for the five display conditions are shown in Figure 25. Workload ratings were almost identical across the conditions, which supports the hypothesis that differences in workload were not responsible for differences in the objective or subjective dependent variables.



1= Not at All Useful; 5= Very Useful
Figure 23. Average Ratings of Usefulness of Features Added to the Basic EICAS Display



1= Very Difficult; 5= Very Easy
Figure 24. Average Ratings of Overall Ease of Interpreting Features Added to the Basic EICAS Display

In general, what did you like about the features associated with the augmented EICAS displays?

Parameter and monitor messages. (2 subjects)
Easy and quick problem analysis. The oil temperature and oil pressure messages were very helpful.
Good for trend monitoring only.
Monitor and parameter messages were a nice addition to the EICAS.
More useful information.
Called attention to the exact problem or impending problem.
Engine parameter messages were good for alerting to a particular problem.
Catches your eye.
Allows a more rapid recognition of change.

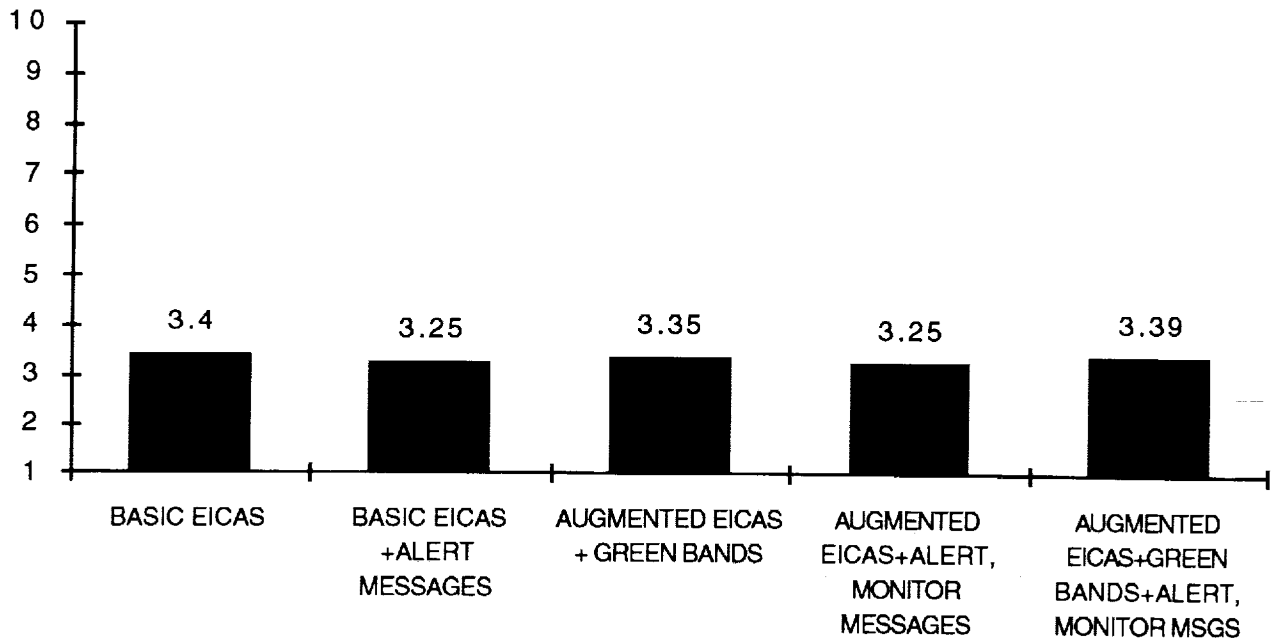
In general, what did you dislike about the features associated with the augmented EICAS displays?

Monitor messages were somewhat distracting in that you had to follow up the message by looking at the particular gauge.
Normal range of parameter not as useful as EICAS message.
Green bands seemed unnecessary.
Green bands of minimum use.
Requires more observation to detect changes.

If you have any additional comments, please include them here.

Possible difficulty interpreting messages with multiple messages on EICAS
Quantitative data will most likely be more useful in this evaluation than the questionnaires.
I found myself concentrating more on the EICAS display than is realistic. Otherwise the information presented during malfunctions was useful.
Lower EICAS screen should receive more augmentation because it is scanned less.
I like EICAS with parameter and monitor messages.
Bar displays are more recognizable when changes occur in the parameters than dial displays.

Table 10. Summary of Responses to Open-Ended Questions on Final Questionnaire.



Ratings: 3= Enough Spare Capacity for Additional Tasks
4= Insufficient Spare Capacity for Easy Attention to Other Tasks

Figure 25. Average Bedford Scale Workload Ratings by Display Condition

8. DISCUSSION AND CONCLUSIONS

In general, both the objective and subjective data showed that adding alphanumeric alert (caution and warning) messages to the basic EICAS displays, similar to those used for other systems problems, decreased response time. The data also indicated that the alert messages were the added feature most preferred by the subjects. Adding alphanumeric messages to "monitor" a parameter that deviated from a nominal range also decreased response time, and was the added feature subjects preferred next. Adding green "nominal range" bands did not appear to decrease response time, and was the least-preferred feature. The fastest average response time was associated with Display Condition 5, which included all three added display features and was ranked highest by the subjects; the slowest average response time was associated with the basic EICAS display format, which included none of the added features and was also least preferred by the subjects.

8.1 Objective data

Technical difficulties with the data collection procedures made this data difficult to interpret. As noted earlier, response time was measured from when a problem was triggered. But the display conditions differed in the amount of time it took for certain display cues (color changes, appearance of alphanumeric messages) to indicate that a problem had occurred. These circumstances made it impossible to make direct comparisons among the display conditions on the objective measures, because both response time and identification accuracy were sensitive to the amount of time available. An inspection of the means for response time across display conditions shows that performance was better, as expected, for the conditions that provided the earliest display cues: Display Conditions 3, 4, and 5 were better than Display Conditions 1 and 2. Note that this does not support one possible hypothesis that subjects would detect a developing engine problem on the basis of changes in the digital readout and/or pointer movement, before a color change occurred or a message appeared. Even though the timing of these readout and pointer cues was identical for all display conditions, the average response times were not.

Comparisons between specific display conditions, however, allow the following conclusions to be drawn. Even though the differences between the display conditions discussed below were not statistically significant, it can be seen from Figure 19 that adding alphanumeric engine parameter alert or "monitor parameter" messages decreased response time. Display Conditions 1 and 2 were identical in the timing of the color changes in the pointers/carets and digital readouts that occurred when an engine parameter exceeded caution and warning limits. But in Display Condition 2, an alphanumeric caution or warning message appeared concurrently with the color change, and the response time was faster than for Display Condition 1. Similarly, Display Conditions 3 and 5 differed only in that alphanumeric "monitor parameter" messages accompanied the color change cues that occurred when an engine parameter departed from the "nominal range" band generated by the engine model. Again, average response time was faster for Display Condition 5, which included alphanumeric messages, than for Display Condition 3, which did not. These comparisons show that the effect on response time holds whether or not green bands graphically depict the nominal range; it also holds whether the alphanumeric messages are caution and warning messages similar to those used for other systems, or messages to "monitor" a given parameter. Presenting an alphanumeric message, especially one that is similar in location and color to caution and warning alert messages for other systems, appears to decrease the amount of time it takes to detect a problem that involves an engine parameter presented on the EICAS displays.

There does not, however, appear to be an effect for adding green bands that graphically depict the range of nominal values generated by the engine model. The only direct comparison that is appropriate for this hypothesis is between Display Conditions 4 and 5 (Figure 19). This comparison indicates that the addition of green bands does not make much difference in the average response time. The lack of a substantial difference in response time may be masked by the overall effectiveness of adding alphanumeric messages to the display. There is no pair of display conditions that would allow an unambiguous comparison of the effects of green bands alone, because the appropriate pair of conditions (Display Conditions 1 and 3) differed in the point at which other changes occurred in the display (color cues changed when the value of the parameter departed from the nominal range in Display Condition 3, but only when the value of the parameter exceeded a caution or warning limit in Display Condition 1).

