Aiding the Pilot in Flight Control Fault Detection

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Jerónimo José Andrés Chiecchio

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Aiding the Pilot in Flight Control Fault Detection

Approved by

Dr. Amy R. Pritchett
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Eric N. Johnson
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Michael D. New
Director of Research and Development
Delta Airlines

December 10, 2004

To Paula

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Summary

Three flight simulator experiments examined how a health monitoring system may aid pilots in detecting flight control faults. The first experiment introduced an unexpected fault in the flight control system during an approach to a fictitious airport. The second experiment used a factorial design of (1) presence – or not—of a Fault Meter display and (2) presence – or not – of an Alerting System, which could have one or two phased alerts. In half the runs, a fault was triggered at some point, and pilot response was recorded. The next experiment comprised one flight in which pilots were given a false alarm by these systems, testing for automation bias.

No consistent pilot response was found to the faults, with pilots sometimes successfully landing the aircraft, sometimes immediately or eventually initiating a go-around, and sometimes loosing aircraft control and crashing. The pilots were not able to identify the fault in 11% of the cases. Tunnel tracking error increased following the faults and the false alarm, suggesting it may be both a manifestation of attempts to diagnose a fault and a cue to pilots of a problem. Finally, the triggering of a false alarm showed the existence of automation bias induced after a small number of interactions with the HMS.

1 Introduction

New technology can provide real time information about the health of the aircraft, potentially aiding pilots to manage flight control system problems and other issues that have an effect on flight control. (In this dissertation the word “fault” is used in reference to any fault, failure or problem that affects flight control.) Analysis of the possible advantages of such a technology requires an understanding of the fault management processes used by pilots, and also the functions by which a health monitoring system could help the pilot. As illustration, consider the following examples:

> *After performing the required weight and balance calculations, the crew of a regional turboprop aircraft found that the weight was 200lb over the MTOW. Eight bags were removed from the cargo bay and the flight departed. During take off roll, the pilot noticed that the nose wheel lifted of the ground before V1, and needed to apply unusual down elevator pressure to keep the nose down. At Vr, the aircraft rotated and lifted up with no further problems. The climb continued and the autopilot was engaged. “At FL203, climbing to FL210, the airplane was on autopilot, in climb mode. I felt a buffet and looked at the VSI which showed +100 FPM[…]Calibrated airspeed showed 135 kts, 15 below minimum…[…] I promptly disconnected the autopilot and pitched down. We leveled off at FL190 and everything was right. We never got a [stick] shaker.” After the flight landed without further events, the crew requested a bag count and found that there were 13 more bags than declared in the manifest. Also, the crew reported that some of the bags should have been counted double for their weight. Since the baggage compartment is located in the aft section of the fuselage, the center of gravity was definitely out of the flight envelope.*

Another regional turboprop aircraft crew required a second de-icing after observing snow on the wings after the first de-icing. Subsequently, during take off and initial climb the first officer (F/O) noticed that he needed unusual forward pressure to keep the desired attitude. He also noted that the elevator trim indicator was full down. The captain mentioned that it was probably an inoperative trim indicator gauge, and ordered the F/O to continue the flight as planned. When cruise altitude was reached and the aircraft accelerated to cruise speed, the F/O needed an "unusual large amount of forward pressure" and had a hard time maintaining altitude because the aircraft wanted to climb. The captain took control of the aircraft and agreed that there was a problem. He reduced power and asked the flight attendant to move all passengers to the forward section of the cabin. This resolved the aircraft tendency to climb and the captain decided to continue the flight to its destination. The F/O argued that he wanted to divert to nearest airport for possible tail icing, flight control problems and flying out of the CG envelope. After some arguing, the captain finally agreed to divert and land. During the descent, the situation normalized and the trim returned to normal position. A safe landing was performed. It was later found that the de-icing personnel had little experience and had not de-iced the tail of the aircraft.

These are two examples of problems that can have a severe impact on flight control. The common characteristic is that both problems were not detected by any monitoring or detection system of the aircraft. It may be argued that weight sensors in the landing gear could detect weight and balance problems, but those systems are currently only installed in the bigger wide body aircraft and would not sense, for example, a load shift in flight. Icing detectors and sensors are available, but they only inform the pilot that icing conditions exist in the location of the aircraft where the sensor is installed. They do not inform the pilot of previous accumulation of ice, or of the impact of the existing ice accumulation on the performance of the aircraft. Another characteristic of these problems is that they may only be noticeable to the pilot in certain areas of the flight envelope or in certain configurations of the aircraft. For example, center of gravity out of range condition may not be a problem until flaps are lowered and the elevator trim has not enough capacity to compensate for the excessive pitch moment.

Problems that impact flight control and are difficult to detect via the aircraft's sensing systems may appear not only as a result of external causes such as icing or a careless cargo load, but also from the aircraft itself. Sensors may fail to provide correct information and disturbances may arise in the autopilot or the Flight Control System (FCS). For example, consider the following case:

> *"On two consecutive days, the same airplane experienced un-commanded rolls during flight with the autopilot engaged. Both incidents occurred during final phase of the flight, but the crews managed to land the aircraft without further problems. Inspection of the airplane systems revealed a defect in a roll potentiometer located in the captain's side-stick transducer unit."*

In this specific case, the FCS computer displayed a generic fault message to the pilot when the fault occurred, but after the warning message was given, no extra information helped the pilot determine if the fault was still affecting the handling of the aircraft, or, if it was, how severe the problem was. In the most advanced fly-by-wire systems, where the FCS itself may be compensating for the problem by itself, the pilot's detection of the problem may be very difficult.

1.1 Health Monitoring System Concept

It has been proposed that new technology using advanced control and estimation techniques could provide the pilot with information about the general health of the aircraft. For the objective of the proposed research, it is important to describe the expected characteristics of the information that this system could provide to the pilot.

Model-based observers such as Kalman filters can be fed with the same control inputs that the human pilot or autopilot puts in the real aircraft. An examination between current measured states and observer state estimates may indicate deterioration in the flying characteristics of the aircraft. This error could be presented to the pilot to help him/her manage problems that can affect flight control. (In this document, this type of system is referred as a health monitoring system [HMS].)

The main limitation of the information provided by this type of HMS is that the cause of the error is neither directly sensed nor shown to the pilots. Considering the previous examples of the regional turboprops, we could assume that a HMS would have measured an error in both cases and the magnitude of the error could provide information about the severity of the problem. However, the system does not have any the ability to determine the cause of the error.

As aircraft system complexity grows, it would be intuitive to assume a growth in the number of monitoring systems could grow to try to cover as many possible faults or malfunctions as possible. However, complexity and cost can definitely be limiting factors for the implementation of additional sensors and monitors of performance and systems. In this context, the information provided by this type of HMS not only would complement the situations where common alerting systems have no detection or sensing capacity, but it would also supplement information provided by aircraft alerting systems by providing a continuous assessment of the existence and severity of a fault.

1.2 Pilot Response to Faults

The analysis of the effects of an HMS in the process of fault management requires an understanding of the possible contexts in which the event may occur. The context is characterized by many factors such as: time pressure and constraints (e.g. meeting departure or arrival times, complying with air traffic control [ATC] commands in heavy traffic); environment characteristics (e.g. bad weather or night flying, smoke in the cockpit); pilot personal conditions (e.g. fatigue, emotional state); workload; availability of relevant operating procedures; and different tasks or phases of flight.