In general, although differences in response accuracy were not statistically different, the data for response accuracy support the conclusions drawn by examining the response time data. Figure 20 in section 7 shows the accuracy of verbal identification responses for each display condition. Recall that a response was scored as accurate only if the subject correctly provided all three pieces of information about the problem: which parameter was involved, in which direction the deviation occurred, and which engine or engines were affected. Accuracy was higher in Display Condition 2 (98%), which included alphanumeric engine parameter alert messages than for the baseline EICAS format without messages (Display Condition 1, 92%). But accuracy in Display Condition 3 (92%), which added green bands to depict the range of nominal values, was identical to the baseline. Identification accuracy was lower than the baseline in Display Conditions 4 (82%) and Display Condition 5 (80%). In both these display conditions, the first alphanumeric message that appeared was one that advised the subject to monitor a parameter as it departed from the nominal range. These "monitor parameter" messages differed from the caution and warning messages that appeared first in Display Condition 2. The caution and warning messages in general included information about each of the three required pieces of information, e.g., "L EGT HIGH." Because of constraints on the number of letters that could be used in an alphanumeric message, the "monitor parameter" messages did not always contain the same amount of information, e.g., "MONITOR L EGT". This meant that subjects generally only had to read the alphanumeric message to obtain all the required pieces of information in Display Condition 2, but often had to cross-check the graphic display to do so in Display Conditions 4 and 5. In addition, subjects often read the "monitor parameter" message before they realized that it did not contain all the information that was required. They then had to cross-check the information on the graphical portion of the display. However, five seconds after the response switch was hit, the problem resolved itself, and the information may no longer have been available. Display Condition 2, with the addition of caution and warning alert messages only, had the most similar, highly salient display cues (alphanumeric caution and alert messages) for both engine and non-engine problems, and this may have increased accuracy by reducing response uncertainty. In addition, alphanumeric messages accumulated in all the display conditions that included messages until the problem was resolved. This meant that Display Conditions 4 and 5 could have twice as many messages displayed (both alert and "monitor parameter" messages) as Display Condition 2 by the time an engine problem was fully developed. This increase in the number of displayed messages could also have increased response uncertainty and thus decreased the response accuracy of Display Conditions 4 and 5 relative to Display Condition 2.

As shown earlier in Figure 14, there was a highly significant effect of Problem Onset Time on response time; this was expected because problems with a slow-onset time took longer to develop and appear in the EICAS displays, and thus longer to detect. The effect of Number of Engines on response time, however, was not significant. It took just as long to detect a problem that occurred in two engines as it did to detect a problem that occurred in one engine (Figure 15). It was hypothesized that the effect of adding green "nominal range" bands to the graphical parameter displays might have a greater effect for two-engine problems than for one-engine problems. This hypothesis, however, was not supported by the data. The interaction between Display Condition and Number of Engines was not significant. Figure 26 shows that responses were marginally faster for two-engine than for one-engine problems for the display conditions that included green bands (Display Conditions 3 and 5), and almost equal or marginally slower in the remaining conditions, but the interaction was not significant. Identification accuracy was equal or higher for the two-engine problems in all the display conditions (Figure 27).

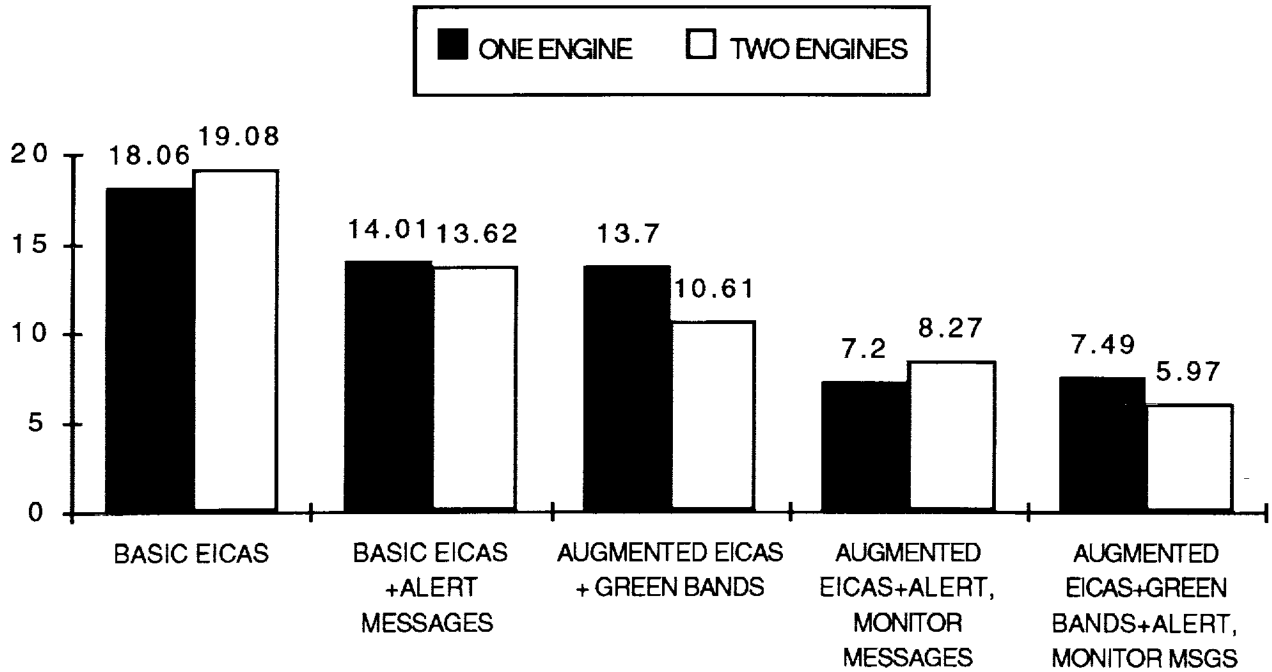


Figure 26. Average Response Time (sec) for Display Condition by Number of Engines

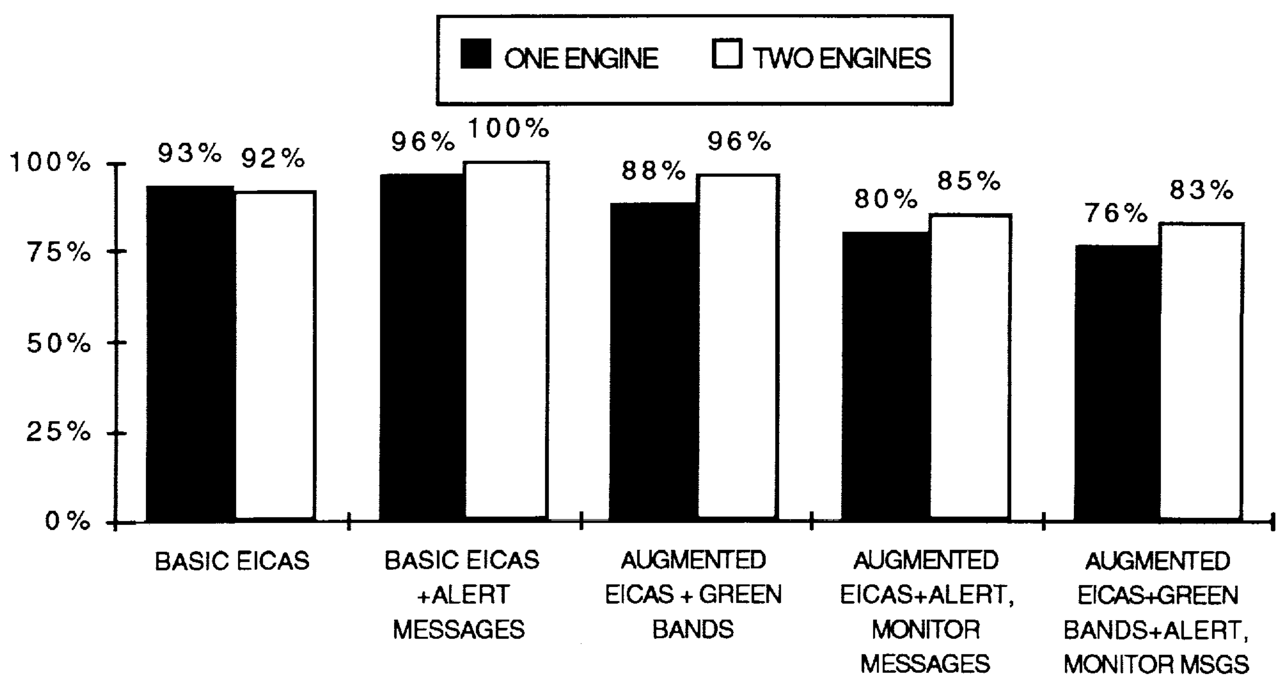


Figure 27. Average Identification Accuracy for Display Condition by Number of Engines

8.2 Subjective data

The subjective data generally supported the conclusions drawn from the objective data. Subjects rated the overall ease of use of each of the five display conditions immediately after the test flights that incorporated the display condition, and then rank-ordered the five display conditions after all test flights were completed. When subjects rated the display conditions immediately after the trial block, the ratings were fairly similar for four of the five display conditions, and the ratings increased in order from Display Condition 1 to Display Condition 5. Slight increases in the ratings were associated with the addition of either alphanumeric messages or green bands alone (Display Conditions 2 through 4); a significantly higher rating was associated with the addition of <u>both</u> messages and green bands (Display Condition 5). However, when forced to rank-order the five display conditions, subjects ranked highest the display conditions that included alphanumeric engine parameter messages (both alert and "monitor parameter" messages), with or without the addition of green "nominal range" bands (Display Conditions 2, 4, and 5). These were followed by the display condition that included green bands alone (Display Condition 3); least preferred was the basic EICAS (Display Condition 1), which did not include either messages or green bands. Ratings of the usefulness and ease of interpreting these features agreed with the relative rankings of the display conditions: engine parameter alert messages, "monitor parameter" messages, and green bands, respectively, were rated most to least useful and easy to interpret.

Answers to the open-ended questions at the end of all session, summarized earlier in Table 10, were consistent with these findings. Subjects mentioned that the alphanumeric engine parameter messages were useful additions to the display. One subject noted that the monitor messages were somewhat distracting and required a follow-up look at the graphic display of the parameter. When asked what they disliked about the displays, some subjects responded that the green bands and the "normal range" information were not as useful or necessary. Thus, in general, subjects found unambiguous alphanumeric messages about engine parameters a useful addition to the displays; they did not find the nominal range information, at least as implemented in this study, as useful.

8.3 Recommendations

One conclusion that may be drawn from both the objective and subjective data is that adding alphanumeric alert messages for problems involving engine parameters would aid in their detection and identification. Subjects made it clear that they found the alphanumeric engine parameter alert messages both useful and easy to interpret; they also responded faster and with greater accuracy when such messages were included in the display. Thus, one recommendation made as the result of this study would be to integrate engine parameters into the caution and warning alert system. That would involve adding caution, warning and status messages to the current list of messages available for other systems, and would provide an aural alert for all caution- and warning-level engine parameter problems. This change would provide the major advantage of consistency of coding across all systems problems. In addition, the alphanumeric engine parameter messages should be coded so that all the crucial information about the problem is included in the message: the engine and parameter that are involved, and if appropriate, the direction of the problem. This would make easily-assimilated information about engine-parameter problems complete in a single location, so that cross-checking with graphics would not be required. This is especially important in conditions in which the information is out of the pilots' primary scan (for example, on the lower EICAS screen) and for which a timely and rapid response is required.

Conclusions about the utility and interpretability of the green bands to depict nominal range values and the "monitor parameter" messages, and recommendations about their inclusion are less certain. These features were added to the display to enable the subjects to monitor and detect potential problems in engine parameters as they develop, but subjects had mixed responses to them. It is important to note that any conclusions must be based on the features as they were implemented and tested in this study. Subjects clearly preferred the addition of alphanumeric "monitor parameter" messages to having no messages at all, and the addition of these messages decreased the time required to detect a developing engine parameter problem. As discussed above, however, the wording of these messages should be clear and unambiguous. Further work should be done to determine the optimum wording and timing of such messages. The addition of green bands to indicate the range of nominal values for a given parameter, as implemented in this study, was not as useful or well received. Part of the problem may have been that the bands were relatively small and thus less easy to detect than they would have been if implemented in the larger vertical tape format used in the 747. It was hypothesized that subjects would use the location of the green bands to help determine whether the value of a parameter that was departing from the nominal range was high or low. An inspection of the verbal responses given by the subjects, however, indicated that a common form of response was, for example, "right EGT increasing". This indicates that in many cases, subjects were using the direction of movement of the pointer or caret for a parameter, and not its relative location, to determine whether the value of a parameter was high or low. Since relative movement appears to be a more salient and easily interpreted cue than relative location, its use as cue for monitoring engine parameters should be further explored. It should also be noted that the subjects in this study were all captains; first officers are usually responsible for monitoring systems problems, including engine problems. The subjects were not used to keeping the EICAS displays in their scan pattern, and many of them commented on the difficulty of doing so while they were manually flying the aircraft (another infrequent task). Under circumstances where a first officer was more closely monitoring the EICAS displays without the workload of flying, the results obtained in this study may have been different.

Including task-oriented information in a display is clearly the objective of any good human factors design process. Based on the results of this study, the integration of engine parameter information into the EICAS caution and warning system appears to be beneficial and desirable to line and training pilots. Incorporating an engine model that can compare current engine parameter values to those that are normal for the given flight phase and engine history may be an improvement on a system that only flags problems after they have reached a caution or warning level. But the specific circumstances under which this addition may be beneficial, as well as the best format for this additional task-oriented information must be further investigated. The addition of alphanumeric messages to monitor parameters that deviate from a normal range appears to be more beneficial and more preferred than the addition of a graphic depiction of the normal range as implemented in this study. The incorporation of any additional information into a display must carefully take into account the already existing display suite and coding conventions. Further studies should explore the most effective implementation of engine parameter monitoring and alert information consistent with the overall flight deck design philosophy.

9. REFERENCES

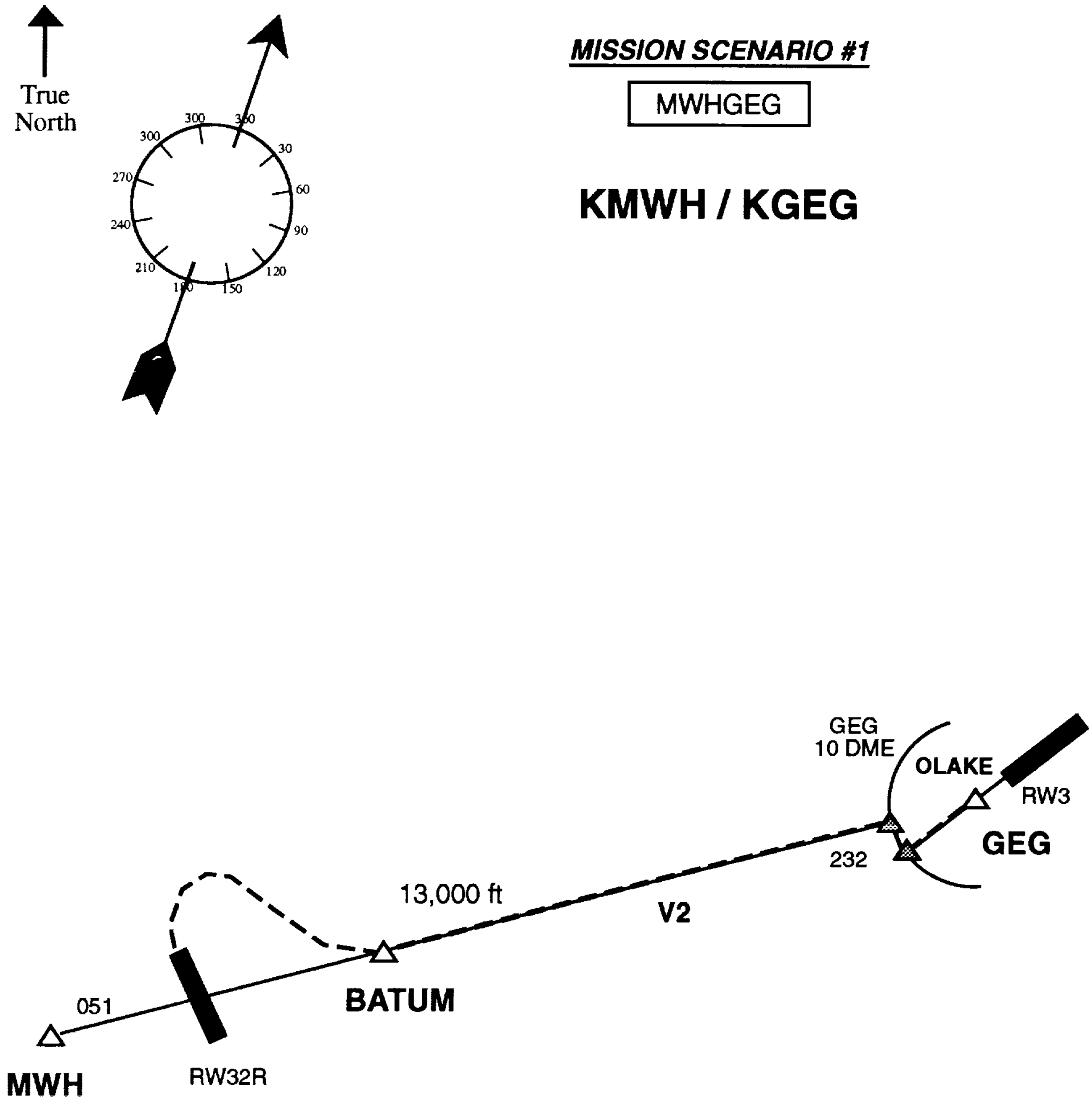
Abbott, T. S., Task-Oriented Display Design: Concept and Example, NASA Technical Memorandum #101685, December, 1989.