Within this operational context, fault management can be identified to occur at three levels: At the system level, the pilot monitors system parameters, diagnoses abnormal system states, makes prognoses and compensates within the system. If compensation is not effective, fault management at this level may impact processes at the aircraft level, which consists in all activities related to maintaining control of the aircraft's attitude, altitude, and speed and direction of flight. For example, compensation at this level may require adapting the pilot's control strategy for maintaining level flight after a cargo shift occurs. Problems that can not successfully be managed at the aircraft level may have an impact at the mission level. This level involves all fault management that impacts the overall flight objectives, such as destination airport, route of flight, etc. Factors at this level can include weather, fuel availability, terrain, Air Traffic Control constraints. Figure 1 represents the fault management tasks at the three operational levels.

For this research, it is most important to understand how pilots react to faults and/or problems that are not detected by the standard alerting and monitoring systems of the aircraft, such as the three cases presented in the system introduction. In such cases, the pilot does not have enough information available to manage the situation at the systems level. Therefore, the focus of interest here will be mostly at the aircraft level. But, as mentioned before, faults occurring at the aircraft level may have a cascading effect at the mission level. Within each level, fault management may be defined as four operational tasks: detection, diagnosis, prognosis and compensation, shown in Figure 1. Not all tasks may be required during every particular fault management process. Rasmussen (Rasmussen, 1983) described Skill Based and Rule Based Behaviors (RBB and SBB) as shortcuts and shunts between elements of the decision ladder. The SBB describe automated response patterns, obtained from extensive training or experience while RBB responses are based on associations between the environmental cues and stored rules or procedures for action. Without these shortcuts, the pilot would have to go through all the tasks of the fault management process, making some faults impossible to manage in time constrained situations.

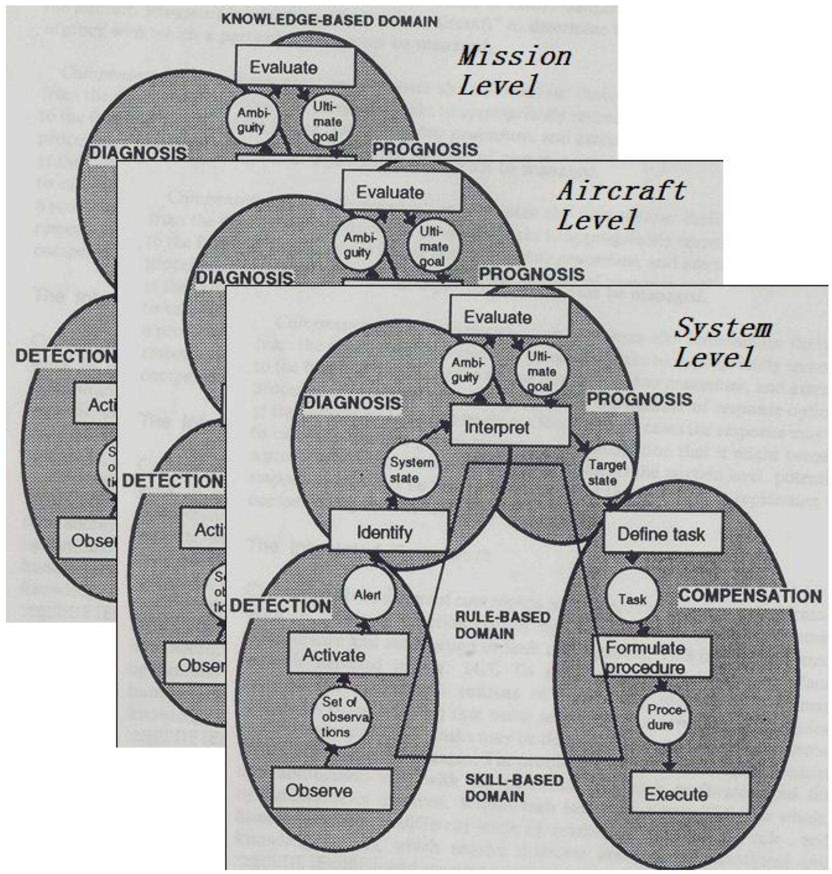


Figure 1- Fault management processes at each operational level.

1.3 The HMS, the Alerting System and the Fault Meter

The HMS output provides a continuous real time measure of the error between the on-board simulation and the real status of the aircraft. This measure could be fed into an automated system set to alert the pilot when the HMS error values reach a certain threshold. But, even with the simplest designs the "alarm problem" (Woods, 1995) describes the set of factors associated with alerting systems that contribute to difficulties in fault management. For example, the costs of miss detection and false alarms are fundamental in selecting of the most effective alerting thresholds and the utility of multi-phase alerts. Of particular concern in the design is the human tendency toward automation bias, which occurs when a human decision maker uses a computer-generated solution as a heuristic replacement for at least part of a fault management process. (Parasuraman and Riley, 1997)

Alternatively, the HMS output can be continuously presented to the pilot (e.g. on a gauge). In the context of this research, an instrument displaying continuously the HMS output is called a "fault meter". The first important additional information provided by the fault meter is trend: pilots can observe the gradual degradation of the health of the aircraft, and have useful additional time to start the diagnosis of the problem. Also, the value can provide information about the severity of the fault within predefined ranges of status. For example, in a scale of 100, values from 0 to 50 could be acceptable or normal. However, constant high values in the vicinity of 40 to 50 could mean that there is a potential problem, even if the aircraft is airworthy. Finally, the fault meter could be used as a tool to evaluate the effectiveness of the pilot's compensation for the fault.

1.4 Objectives and Hypotheses

The health monitoring system concept described in section 1.1 opens several human-system interaction questions. Since degradation of the aircraft health should eventually trigger fault management processes, it is important to investigate how pilots implement these processes and what roles are open to the new HMS concept. The objectives of the experiments are first to investigate how pilots respond to certain faults and problems degrading flight control; and, second, to investigate how a HMS as described in the previous sections can help the pilots detect and manage these faults. The hypotheses associated with these objectives are:

1- Origin and cause of faults degrading flight control can be difficult to detect and diagnose. Response will vary significantly within and between pilots.

2- The HMS information will help pilots detect and respond to faults degrading flight control.

3- The fault meter will be preferred over the alerting system because of the additional trend information allowing for continuous health status monitoring and earlier detection of health degradation.

4- The HMS will not affect pilot performance at their normal tasks. Workload and flying performance will not be affected by the fault meter or alerting system.

5- Automation bias in pilot responses can be induced by the HMS. Specifically, a false alarm can trigger fault management processes resulting in inappropriate responses.

2 Experimental Method

2.1 Overview

This study was a collaboration effort between the School of Aerospace Engineering of the Georgia Institute of Technology and the Control and Simulation Research Group of the Aerospace Faculty at Delft University of Technology (TUDelft), The Netherlands. The experiments were conducted in the Netherlands during the summer of 2002 under the direction of Dr. M. Mulder, Dr. M. M. van Paassen and Dr. A. Pritchett.

Each pilot participated in a series of four experiments lasting for a day. The experiments investigated different objectives. They were conducted sequentially and the transition from one to the next was not salient from the pilot's perspective.

The first experiment examined different FCS and simulator motion settings impact on pilot performance while flying a Tunnel-in-the-Sky display. Pilots flew 18 curved approaches to a fictitious airport in instrument meteorological conditions and light turbulence. Three different flight control systems were used. Before each run, the simulator's motion system was turned on or off. (The pilots were briefed that different motion system settings were going to be tested.)