Boucek, G. P., Erickson, J. B., Berson, B. L., Hanson, D. C., Leffler, M. F., Aircraft Alerting Systems Standardization Study - Phase I Final Report, Department of Transportation Report # FAA-RD-80-68, February, 1980.

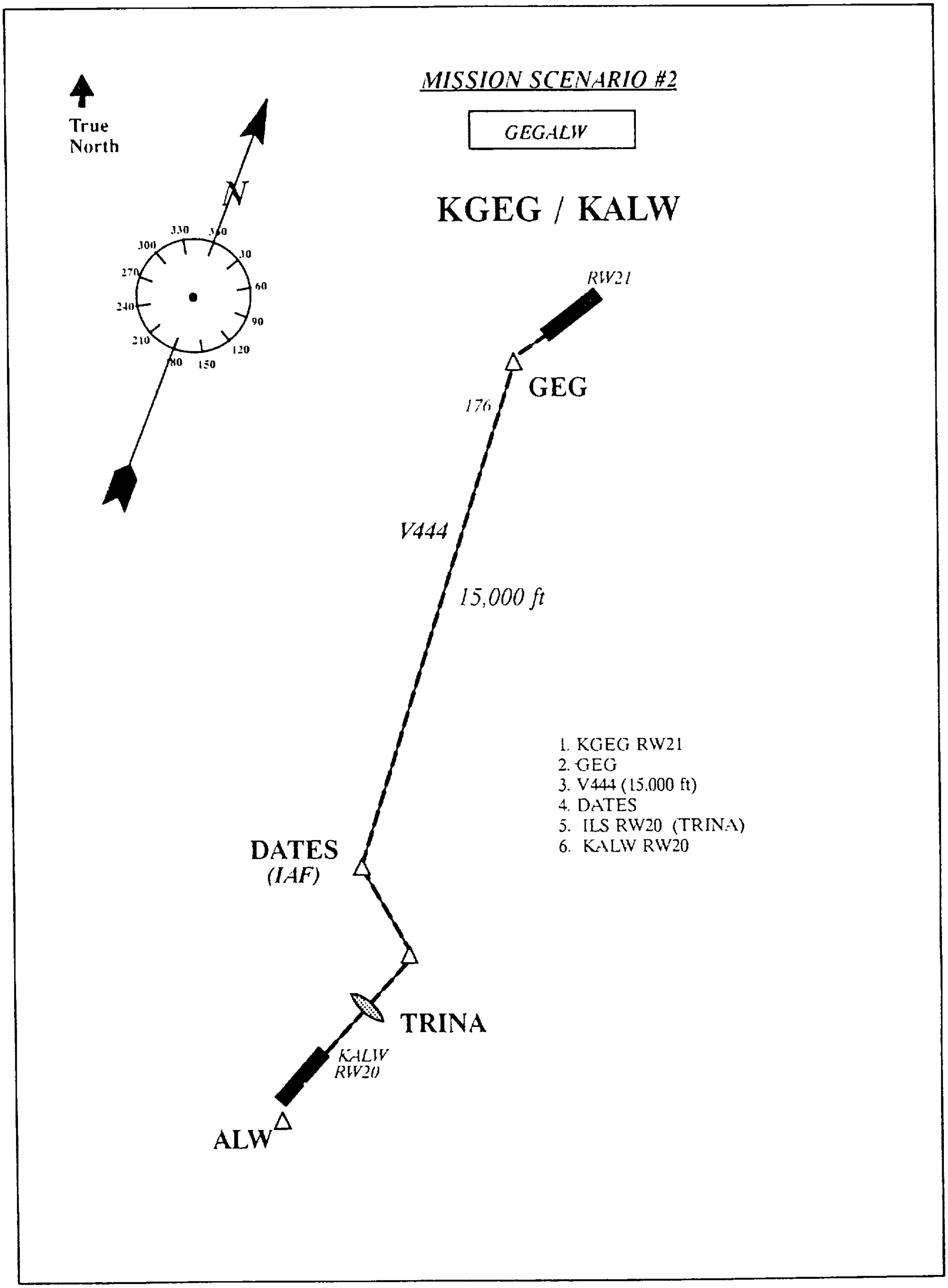
Corwin, W. H., Sandry-Garza, D. L., Biferno, M. H., Boucek, G. P., Logan, A. l., Jonsson, J. E., Metalis, S. A., Assessment of Crew Workload Measurement Methods, Techniques and Procedures, Report # WRDC-TR-89-7006, September 1989.

APPENDIX A
Flight Routes and ATC Scripts for Full-Flight Scenarios

This appendix includes the planned flight routes and the associated Air Traffic Control scripts for the full-flight scenarios used in the study.



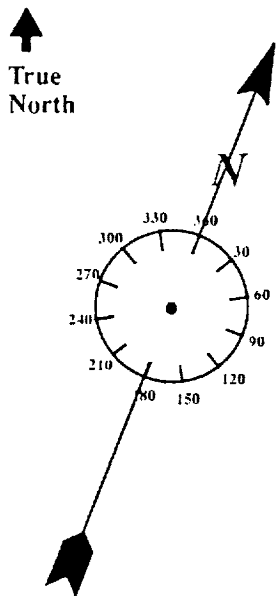
1. KMNH RW32R
2. BATUM
3. GGIAF3
4. GGLOC3
5. OLAKE (GEG)
6. KGEG RW3

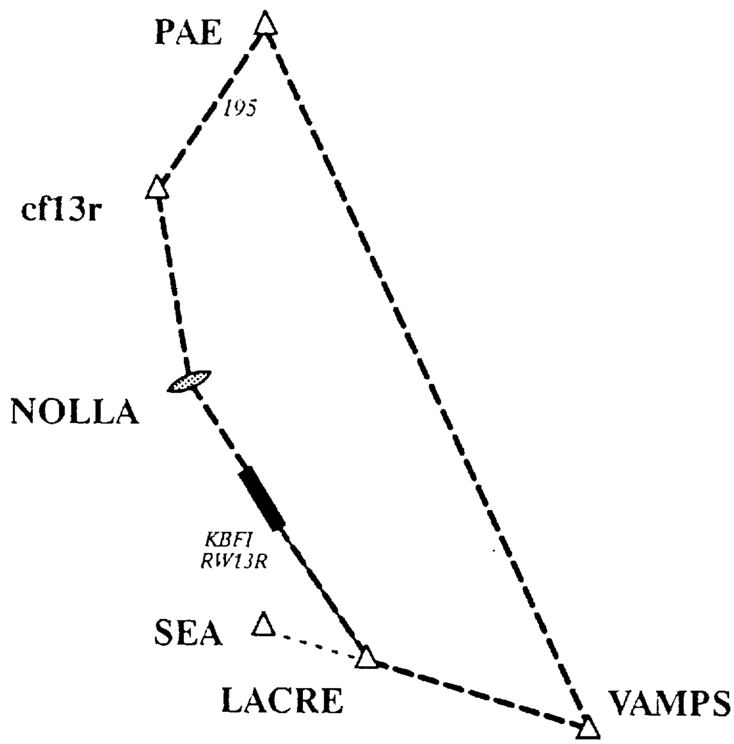

MISSION SCENARIO #2
GEGALW
KGEG / KALW
True North
N
330
360
300
30
270
60
240
90
210
120
180
150
RW21
GEG
176
V444
15,000 ft
1. KGEG RW21
2. GEG
3. V444 (15,000 ft)
4. DATES
5. ILS RW20 (TRINA)
6. KALW RW20
DATES
(IAF)
TRINA
KALW
RW20
ALW

MISSION SCENARIO #4

Company Route -- FTU01

KBFI / KBFI



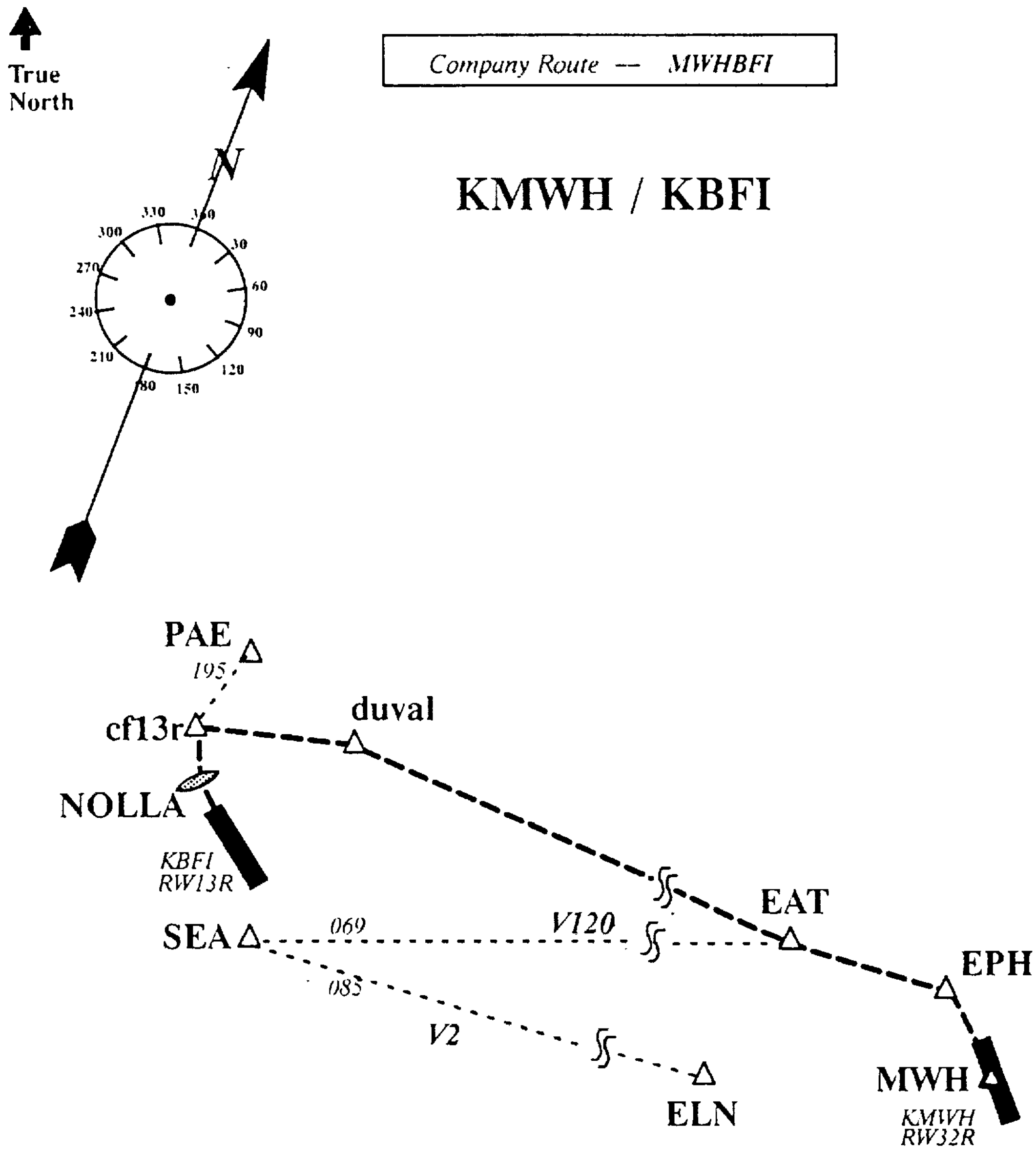


1. KBFI RW13R
2. LACRE
3. VAMPS
4. PAE
5. cf13r
6. NOLLA

MISSION SCENARIO #5

Company Route — MWHBFI

KMWH / KBFI



1. KMWH RW32R
2. EPH
3. EAT
4. duval
5. cf13r
6. NOLLA
7. ILS13R

ATC Script - Mission Scenario 1
KMWH/KGEG

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Spokane International Airport as filed. Climb and Maintain 8,000. Expect 13,000 five minutes after departure. Leaving 3,000 turn right to heading 100 to intercept V2. Squawk 7571. Departure Control frequency will be 120.85
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 32R at Taxiway A.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 32R.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 126.1.
One minute after level at 8,000 ft. MSL	Boeing 757, radar contact, climb and maintain 13,000.
One minute after level at 13,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
Aircraft passes D40/GEG	Boeing 757, contact Spokane Approach Control on 124.3.
Crew contacts Spokane Approach Control	Boeing 757, for traffic ahead, reduce speed to 210, then descend and maintain 5,000. Plan an ILS Runway 03 approach. Intercept the ILS Runway 03 localizer via the 10 DME Arc. Report crossing the 216 radial of the Spokane VOR.
Crew reports crossing GEG radial	Boeing 757, cleared for an ILS Runway 03 approach to the Spokane International Airport. Contact the Spokane tower 118.3 at OLAKE.
Crew reports OLAKE	Boeing 757, cleared to land, Runway 03. Wind 340 at 25 with gusts to 35. RVR Runway 03 2,400. Runway 03 braking action reported poor by a 737.
Aircraft slows to 60 knots	Boeing 757, clear the runway at taxiway C, if able, then contact Ground Control on 121.9.
Crew calls ground control	Boeing 757, taxi to the terminal via taxiways M and H.

ATC Script - Mission Scenario 2
KGEG/KALW

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Walla Walla Airport as filed. Climb and maintain 9,000. Expect 15,000 within 40 miles of the Spokane VORTAC. Squawk 7572. Departure Control frequency will be 124.7
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 21 via Taxiways G, M, and D.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 21.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff. Fly heading 205 after takeoff.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 126.1.
One minute after level at 9,000 ft. MSL	Boeing 757, radar contact, climb and maintain 15,000.
One minute after level at 15,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
Aircraft passes D40/ALW	Boeing 757, contact Tri-Cities Approach Control on 133.15.
Crew contacts Tri-Cities Approach Control	Boeing 757, for traffic ahead, reduce speed to 210, then descend and maintain 5,000. Plan an ILS Runway 20 approach. After DATES fly heading 126 to intercept the localizer. Report established on the localizer inbound.
Crew reports established on the localizer inbound.	Boeing 757, cleared for an ILS Runway 20 approach to the Walla Walla Airport. Contact the Walla Walla tower 118.5 at TRINA.
Crew reports TRINA	Boeing 757, cleared to land, Runway 20. Wind calm. RVR Runway 20 2,400. Runway 20 braking action reported fair by a 737.
Aircraft slows to 60 knots	Boeing 757, clear the runway at taxiway D, if able, then contact Ground Control on 121.7.
Crew calls ground control	Boeing 757, taxi to the terminal.

ATC Script - Mission Scenario 3
KBFI/KMWH

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Grant County Airport via a Kent Two departure, then as filed. Fly runway heading after departure. Climb and maintain 2,000. Expect 17,000 within 6 miles of Boeing Field. Squawk 7573. Departure Control frequency will be 119.2. Do not exceed 250 knots until advised.
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 13R at B1.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 13R.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff Runway 13R. Wind 210 at 25 with gusts to 35.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger, radar contact, climb and maintain 9,000.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 134.95.
One minute after level at 9,000 ft. MSL	Boeing 757, radar contact, climb and maintain 17,000. Cleared to the Grant County Airport via present position direct Wenatchee, then a Potholes 1 Arrival.
Climbing through 15,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
Aircraft passes EAT	Boeing 757, contact Seattle Center on 126.1.
Crew calls on Seattle Center on 126.1	Boeing 757, slow to 250 knots, then descend and maintain 9,000.
Aircraft passes D40/MWH	Boeing 757, contact Grant County Approach Control on 126.4.
Crew contacts Grant County Approach Control	Boeing 757, for traffic ahead, reduce speed to 210, then descend and maintain 5,000. Plan an ILS Runway 32R approach. Report crossing the 182° radial of the MWH VORTAC.
Crew reports crossing the 182° radial of the MWH VORTAC	Boeing 757, descend to 3,000. Maintain 3,000 until established inbound on the localizer. Cleared for an ILS Runway 32R approach to the Grant County Airport. Contact the Grant County Tower on 118.1 at PELLY.
Crew reports PELLY	Boeing 757, cleared to land, Runway 32R. Wind 200 at 15.
Aircraft slows to 60 knots	Boeing 757, turn left on Runway 21, if able, then contact Ground Control on 121.9.
Crew calls ground control	Boeing 757, taxi to the terminal via taxiways J, B, and A.