Although the motivation and objectives of this experiment are not the focus of this thesis, a detailed description is included in section 2.4, since it is closely related to all other experiments and it served as training for the pilots in the simulator for the subsequent experiments. Results of experiment #1 can be found in Mulder et al. (2003).

Since the pilot was never informed about the exact number of approaches he was going to fly, experiment #2 was appended to experiment #1 as a single additional approach. During this approach, a fault was introduced reducing pitch and roll control effectiveness. The objective was to investigate pilot reaction to an unexpected problem without any warning or change in the conditions used for experiment #1.

Experiment #3 is the core of this thesis. During this experiment, pilots were told about the possibility of encountering faults, and health monitoring system information was provided through the fault meter and alerting system. In half of these runs, a different single fault or problem that affected the flight control was triggered. These approaches were flown in visual meteorological conditions and the motion system was always on.

For Experiment #4, each pilot flew one additional approach after experiment #3. This run was identical to those in the previous experiment except that a false alarm was triggered. The pilot was not aware of the number of runs in experiment #3 and no additional briefing was given for this experiment. Therefore, the transition from experiment #3 was not noticeable to the pilot. Its objective was to investigate for possible automation bias.

A typical day for a pilot was:

8:00 – 8:30	briefing
8:30 – 11:40	experiment #1 and #2, about 28 approaches
11:40 – 12:00	debriefing on morning runs
12:00 – 12:40	lunch
12: 45 – 1:10	briefing
1:10 – 4:50	experiment #3 and #4, about 26 approaches
4:50 – 5:10	debriefing on afternoon runs

This schedule was designed such that experiments #1 and #2 were conducted during the morning and experiments #3 and #4 were conducted during the afternoon. However, unexpected simulator problems often made it difficult to complete the 54 approaches planned for each pilot before the end of the day. Therefore, while some pilots finished all the approaches in one day-long session, most pilots were scheduled to complete the experiment in two half-day sessions on different days, experiments #1 and #2 on one day, and #3 and #4 on a second day. The second session was usually scheduled within a few days.

2.2 Subjects

Twelve professional pilots participated in the experiments. All were current in jet air transport aircraft, ranging from regional jets to the Boeing 747-400. Their demographics are summarized in. They had an average of 4100 flight hours, and all had at least 1000 flight hours in glass cockpits. Table 1 shows the pilot's information in descending order of experience. This ranking was prepared by taking into account the total number of hours, the current position (Captain, First Officer, Second Officer) and the number of aircraft in which they have been trained. For example, Pilot #8, with only 1500 hours as First Officer was considered to have more experience than Pilot #4 with 4000 hours as Second Officer. Second officers (also know as cruise relief pilots) are usually limited to very few tasks during the cruise portion of long flights and are not allowed to fly the aircraft below 10,000 ft. All pilots obtained their initial flight training from civilian flight schools and none had any military flying experience.

Table 1 – Pilot data in descending order by experience..

Experience	Pilot #	Flight Hours	A/C Current On	Last Position	University Education
1	1	13000	B747	Captain	M.S. Aero. Eng.
2	2	7000	B757/767	Captain	B.S. Mech. Eng.
3	7	4500	B757/767	First Officer	M.S. Aero. Eng.
4	6	4500	B757/767	First Officer	None
5	12	4800	B757/767	First Officer	None
6	9	1900	B737	First Officer	B.S. Aero.Eng.
7	10	1800	B757/767	First Officer	None
8	8	1500	CRJ-100	First Officer	M.S. Aero.Eng.
9	4	4000	MD-11	Second Officer	M.S. Aero.Eng.
10	3	3700	B747	Second Officer	None
11	11	1500	B747	Second Officer	M.S. Aero.Eng.
12	5	1300	B747	Second Officer	M.S. Aero.Eng.

2.3 Apparatus

2.3.1 The SIMONA Research Simulator

The experiments were conducted at the International Research Institute for Simulation, Motion and Navigation (SIMONA), part of the Delft University of Technology (TUDelft). The Institute operates an advanced research flight simulator which was designed and built by several groups within the University in cooperation with partners from government and industry.

The SIMONA research simulator, shown in Figure 2, offers uncommon motion capability due to its light weight design and sophisticated motion system. The cab weight in operating conditions, including all visual hardware, avionics equipment and a crew of two pilots, is less than 4500 kg. The six degree of freedom hydraulic motion system uses six 1.25 meter stroke actuators that can produce instantaneous accelerations ranging from 0.02 to 1.5g.

The visual system provides a 180^{o} horizontal and 40^{o} vertical field-of-view with a high resolution, collimated out-the-window projection onto a dome mounted around the simulator cab. A detailed visual scene was created for the airport that included the runway, taxiways, and local features such as trees and buildings.

The simulator is operated from an external control room in which most of the simulator's computer hardware is located. The basic controls for regular operations are commanded through two computers with a simple user interface. Most parameters needed to run the different scenarios for this experiment were programmed in two short files to be loaded before each run. These files contained information such as initial position of the aircraft, airspeed, turbulence levels, faults, meteorological conditions, etc.

The simulator recorded 80 different parameters at 25 Hz from. A complete list of these parameters is included in Appendix A. Additional parameters were obtained from the original data using numerical methods, such as derivatives of the track angle error or pitch and roll control inputs. Each run produced a 3 to 4 MB data file, depending on the flight time of each approach.

Figure 2 – SIMONA research simulator at Delft University of Technology.

2.3.2 Aircraft and Flight Control System Models

The aircraft dynamic model used for the experiments was developed at TUDelft and based on the institute's flight test aircraft, a Cessna Citation II. This aircraft has a Maximum Take-Off Weight (MTOW) of 6400 kg and a payload of 1400 kg. During the experiment, the mass was kept constant at 5000 kg since each approach lasted less than 4 minutes. The maximum Indicated Airspeed (IAS) of the aircraft at sea level is 262 knots IAS, and the stall speed at maximum landing weight and in landing configuration is 84 knots IAS. Typical approach speeds (Vref) vary between 115 and 130 knots.

Three different FCS were used in this set of experiments. The "conventional" FCS simulates the Cessna Citation FCS, consisting of direct mechanical/hydraulic links between the yoke and the control surfaces. The control column and aerodynamic surface movements are proportional. The "Attitude Oriented" FCS allows the pilot to command roll and pitch rates with the control column. If the stick is centered, the aircraft will maintain the bank and pitch angles, regardless of external disturbances such as gusts and turbulence.

The third FCS, referred as Flight Path FCS, was developed at TUDelft to investigate new command parameters for flying an aircraft through flight-path-relative displays such as tunnel-in-the-sky representations, documented by Veldhuijzen et al. (2003). With this FCS the pilot's flight control inputs command flight path vector (FPV) angle rates. A Command-FPV (CFPV) symbol, similar to the FPV symbol, is always given on the primary flight display. The pilot's inputs on the control column are translated into flight path angle rate ($\dot{\gamma}$) and ground track angle rate ($\dot{\chi}$) changes, proportional to the displayed distance between the FPV and CFPV. With this FCS, the pilot must keep a constant stick deflection to the direction of the turn to maintain a constant turn radius, similar to steering an automobile.

2.3.3 Simulator Flight Deck

The flight deck, shown in Figure 3, used a typical glass cockpit configuration. The subject occupied the left seat in front of a Boeing type control column. The simulator did not have rudder pedals installed in time for the experiments; therefore, all turns were automatically coordinated by the FCS. The center pedestal had throttle, flap and speed-brakes levers from a Boeing 777. Additional reprogrammable switches were available on the pedestal, as well as on the yoke. The front panel contained four 15 inch LCD displays. The Mode Control Panel shown on Figure 3 and the fifth LCD display located between the pedestal and the center displays were not installed during this experiment.

Figure 3 – SIMONA flight deck configuration.

2.3.4 Displays

The Primary Flight Display (PFD) was shown on a 15 inch LCD display in front of the subject. Its tunnel-in-the-sky format, shown in Figure 4, followed the same configuration used in previous studies (e.g. Veldhuijzen, Mulder, Van Paassen, & Mulder, 2003). Using a three-dimensional ego-centric presentation, a ground-referenced tunnel was displayed over a presentation of the outside world. The width and height of the tunnel was 45m x 45m.

Other primary flight information was shown using common formats: altitude, airspeed and vertical speed tapes on the sides and a heading compass on the bottom. On the top, a flight mode annunciation area indicated autothrottle engagement and FCS mode. The bank angle and pitch angle were also displayed on the PFD, both on graphical scales and by text. Aircraft flight path was represented by a green flight path vector (FPV) symbol. When the Flight Path FCS was used, the yellow Command-FPV symbol was displayed as shown on Figure 4.

To the right of the tunnel display, on a separate 15 inch LCD, a navigation display and engine indications were shown. The navigation display represented the horizontal path of the tunnel with a solid line. Other common elements typically used in current navigation displays were included, such as the track indication and range scale. The autopilot heading selector indicator, represented by the dashed line on Figure 5, was not functional, as pilots were always asked to fly the airplane manually. As discussed in 2.6.2, the “fault meter” and the “alerting system” were also displayed for experiments #3 and #4.

Figure 4- Tunnel in the sky primary flight display, in Command-FPV FCS format.

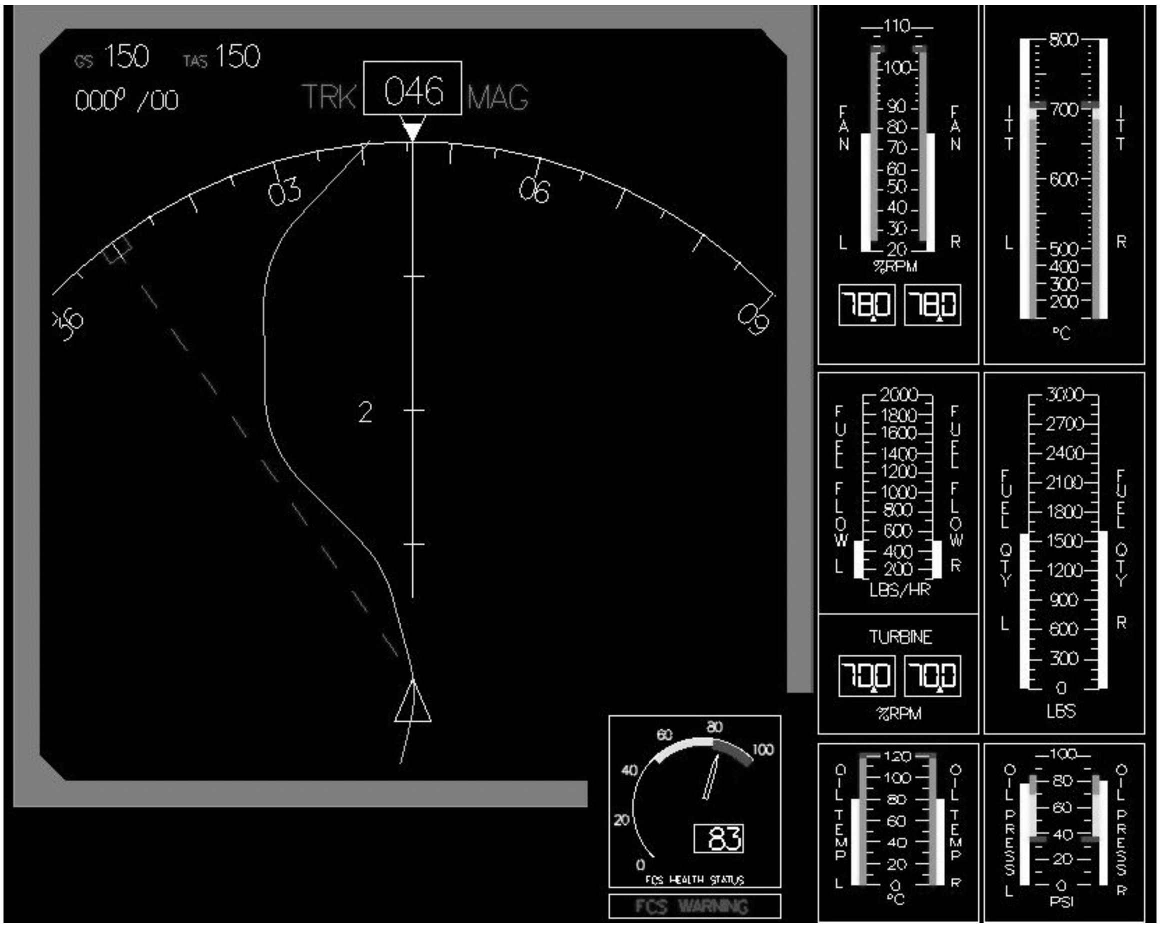


Figure 5 – Navigation and engines displays, fault meter and alerting system..

2.4 Experiment #1 Description

Veldhuizen et al. (2003) previously demonstrated that the combination of the tunnel display with an advanced flight-path-oriented fly-by-wire control system significantly improves the pilot path-following performance and reduces pilot workload. In addition, results of a flight test showed substantial differences in pilot path-following performance in tracking straight tunnel trajectories as compared to earlier experiments conducted in a fixed-base flight simulator (Mulder et al., 2002). For example, tunnel-tracking performance during a straight-in approach was a factor 2 to 3 times worse in real flight as compared in the fixed-base simulator, and workload was reported to be much higher in the flight tests (Mulder, Kraeger, & Soijer, 2002).

These discrepancies raised the question whether results obtained in fixed-base simulators are indeed representative of (or can be extrapolated to) pilot behavior in real flight. They suggested that the task of 'flying a tunnel' may be sensitive to simulator fidelity, including pilot-perceived motion. The objective of experiment #1 was to examine the impact of flight simulator motion on pilot workload, control behavior and performance in tracking a tunnel using different flight control systems.

2.4.1 Independent Variables

Two variables were manipulated in this experiment: first, the flight control system, which could vary among the three described in 2.3.2; and second, the simulator motion, which was either on or off. The scenarios were changed randomly between two symmetrically identical tunnel trajectories, therefore their effect on the dependent variables is assumed nil.

2.4.2 Procedure

As soon as they arrived, the pilots were briefed by the experimenter. A printed document with color images of the cockpit displays was given to the pilot, and the experimenter discussed each paragraph with the pilot. Pilots had ample opportunity to ask questions. The complete briefing text is included in Appendix B.

The briefing first contained an overview of the day activities and an introduction to the simulator operation, including emergency stops, fire procedures and intercom communications with the simulator control room. They were also informed that an experimenter was going to act as copilot and he would engage in some minimal duties. These consisted of calling altitudes (500ft, 100ft, 50ft, 40ft, 20ft, and 10 ft) during each approach, and administering a short questionnaire and TLX workload ratings after each run. The experimenter was to avoid all non-essential conversation during the runs.