ATC Script - Mission Scenario 4
KBFI/KBFI

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Grant County Airport via a Kent Two departure, then as filed. Fly runway heading after departure. Climb and maintain 2,000. Expect 17,000 within 6 miles of Boeing Field. Squawk 7574. Departure Control frequency will be 119.2. Do not exceed 250 knots until advised.
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 13R at B1.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 13R.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff Runway 13R. Wind 210 at 15 with gusts to 25.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger, radar contact, climb and maintain 9,000.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 134.95.
One minute after level at 9,000 ft. MSL	Boeing 757, radar contact, climb and maintain 17,000. Cleared to the Grant County Airport via present position direct Wenatchee, then a Potholes 1 Arrival.
Climbing through 15,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
When crew requests a return to Boeing Field	Boeing 757, turn left to heading 340 and descend to 12,000. Contact Seattle Approach on 120.3.
When crew reports in to Seattle Approach Control	Boeing 757, cleared to the Boeing Field Airport via present position direct to the PAE VORTAC, then expect radar vector to the ILS Runway 13R final approach. Descend and maintain 5,000. Reduce speed to 250 knots. Cross 20 DME Southeast of the PAE VORTAC at or above 10,000.
Aircraft passes PAE	Boeing 757, for traffic ahead, reduce speed to 210 knots, turn left to heading 195, descend to 2,200 and intercept the localizer. Cleared for the straight-in ILS Runway 13R Approach. Contact Boeing Tower at NOLLA on 120.6.
Crew reports NOLLA	Boeing 757, cleared to land, Runway 13R. Wind 200 at 15.
Aircraft slows to 60 knots	Boeing 757, turn right at B5, if able, then contact Ground Control on 121.9.
Crew calls ground control	Boeing 757, taxi to the Boeing Company ramp.

ATC Script - Mission Scenario 5
KMWH/KBFI

Cue	ATC Message
Crew calls for clearance prior to taxi	Boeing 757 is cleared to the Boeing Field as filed. Climb and maintain 8,000. Expect 16,000 five minutes after departure. Leaving 3,000 proceed direct EPH. Squawk 7575. Departure Control frequency will be 126.4.
Crew calls ready to taxi	Boeing 757, taxi to and hold short of Runway 32R at Taxiway A.
Crew calls ready for takeoff	Boeing 757, taxi into position and hold, Runway 32R.
After aircraft is in position on the runway	Boeing 757, cleared for takeoff.
As the aircraft climbs through 1,000 ft. AGL	Boeing 757, contact Departure Control.
Crew checks in on Departure Control	Boeing 757, Roger. Say altitude.
Crew reports altitude	Boeing 757, Roger, radar contact.
Aircraft climbs through 7,000 ft. MSL	Boeing 757, contact Seattle Center on 126.1
One minute after level at 8,000 ft. MSL	Boeing 757, radar contact, climb and maintain 16,000, cleared direct DUVAL for a DUVAL 1 Arrival to Boeing Field.
One minute after level at 16,000 ft. MSL	Boeing 757, maintain airspeed at 320 knots or greater for sequencing.
Aircraft passes GLASR	Boeing 757, descend at pilot's discretion to 10,000. Cross JAKSN at 12,000 and 250 knots.
Aircraft levels at 10,000 ft MSL	Boeing, contact Seattle Approach Control on 123.9.
Crew contacts Spokane Approach Control	Boeing 757, for traffic ahead, reduce speed to 210, then descend and maintain 5,000. Plan an ILS Runway 13R approach to Boeing Field. After JAKSN proceed direct to the SEA 325°/20 nm then fly heading 160 to intercept the localizer. Report established inbound on the localizer.
Aircraft crosses the SEA 360° radial	Boeing 757, Descend and maintain 3,200.
Aircraft crosses the SEA 340° radial	Boeing 757, Descend and maintain 2,200.
Crew reports inbound on the localizer	Boeing 757, cleared for an ILS Runway 13R approach. Contact Boeing Tower 120.6 at NOLLA.
Crew reports NOLLA	Boeing 757, cleared to land, Runway 13R. Wind 200 at 15.
Aircraft slows to 60 knots	Boeing 757, turn right at B5, if able, then contact Ground Control on 121.9.
Crew calls ground control	Boeing 757, taxi to the Boeing Company Ramp.

APPENDIX B
Subjects' Background Questionnaires

This appendix includes both versions of the Pilot Background Questionnaire filled out by the subjects. One version was completed by Boeing training pilots, and the other was completed by United pilots.

[for Boeing Pilots]

Subject: ______________________________ Date: ________

PILOT BACKGROUND QUESTIONNAIRE

We are collecting background data on all pilots who participate in flight deck research simulation studies. To help us evaluate the results of this experiment, we would appreciate your filling out this questionnaire. Your identity will, of course, be completely protected since your name is never associated with the data.

1. How long have you been employed by Boeing? ______ years

2. How long have you served as a pilot in the following categories?

   Military _____ years General Aviation _____ years

   Airline _____ ears Boeing _____years

   Other (specify) _____ years

3. How many 757 hours do you have as:

Prior to Boeing:

Captain - Aircraft	_______	Simulator	_________
First Officer - Aircraft	_______	Simulator	_________

Boeing experience:

	As Pilot	As Instructor
Total 757 hours		
Simulator	______	______
Airplane	______	______
Total 767 hours		
Simulator	______	______
Airplane	______	______
Total 747 hours		
Simulator	______	______
Airplane	______	______

[for Boeing Pilots]

	As Pilot	As Instructor
Total 747-400 hours		
Simulator	_____	_____
Airplane	_____	_____
Total 737-100/200 hours		
Simulator	_____	_____
Airplane	_____	_____
Total 737-300/400/500 Hrs		
Simulator	_____	_____
Airplane	_____	_____

4. How much time have you in other FMC equipped aircraft?

   Aircraft Type _____

   Total Hours - Simulation ____ Flight _____

5. How much time do you spend flying in the following categories?

   Military _____ hours/month

   General Aviation _____ hours/month

   Boeing _____ hours/month

   Other (specify) _____ hours/month

6. What is your present status? Circle all appropriate answers.

   a. Production Test

   b. Engineering Test

   c. Instructor Pilot

   d. Flight Engineer (full time)

   e. Other (specify)

7. How long have you been in your present status? ______ years

8. What is your height? ______ ft _____in.

9. What is your weight? ____ lbs.

10. What is your sex? ______ Male ______ Female

11. What is your age? ______ years

12. Circle the response which best describes your general health?

A	B	C	D	E
Fair				Excellent

13. How often do you exercise?

A	B	C	D	E
0x week	1-2x week	3-4x week	5-6x week	7x week

14. How often do you exercise at about the same time of day?

A	B	C	D	E
Rarely				Frequently

15. Briefly describe the type of physical exercise or sports in which you participate:

____

____

____

16. Do you wear corrective lenses? Yes/No

17. If Yes to #16, what type of lenses do you wear?

Soft Contacts ______

Hard Contacts ______

Bifocal Contacts ______

Glasses/
Bifocals/Verilux ______

Other (specify) ______

[for United Pilots]

Subject: ______________________________ Date: ________

PILOT BACKGROUND QUESTIONNAIRE

We are collecting background data on all pilots who participate in flight deck research simulation studies. To help us evaluate the results of this experiment, we would appreciate your filling out this questionnaire. Your identity will, of course, be completely protected since your name is never associated with the data.