Then, pilots were briefed specifically on this experiment. They were asked to fly a number of curved approaches into a fictitious airport. The exact number of approaches was vaguely discussed to keep experiment #2 included in the main block of approaches as a surprise. Additional information given to the pilot at this point covered weather, different flight control system characteristics, flap and gear configuration, airspeeds, and copilot/experimenter role and interaction. Autothrottle (A/T) use instructions were given particular attention to encourage pilots to disengage it in case they encountered any problem or unusual aircraft behavior so that A/T disengagement could be recorded as an indication of pilot's fault detection. Also, pilots were informed that "different simulator motion models" were going to be used but they were not told that the motion was going to be on or off.

The core of the approaches in which data was collected was composed by three blocks of six runs each. Additional training before each block was encouraged to ensure that the pilots were comfortable with the FCS change, however pilots rarely accepted more than one training run.

2.4.3 Scenarios

Each run started with the aircraft positioned at about 16 kilometers of the airport, at the beginning of a “tunnel”, i.e., a curved approach trajectory. The geometry of one of the tunnels is shown in Figure 6. The other tunnel was mirrored using the runway centerline as an axis of symmetry. The weather during all approaches had a dense cloud cover creating instrument meteorological conditions at all altitudes down to 200 feet Above Ground Level (AGL). Below this altitude, the visibility was very good and, if the pilot was stable during the final segment of the tunnel, it was relatively easy to land. Light-to-moderate turbulence prevailed during the entire approach for all runs.

The aircraft was configured at the start of the run to 25 deg of flaps and landing gear down, providing good handling and airspeeds to fly the entire approach and land. The airspeed for the approach was 150 knots, which was maintained by the autothrottle (A/T). Pilots were asked to always use the A/T until 500 ft AGL unless they felt there was a problem with the aircraft. At 500 ft AGL, the copilot/experimenter would call the altitude and the pilot would disengage the A/T by pressing a button on the throttle levers.

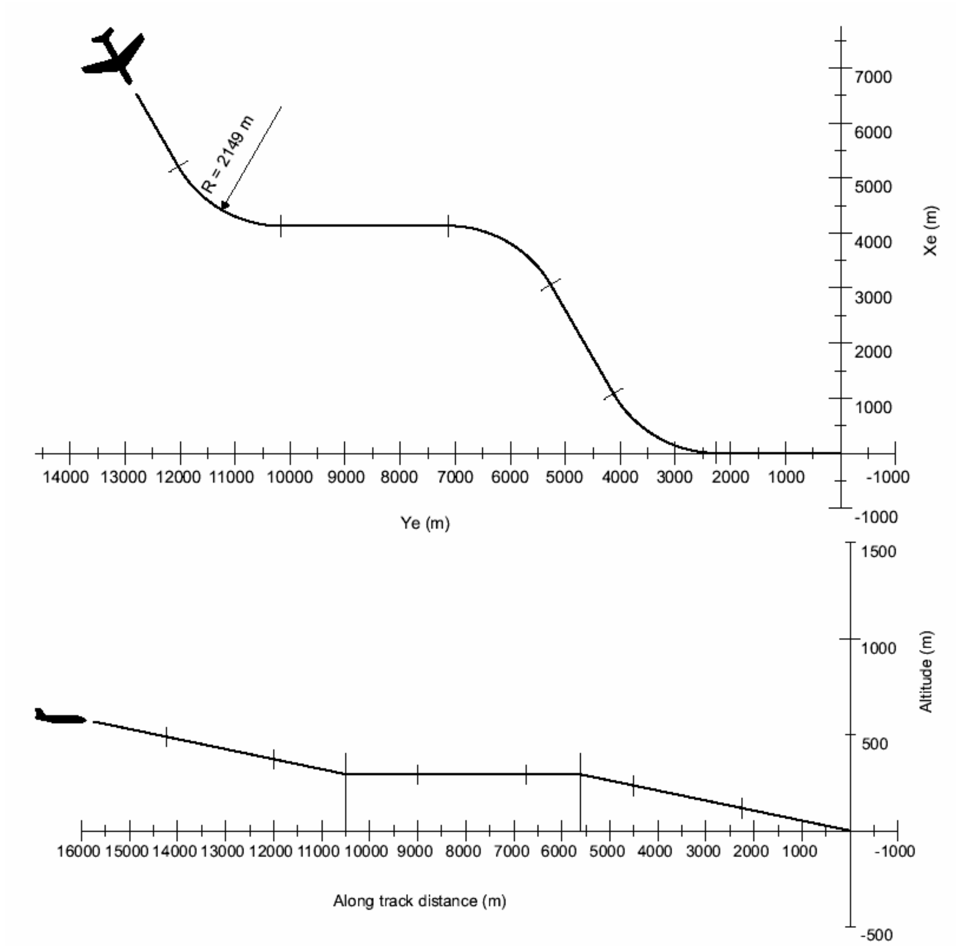


Figure 6 - Tunnel trajectory geometry for experiments #1 and #2.

2.4.4 Experiment Design

A factorial within subjects design was employed, consisting of six conditions defined by three FCS x two motion states. The data runs were blocked by the three FCS with the order of the blocks balanced between pilots. Each block had six runs, i.e., three replications of each FCS-motion condition. Including training runs, a minimum of 24 approaches were flown by each pilot. The specific assignment of conditions to each pilot is given in Appendix C.

2.4.5 Dependent Variables

The dependent measures included: (1) tunnel tracking performance, measured by aircraft off-set from tunnel center, and by flight path angle errors expressed relative to the approach trajectory; (2) pilot control activity, i.e., control column deflections and their rates; (3) aircraft dynamic states, including attitude angles and rates; (4) NASA TLX workload ratings; and (5) pilot responses to questionnaires about simulator realism. Analysis and results of this experiment can be found in Mulder et al. (2003).

2.5 Experiment #2 Description

2.5.1 Objective

The objective of the experiment was to investigate pilot's responses to an unexpected fault affecting the flight control. In addition to contributing information for validation of the first hypothesis, the experiment provided a baseline for experiment #3 in which pilots were briefed to expect faults.

2.5.2 Procedure

After flying experiment #1, the pilots transitioned without notice to experiment #2. This experiment consisted of a single approach in which an unexpected FCS fault occurred. Except for the fault all other experimental conditions remained constant from the last block of approaches flown by each pilot in experiment #1. Therefore, four pilots flew this approach with each of the three FCS.

2.5.3 Scenario

The problem triggered for experiment #2 simulated a FCS fault in which the motion range of the aerodynamic control surfaces was reduced. The severity of the fault was originally designed such that pitch and roll rates would be significantly reduced, but not enough to compromise control of the aircraft. The fault was triggered when the aircraft reached a preset point in the tunnel, about 5 km from the start, giving the pilot at least 10 km to recognize the fault and take appropriate actions with a reasonable margin of altitude and distance to the airport.

2.5.4 Dependent Variables

As with experiment #1, the independent variables were: (1) tunnel tracking performance, measured by aircraft off-set from tunnel center, and by flight path angle errors expressed relative to the approach trajectory; (2) pilot control activity, i.e., control column deflections and their rates; (3) aircraft dynamic states, including attitude angles and rates; (4) NASA TLX workload ratings; and (5) a set of questions presented after each approach regarding the fault and use of the fault meter and alerting system.

2.6 Experiment #3 Description

2.6.1 Objectives

The objectives of experiment #3 are to validate the first four hypotheses presented in section 1.4. Recapitulating, experiment #3 searched for answers to the following questions: how pilots respond to faults affecting flight control, how HMS information can help the pilots in fault detection and management, how the HMS affects pilot performance at their normal control tasks, and how the different methods of displaying HMS information can help the pilot in the fault management process.

2.6.2 Independent Variables

The independent variables for experiment #3 were: (1) availability of fault meter; (2) availability of one or two phase alerts; (3) FCS type and (4) fault type.

A fault meter simulated the "lack of health" of the aircraft: the higher its indicated value, the worse the severity of the problem. The yellow arc, from 50% to 80% of the scale, indicated "caution"; the red arc, from 80% to 100%, indicated a "warning". When the aircraft was in good health, the fault meter gauge moved at random between values of 5 and 15 to give the impression that the instrument was "alive". The ranges for the arcs were set arbitrarily, and no strict definition was given to their meaning during the pilot briefing, although it is assumed that pilots would associate those standard colors to "required pilot action" for yellow and "required immediate action" for red. The pilots had to press a "push-to-see" button on the control yoke to see it, allowing the experimenters to record when it was viewed. Figure 7 shows how the instrument was hidden. The alerting system provided aural and text alerts based on the same information as the fault meter. The text alerts were displayed in a small window below the fault meter. The alerts had either one phase or two phases. With two phase alerts, a distinctive sound and yellow text message indicated a “FCS caution” when the health value reached 50%; when the value reached 80%, a higher pitch sound and red text message indicated a “FCS warning”. The one-phase alert system went off only when the 80% value was reached, displaying the red text message with its associated high pitch sound.

During half of the approaches, twelve faults or problems were implemented. The severity of the faults was set such that tunnel tracking would be difficult, but aircraft control could be maintained, especially if the pilot was able to recognize the fault and develop an appropriate coping strategy.

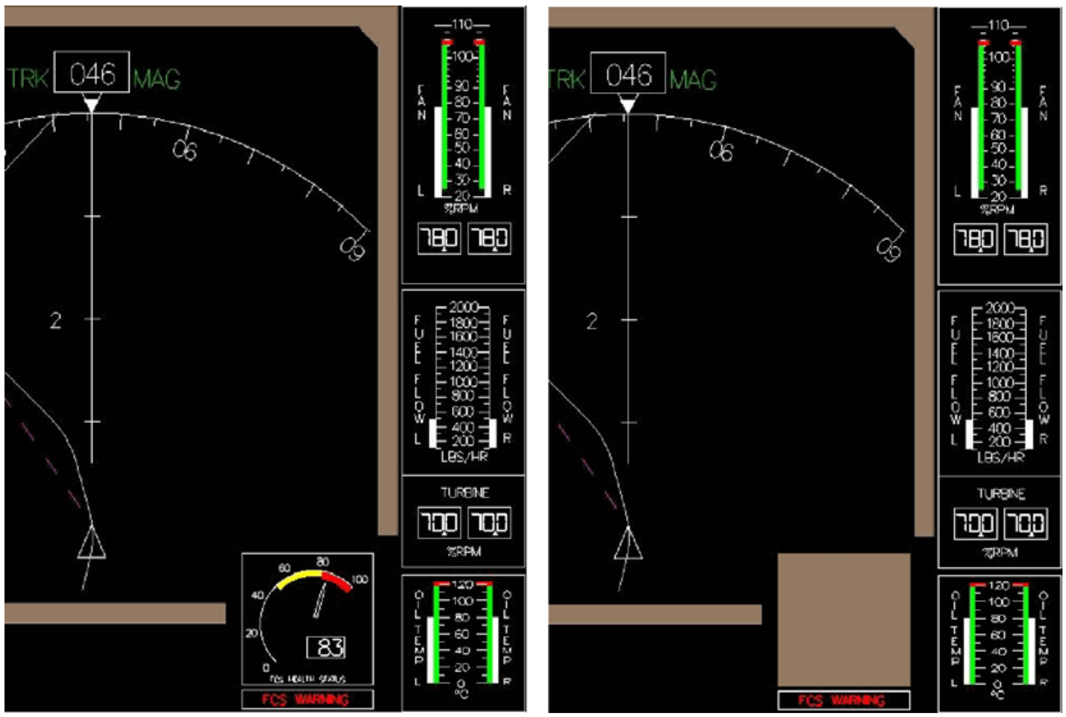


Figure 7 – Fault meter push-to-see button, pressed (left) and not pressed (right).

The design and implementation of the faults and problems was specific to each FCS: six faults were specific to the conventional FCS and six to the flight-path-oriented FCS.

For the conventional FCS, the faults were:

1- Elevator and 2- Aileron Deflection Reduction: After the fault was triggered, the elevator or aileron deflection range was reduced to limit the controllability of the aircraft by the pilot. The fault fully developed in approximately 10 seconds. After this period of time, full deflection of the yoke produced about 30% of the normal aileron deflection. Setting the deflection range for the elevator was critical. The objective was to produce a fault severe enough to be noticeable during the approach, but not enough to prevent the pilot from flaring.

3- Flight Path Vector (FPV) Drift Down. When the fault was triggered, the flight path vector started to slowly drift down at less than ½ degree per second. This fault simulated a sensor failure, such as an angle of attack sensor. When the FPV slowly drifts down, there was a period of time in which the deviation was not noticeable but, if used continuously as a reference to keep the aircraft in the approach trajectory, a noticeable aircraft deviation from the tunnel would eventually occur. Pilots may compensate for this deviation with normal inputs and the aircraft position in the tunnel can be corrected. But, as the aircraft returns to the center of the tunnel, the pilot may use again the faulty FPV as a reference to fly the tunnel, and another deviation occurs, resulting in a series of oscillations which are eventually easily noticeable to the pilot as the fault fully develops. Other than the faulty FPV indication, the aircraft remains totally airworthy.

4- Static Port Blocked: When the fault was triggered, the static port of the air data system was blocked. As in a conventional system, the altimeter and the vertical speed indicator froze, and the airspeed indication became function of the altitude, reading lower in a climb and higher in a descent. In a tunnel in the sky display system there can be additional consequences to a static port blockage. In this case, since the only altitude information was provided by air data system, the display system assumed that the aircraft was not descending anymore, but the tunnel was generated using the actual horizontal position of the aircraft. Therefore, the PDF showed a faulty “Tunnel in the Sky”, below the intended approach trajectory.

5- Autothrottle Failure: When the fault was triggered, the autothrottle reference speed was gradually changed to lower values, reducing the engine thrust accordingly. There were no cues that would indicate the problem except for the airspeed indication since the throttle levers did not move while in Auto Throttle (A/T). In addition, as no mode control panel was installed, there wasn’t any other indication of the selected reference speed in the cockpit, and the A/T message on the PFD mode indication area remained on all the time. The reduction in airspeed would continue to the point of a stall if the pilot did not react by disconnecting A/T and managing power manually. The aircraft was 100% airworthy after the pilot disconnected the A/T and restored the power to normal levels.

6- Load Shift: The fault was simulated a load shift in the aircraft. (i.e., CG shift). The change in the simulated dynamic model was equivalent to moving a 1000 kg mass about one meter back from the original CG location. The effects were easily noticeable. A strong pitch down input to the control column and immediate use of the trim was required to maintain straight flight. The aircraft became more unstable in pitch, roll and yaw. Once the aircraft was trimmed and the new flying qualities were recognized, it was possible to fly the approach trajectory and attempt a landing. However, if the A/T was disengaged and airspeed diminished, the aircraft became less and less stable, and more difficult to control.