1. How long have you been employed by United? ______ years

2. How long have you served as a pilot in the following categories?

   Military _____ years General Aviation _____ years

   Airline _____ ears Other (specify) _____ years

3. How many 757 hours do you have as:

   Captain - Aircraft _______ Simulator _________

   First Officer - Aircraft _______ Simulator _________

4. How many 767 hours do you have as:

   Captain - Aircraft _______ Simulator _________

   First Officer - Aircraft _______ Simulator _________

5. How many 747-400 hours do you have as:

   Captain - Aircraft _______ Simulator _________

   First Officer - Aircraft _______ Simulator _________

6. How much time do you spend flying in the following categories?

   Military ______ hours/month

   General Aviation ______ hours/month

   Boeing ______ hours/month

   Other (specify) ______ hours/month

6. What is your present status? Circle all appropriate answers.

   a. Captain

   b. First Officer

   e. Other (specify)

7. How long have you been in your present status? ______ years

8. What is your height? ______ ft _____in.

9. What is your weight? ____ lbs.

10. What is your sex? ______ Male ______ Female

11. What is your age? ______ years

12. Circle the response which best describes your general health?

A	B	C	D	E
Fair				Excellent

APPENDIX C

Subjective Questionnaires and Data Summaries

This appendix includes the subjective data questionnaires given after each trial block, with responses summarized on the questionnaires. It also includes a copy of the final questionnaire given after all trial blocks were completed. Rating and ranking esponses to the trial block and final questionnaires are summarized at the end with original and transformed scores data included.

Subject #: **Date:**

<u>QUESTIONNAIRE SUMMARY</u>

BASIC EICAS - DISPLAY CONDITION 1

This is a mark-the-block questionnaire. For each question, put an X inside the block that best describes your opinion.

Definitions:

Extremely easy:	Intuitive, no mental effort is required to use.
Fairly easy:	Moderate mental workload, some thought is required to use.
Extremely rapid:	Instantaneously.
Fairly rapid:	With only a moderate delay.

1. Overall, how easy did you find this display format to use?

extremely easy				fairly easy
	3	4	2	1

Questions 2 and 3 concern use of the ROUND DIAL EICAS indicators.

2. How easy to use did you find the display elements for monitoring N_1, N_2 and EGT?

extremely easy				fairly easy
	4	3	2	1

3. How rapidly were you able to detect an out-of-tolerance condition for N_1, N_2 and EGT?

extremely rapidly				fairly rapidly
	3	3	3	1

Questions 4 and 5 concern use of vertical scale EICAS indicators.

4. How easy to use did you find the vertical scale display elements for monitoring oil,pressure, oil temperature, oil quantity and vibration?

		5	4	1

extremely easy — fairly easy

5. How rapidly were you able to detect an out-of-tolerance condition for oil,pressure, oil temperature, oil quantity and vibration?

		4	1	5

extremely easy — fairly easy

Subject #: **Date:**

<u>QUESTIONNAIRE SUMMARY</u>

EICAS PLUS ENGINE PARAMETER MESSAGES - DISPLAY CONDITION 2

This is a mark-the-block questionnaire. For each question, put an X inside the block that best describes your opinion.

Definitions:

Extremely easy:	Intuitive, no mental effort is required to use.
Moderately easy:	Moderate mental workload, some thought is required to use.
Extremely rapid:	Instantaneously.
Moderately rapid:	With only a moderate delay.

1. Overall, how easy did you find this display format to use?

	3	3	4	
extremely easy				moderately easy

Questions 2 and 3 concern use of the ROUND DIAL EICAS indicators.

2. How easy to use did you find the display elements for monitoring N_1, N_2 and EGT?

	2	4	3	1
extremely easy				moderately easy

3. How rapidly were you able to detect an out-of-tolerance condition for N_1, N_2 and EGT?

1	2	2	4	1
extremely rapid				moderately rapid

Questions 4 and 5 concern use of vertical scale EICAS indicators.

4. How easy to use did you find the vertical scale display elements for monitoring oil, pressure, oil temperature, oil quantity and vibration?

		4	4	2
extremely easy				moderately easy

5. How rapidly were you able to detect an out-of-tolerance condition for oil, pressure, oil temperature, oil quantity and vibration?

		4	3	3
extremely rapid				moderately rapid

Subject #: **Date:**

QUESTIONNAIRE SUMMARY

AUGMENTED EICAS - DISPLAY CONDITION 3

This is a mark-the-block questionnaire. For each question, put an X inside the block that best describes your opinion.

Definitions:

Extremely easy:	Intuitive, no mental effort is required to use.
Moderately easy:	Moderate mental workload, some thought is required to use.
Extremely rapid:	Instantaneously.
Moderately rapid:	With only a moderate delay.

1. Overall, how easy did you find this display format to use?

1	3	2	3	1
extremely easy				moderately easy

Questions 2 and 3 concern use of the ROUND DIAL EICAS indicators.

2. How easy to use did you find the display elements for monitoring N_1, N_2 and EGT?

1	2	3	3	1
extremely easy				moderately easy

3. How rapidly were you able to detect an out-of-tolerance condition for N_1, N_2 and EGT?

	3	3	3	1
extremely rapid				moderately rapid

Questions 4 and 5 concern use of vertical scale EICAS indicators.

4. How easy to use did you find the vertical scale display elements for monitoring oil, pressure, oil temperature, oil quantity and vibration?

	1	3	2	4
extremely easy				moderately easy

5. How rapidly were you able to detect an out-of-tolerance condition for oil, pressure, oil temperature, oil quantity and vibration?

	2	3	1	4
extremely rapid				moderately rapid

Subject #: **Date:**

QUESTIONNAIRE SUMMARY

EICAS PLUS MONITOR AND PARAMETER MESSAGES - DISPLAY CONDITION 4

This is a mark-the-block questionnaire. For each question, put an X inside the block that best describes your opinion.

Definitions:

Extremely easy: Intuitive, no mental effort is required to use.

Moderately easy: Moderate mental workload, some thought is required to use.

Extremely rapid: Instantaneously.

Moderately rapid: With only a moderate delay.

1. Overall, how easy did you find this display format to use?

	5	2	3	
extremely easy				moderately easy

Questions 2 and 3 concern use of the ROUND DIAL EICAS indicators.

2. How easy to use did you find the display elements for monitoring N_1, N_2 and EGT?

	4	3	2	1
extremely easy				moderately easy

3. How rapidly were you able to detect an out-of-tolerance condition for N_1, N_2 and EGT?

	3	4	2	1
extremely rapid				moderately rapid

Questions 4 and 5 concern use of vertical scale EICAS indicators.

4. How easy to use did you find the vertical scale display elements for monitoring oil, pressure, oil temperature, oil quantity and vibration?

	1	2	3	4

extremely easy — moderately easy

5. How rapidly were you able to detect an out-of-tolerance condition for oil, pressure, oil temperature, oil quantity and vibration?

	2	2	2	4

extremely rapid — moderately rapid

Subject #: **Date:**

QUESTIONNAIRE SUMMARY

AUGMENTED EICAS PLUS MESSAGES - DISPLAY CONDITION 5

This is a mark-the-block questionnaire. For each question, put an X inside the block that best describes your opinion.

Definitions:

Extremely easy:	Intuitive, no mental effort is required to use.
Moderately easy:	Moderate mental workload, some thought is required to use.
Extremely rapid:	Instantaneously.
Moderately rapid:	With only a moderate delay.

1. Overall, how easy did you find this display format to use?

4	3	2	1	
extremely easy				moderately easy

Questions 2 and 3 concern use of the ROUND DIAL EICAS indicators.

2. How easy to use did you find the display elements for monitoring N_1, N_2 and EGT?

1	5	1	3	
extremely easy				moderately easy

3. How rapidly were you able to detect an out-of-tolerance condition for N_1, N_2 and EGT?

1	4	3	2	
extremely rapid				moderately rapid

Questions 4 and 5 concern use of vertical scale EICAS indicators.

4. How easy to use did you find the vertical scale display elements for monitoring oil, pressure, oil temperature, oil quantity and vibration?

	2	3	3	2
extremely easy				moderately easy

5. How rapidly were you able to detect an out-of-tolerance condition for oil, pressure, oil temperature, oil quantity and vibration?

	3	4	1	2
extremely rapid				moderately rapid

Subject #: **Date:**

Final Questionnaire Summary

1. Rank the displays according to ease of use, where 1 is easiest to use, and 5 is least easy to use:

   4.4 Basic EICAS
   2.2 EICAS plus engine parameter messages (L ENG LOW EGT)
   3.6 EICAS plus monitor messages (MONITOR L EGT)
   2.5 Augmented EICAS (with green NORMAL RANGE bands)
   2.5 Augmented EICAS with geen bands and messages

2. How useful were the following features added to the standard EICAS display?

   2a. Engine parameter messages (L ENG LOW EGT)

		2		8
not at all useful				very useful

   2b. Monitor messages (MONITOR L EGT)

	1		5	4
not at all useful				very useful

   2c. Green bands to show normal range for parameter

1	3	4	2	
not at all useful				very useful

3. How easy to interpret were the following features added to the standard EICAS display?

3a. Engine parameter messages (L ENG LOW EGT)

			2	8

extremely easy to interpret — very easy to interpret

3b. Monitor messages (MONITOR L EGT)

	1		5	4

extremely easy to interpret — very easy to interpret

3c. Green bands to show normal range for parameter

1	2	1	5	1

extremely easy to interpret — very easy to interpret

4. In general, what did you like about the features associated with the augmented EICAS display?

5. In general, what did you dislike about the features associated with the augmented EICAS display?

6. If you have additional comments, please include them here.

DISPLAY CONDITION QUESTIONNAIRES												AVG.	STD	TRANS.
SUBJECT#	1	2	3	4	5	6	7	8	9	10			DEV.	AVG.
BASIC EICAS														
OVERALL EASE OF INTERPRETATION	3	3	3	4	3	4	3	2	5	2		3.2	0.9	1.8
ROUND-DIAL INDICATORS-EASE OF INTERPRETATION	3	3	3	4	4	2	3	2	5	2		3.1	1.0	1.9
ROUND-DIAL INDICATORS-SPEED OF INTERPRETATION	3	3	2	4	4	4	3	2	5	3		3.3	0.9	1.7
VERTICAL-SCALE INDICATORS-EASE OF INTERPRETATION	3	3	4	5	5	3	3	3	5	5		3.9	1.0	1.1
VERTICAL-SCALE INDICATORS-SPEED OF INTERPRETATION	3	3	4	5	5	5	3	3	5	5		4.1	1.0	0.9
EICAS + ALERTS														
OVERALL EASE OF INTERPRETATION	2	4	3	3	2	4	3	2	4	4		3.1	0.9	1.9
ROUND-DIAL INDICATORS-EASE OF INTERPRETATION	2	3	3	3	4	4	3	2	5	4		3.3	0.9	1.7
ROUND-DIAL INDICATORS-SPEED OF INTERPRETATION	1	2	3	4	4	4	3	2	5	4		3.2	1.2	1.8
VERTICAL-SCALE INDICATORS-EASE OF INTERPRETATION	3	3	4	4	5	5	3	4	3	4		3.8	0.8	1.2
VERTICAL-SCALE INDICATORS-SPEED OF INTERPRETATION	3	3	4	4	5	5	3	5	3	4		3.9	0.9	1.1
AUGMENTED EICAS														
OVERALL EASE OF INTERPRETATION	3	2	1	4	3	5	2	2	4	4		3.0	1.2	2.0
ROUND-DIAL INDICATORS-EASE OF INTERPRETATION	2	3	1	4	3	5	2	3	4	4		3.1	1.2	1.9
ROUND-DIAL INDICATORS-SPEED OF INTERPRETATION	2	3	3	4	3	5	2	2	4	4		3.2	1.0	1.8
VERTICAL-SCALE INDICATORS-EASE OF INTERPRETATION	3	3	4	5	5	5	2	3	4	5		3.9	1.1	1.1
VERTICAL-SCALE INDICATORS-SPEED OF INTERPRETATION	2	3	3	5	5	5	2	4	3	5		3.7	1.3	1.3

Questionnaire Data Summary

DISPLAY CONDITION QUESTIONNAIRES												AVG.	STD	TRANS.
SUBJECT#	1	2	3	4	5	6	7	8	9	10			DEV.	AVG.
EICAS + ALERTS AND "MONITOR" MESSAGES														
OVERALL EASE OF INTERPRETATION	2	2	2	3	4	2	3	2	4	4		2.8	0.9	2.2
ROUND-DIAL INDICATORS-EASE OF INTERPRETATION	2	2	2	3	4	2	3	3	5	4		3.0	1.1	2.0
ROUND-DIAL INDICATORS-SPEED OF INTERPRETATION	2	3	2	3	5	2	3	3	4	4		3.1	1.0	1.9
VERTICAL-SCALE INDICATORS-EASE OF INTERPRETATION	3	3	5	4	5	2	4	4	5	5		4.0	1.1	1.0
VERTICAL-SCALE INDICATORS-SPEED OF INTERPRETATION	3	3	5	5	2	2	4	5	4	5		3.8	1.2	1.2
AUGMENTED EICAS + ALERTS AND "MONITOR" MESSAGES														
OVERALL EASE OF INTERPRETATION	1	1	2	3	3	2	2	1	4	1		2.0	1.1	3.0
ROUND-DIAL INDICATORS-EASE OF INTERPRETATION	2	1	2	3	4	2	2	2	4	4		2.6	1.1	2.4
ROUND-DIAL INDICATORS-SPEED OF INTERPRETATION	1	2	3	3	4	2	2	2	4	3		2.6	1.0	2.4
VERTICAL-SCALE INDICATORS-EASE OF INTERPRETATION	3	3	3	4	5	2	2	4	4	5		3.5	1.1	1.5
VERTICAL-SCALE INDICATORS-SPEED OF INTERPRETATION	2	3	3	3	5	2	2	4	3	5		3.2	1.1	1.8

Questionnaire Data Summary

FINAL QUESTIONNAIRE												AVG.	STD	TRANS.
SUBJECT#	1	2	3	4	5	6	7	8	9	10			DEV.	RANKING
DISPLAY RANKING														
BASIC EICAS	4	5	5	5	4	5	5	3	5	3		4.4	0.8	1.6
EICAS PLUS ALERTS	2	2	4	1	1	1	4	2	3	2		2.2	1.1	2.8
AUGMENTED EICAS	3	4	2	4	5	4	2	4	3	5		3.6	1.1	2.4
EICAS + ALERTS AND "MONITOR" MESSAGES	5	3	3	2	2	2	3	1	3	1		2.5	1.2	2.5
AUGMENTED EICAS+ALERTS AND "MONITOR MESSAGES"	1	1	1	3	3	3	1	5	3	4		2.5	1.4	2.5
USEFULNESS OF ADDED FEATURES														
ENGINE PARAMETER MESSAGES	3	5	5	5	5	5	3	5	5	5		4.6	0.8	-
MONITOR PARAMETER MESSAGES	2	4	5	4	4	5	4	4	5	5		4.2	0.9	-
GREEN NOMINAL-RANGE BANDS	3	4	3	2	1	2	4	3	3	2		2.7	0.9	-
EASE OF INTERPRETATION OF ADDED FEATURES														
ENGINE PARAMETER MESSAGES	5	4	5	5	5	5	4	5	5	5		4.8	0.4	-
MONITOR PARAMETER MESSAGES	2	4	4	4	4	5	4	5	5	5		4.2	0.9	-
GREEN NOMINAL-RANGE BANDS	4	4	4	3	1	2	4	4	2	5		3.3	1.3	-

Questionnaire Data Summary

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1992	Contractor Report

4. TITLE AND SUBTITLE
Engine Monitoring Display Study

5. FUNDING NUMBERS
C NAS1-18027
WU 505-66-41-04

6. AUTHOR(S)
Mary E. Hornsby

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boeing Commercial Airplane Group
P.O. Box 3707, M/S 6U-ER
Seattle, WA 98124-2207

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665-5225

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-4463

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Terry S. Abbott
Langley Contracting Officer's Technical Representative: Cary R. Spitzer
Final Report - Task 18

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 08

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The current study is part of a larger NASA effort to develop displays for an engine-monitoring system to enable the crew to monitor engine parameter trends more effectively. The objective for this study was to evaluate the operational utility of adding three types of information to the basic Boeing Engine Indicating and Crew Alerting System (EICAS) display formats: alphanumeric alerting messages for engine parameters whose values exceed caution or warning limits; alphanumeric messages to "monitor" engine parameters that deviate from expected values; and a graphic depiction of the range of expected values for current conditions.

Ten training and line pilots each flew 15 simulated flight scenarios with five variants of the basic EICAS format; these variants included different combinations of the added information. The pilots detected engine problems more quickly when engine alerting messages were included in the display; adding a graphic depiction of the range of expected values did not affect detection speed. The pilots rated both types of alphanumeric messages (alert and "monitor parameter") as more useful and easier to interpret than the graphic depiction. Integrating engine parameter messages into the EICAS alerting system appears to be both useful and preferred.

14. SUBJECT TERMS
Engine Alerting and Monitoring Systems, Caution and Warning Displays

15. NUMBER OF PAGES
96

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

NASA-Langley, 1992

END DATE OCT 6, 1992