For the flight-path-oriented FCS, the faults were:

7- FPV Horizontal Drift: When the fault occurred, the FPV slowly started to drift horizontally to the left. The fault is similar to the previously described fault #3 for the conventional FCS. The major difference is the presence of the Command-FPV. Discrepancies between Command-FPV and FPV will display the problem. However, since the drift is slow, for a period of time the pilot may try to keep the aircraft centered in the tunnel using the FPV. Also, the time of triggering to the time when the pilot definitely abandons the FPV as a reference for flying the aircraft may be dependent on the position in the tunnel.

8- Aileron Deflection Reduction: The fault was similar to the aileron range reduction implemented for the conventional FCS (Fault #1). However, from the pilot's perspective, the problem is manifested by changes in the proportionality between stick inputs and the distance between the FPV and Command FPV. Increasing the stick roll input does not increase the roll rate and turn rate, but does increase the distance between the two symbols, to the point where it is possible for the CFPV to reach the edges of the PFD. The pilot may try to force the aircraft to a roll in the desired direction by applying constant stick deflection, which translates to constant increase in distance between the CFPV and FPV symbols. Once the aircraft has slowly rolled to the desired position, the pilot will attempt to stop the roll, therefore, the stick is returned to the neutral position, but because the CFPV is slow to respond, the aircraft does not stop rolling. The reaction is a constant stick deflection to the opposite side, bringing the CFPV to the opposite side and beginning the cycle again, leading to a series of slow oscillations in roll which can sometimes lead to very high bank angles. With a good understanding of the FCS, the pilot may realize that it is very possible to control the aircraft by keeping the CFPV on the side of desired roll but at a constant and short distance from the center of the PFD.

9- FPV Drift up: This fault is similar to fault 3, but in this case the FPV drifted up, falsely indicating a climb. However, the CFPV is an important cue showing that the FPV may be having problems. It was expected a possibility that similar oscillations to fault #3 would be observed, but of lower amplitude, since the CFPV could be used as a cue for guidance.

10- and 11- Additional Stick Input in Pitch and Roll: The design of these faults was inspired by the real problem encountered on an A320 described in chapter 1 in which a defective transducer in the pilot's stick sporadically produced un-commanded rolls. To simulate this, a roll or pitch command was added to the input of the pilot. The pilot would not notice through the position of the yoke that the flight control system was receiving an additional command. This roll or pitch command would be the equivalent of a stick deflection of about 50% to one side, for a short amount of time, one or two seconds. This deflection was repeated at 6 seconds intervals until the end of the simulation. The pilot could cancel the effect of these additional fault inputs by applying yoke inputs in the opposite direction, thus canceling the total input to the flight control system. If the pilot recognizes the problem as periodic oscillations, the aircraft can be flown to a landing.

12- Gain Change in Stability Augmentation System: The fault produced a change in the gains of the pitch axis of the stability augmentation system which translated to a reduction of the effectiveness of the pitch control inputs, similar to a reduction in the elevator effectiveness. If the distances between the FPV and the CFPV became unusually large, the fault became evident. As with the elevator reduction effectiveness, it was difficult to tune the fault to allow a margin of controllability that would allow flaring for landing, although tunnel tracking was possible.

2.6.3 Procedure

As with the briefing for experiment #1, the pilot was briefed before starting experiment #3. Pilots were asked to fly additional approaches to the same airport, but they were warned that faults could occur at any time. They were also told these differences with the previous experiment approaches:

1- The weather was significantly better, i.e., ceiling and visibility were unlimited, although light to moderate turbulence continued.

2- Only the conventional and the flight path flight control systems were used.

3- The motion system of the simulator was always on.

4- The fault meter and alerting systems were occasionally available to the pilot. The following are the briefings given on both systems:

Fault meter: “In half of the runs, an instrument (called the fault meter) will display the (lack of) health on a scale from 0 to 100. The higher the value, the worse is the severity of the problem. Any indication in the white arc range is normal. The yellow arc, starting at 60%, is considered a Caution, and the red arc, starting at 80% is considered a Warning.

So that we can measure how and when you use the fault feter, you will need to press a button in the yoke to see it: [Push-To-See]. Please use this instrument as you find it helpful to you."

Alerting system: "The alerting system will provide caution and warning alerts based on the same information source as the fault meter. A caution aural alert will sound and a message will be displayed in yellow when the fault value is over 60%. If the fault continues to deteriorate and the fault value goes over 80%, a warning alert will sound and a warning message will be displayed in red. In some runs, the alerting system will only give warning alerts, while on other runs, both caution and warning alerts will be given. Before each run, the experimenter will let you know which alerting system configuration you will be flying with." The complete briefing document is included in Appendix B.

Pilots were asked again to use their best judgment to continue or abort the approach and go around, as if they were flying an airliner with passengers, both in their way of handling the aircraft and in the overall situation. Again, it was mentioned that the A/T should be disconnected if any problem or unusual behavior was detected.

The first run of the session was for training. Pilots were encouraged to repeat this run if they felt it was necessary, especially when more than a few days had elapsed since they finished experiment #1 and #2 session. During this run, both the fault meter and the alerting system were presented to the pilot, but no fault was triggered. The pilots then flew 24 runs, with a short break after the 12^{th}.

2.6.4 Scenarios

Each run started with the aircraft positioned in a 16 km long tunnel to the runway, properly configured for the approach with the autothrottle engaged. The approach trajectories used in these experiments were slightly more complex than the ones used during the previous experiments.

The approach geometry, shown in Figure 8, had five turns and three different descent angles, in contrast with the three turns and two descent angles of the tunnels for experiments #1 and #2. In half of the runs, a fault that affected flight control was triggered. The faults were automatically triggered at different points during the approach in the different scenarios, to limit their predictability. Special care was taken in finding the best point for each specific fault to ensure that the pilot would have a chance to recognize during its development. For example, faults that would affect the roll controllability were triggered before a tunnel turn, rather than during long straight segments. As the fault developed, the fault meter and/or alerting system (depending which combination was present) indicated that the overall health of the aircraft had deteriorated. With the exception of dealing with the faults, the pilot's task was identical to experiment #1, i.e., flying the aircraft to a landing.

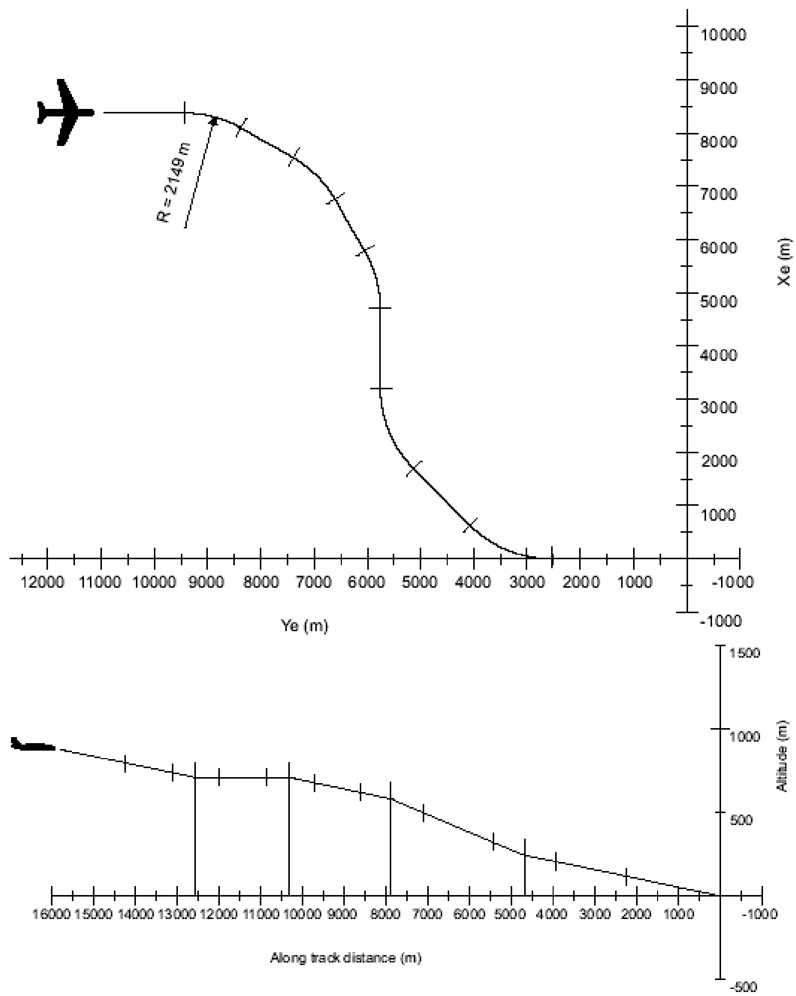


Figure 8 - Tunnel geometry for experiments #3 and #4.

2.6.5 Experiment Design

A total of 24 approaches were flown in experiment #3. The runs were blocked in 2 sets of 12 by FCS, and the order of these blocks was varied between pilots. The 24 conditions, each replicated once by each pilot, were defined by 2 FCS x 2 fault/no fault x 2 fault meter x 3 alerting system. Within the fault conditions, 12 different faults were implemented, each seen only once by each pilot. The faults were randomly assigned within each block: faults 1 through 6 for the conventional FCS and 7 to 12 for the Flight Path FCS.

All combinations of alerting system and fault meter were used. The fault meter was either present or not, and the alerting system had one phase, two phases or was not present at all. The assignment of faults to the conditions was balanced between pilots to mitigate any impact on the dependent measures. The complete experiment design is included in Appendix C.

2.6.6 Dependent Variables

The dependent variables for experiment #3 are: (1) approach outcomes, described in four different categories: immediate go around, continued approach (but not landed), landing, and others (including simulator software or hardware problems, simulator automatic stop, etc.); (2) pilot’s written descriptions of the faults and confidence levels of their descriptions; (3) pilots’ written comments on the use of the alerting system and fault meter; (4) use of the fault meter measured through Push-To-See button; (5) NASA TLX Task Load Index (Rating Scales Only); and (6) pilot tunnel tracking performance.

2.7 Experiment #4 Description

2.7.1 Objective

The objective of this experiment was to investigate the possibility of automation bias in pilots' responses to a false alarm from the HMS.

2.7.2 Experiment Conditions

After the 24 runs for experiment #3, pilots were not aware they were transitioning to experiment #4, which consisted of a single last run. At some point during the approach, a false alarm was indicated both by the fault meter and the 2-phase alerting system. All experimental conditions remained constant from the previous experiment, except for the false alarm. The aircraft, systems and displays operated normally during the approach, before and after the false alarm was triggered.

Since the previous experiment was blocked by FCS and the blocks were randomly varied between pilots, the FCS used for the last block of experiment #3 was used for experiment #4. Therefore, six pilots flew experiment #4 with the conventional FCS, while the other six used the Flight Path FCS.

2.7.3 Dependent Variables

The dependent variables for experiment #4 are: (1) approach outcomes, described in four different categories: immediate go around, continued approach (but not landed), landing, and others (including simulator software or hardware problems, simulator automatic stop, etc.); and (2) pilots' questionnaire answers and comments.

3 Experiment Results

Multiple analyses were performed on the data from the four experiments. The results presented in this chapter are those most relevant to the research hypotheses and thus are primarily focused on experiments #2, #3 and #4. The motivation and objectives of experiment #1 are not the focus of this thesis. Its description was included in this dissertation because it served as training for the pilots in the simulator for the experiments of interest here. Analysis and results of experiment #1 can be found in Mulder et al. (2003).

The total number of approaches flown by all pilots was 12 for experiment #2, 264 for experiment #3 and 12 for experiment #4, but some files were not available or used for data analysis. For experiment #2, 92% of the data (11 approaches) was available for analysis; one file was lost due to a simulator setup problem. For experiment #3, 98% of the data (281 approaches) was available: Only 7 data runs were lost, 6 of them placebo runs in which no faults were introduced. The data for experiment #4 was 92% complete with only 1 data run out of 12 not flown.

After each run, a subjective workload assessment was performed using a simplified NASA TLX Task Load Index, in which ratings for six different sources of load were requested. Due to the limited time between experiment runs, the TLX weights measures were not collected in the experiment.

In addition to the TLX ratings, the pilots were asked to answer a set of questions specific to each run. After each experiment, another questionnaire with more general and demographic questions was presented to the pilots. All questionnaires are included in Appendix D.

3.1 Experiment #2 Results

3.1.1 Objective

The objective of the experiment was to observe pilot's response to an unexpected fault affecting flight control. This data also provided a control for experiment #3 in which pilots were briefed to expect faults and problems.

3.1.2 Collected Data

From the original 12 runs, data from 11 runs were successfully recorded. Pilot #9's file was lost due to a simulator setup problem. 76 parameters from simulator data were recorded at 25 Hz; in addition, subjective questionnaires were presented to the pilots after each run.

3.1.3 Analysis Methods and Results

During this experiment, a FCS fault was triggered during the approach. The fault reduced the motion ranges of the aerodynamic control surfaces. The severity of the fault was originally designed such that pitch and roll rates would be significantly reduced, but not enough to compromise the total control of the aircraft could be maintained.

The impact of the fault in the operation of the aircraft at a mission level can be observed in the outcome of the approach. The different possible outcomes of an approach are “landing”, “continuing approach with later go around”, “immediate go around” and “other (crash, simulator problems, etc)”. To determine the outcome, the first step was to observe the last position of the aircraft. When the aircraft was at 0 ft and over the runway, it was considered a landing. The flare and landing was not analyzed; from the experimenter’s observations, the landings were mostly considered as acceptable for normal aircraft operations. If the aircraft did not reach the runway, several other situations could have occurred. This required a more detailed study of the trajectory and other performance parameters. Plots of the vertical and horizontal aircraft positions with respect to the tunnel provided a good insight on situation and probable intentions of the pilot.

The next indication that helped categorize the outcome was the autothrottle disconnection. As mentioned before, the pilots were briefed to disconnect the autothrottle when reaching 500 ft (to bleed airspeed for the landing) or when they felt that something was abnormal.

Based on this categorization and an analysis of the simulator data, some issues with the experiment #2 simulator setup were discovered: during the approach flown by the first pilot, the fault was unexpectedly triggered only a few seconds after the start, instead of at the preset point at about 4000m down the tunnel. In addition, it was observed that the fault was not severe enough to have an impact on the aircraft handling, allowing the pilot to land without much effort. Corrections were made and the fault severity was increased to achieve the desired effects. After this correction, no pilot could land the aircraft, and all runs ended with imminent crashes. The severity was then changed again after run #5. For unknown reasons, the severity of the faults was changed several times during the remaining of the runs with significant impact on the outcomes of the approaches. Table 2 shows the parameters used to define the severity of the fault. These parameters are directly related to the maximum control surface deflection allowed after the fault was triggered.

Table 2 - Aileron and elevator severity parameters and approach outcome.

Pilot	FCS	Aileron	Elevator	Outcome
1	3	0.030	0.042	Landing
2	1	0.018	0.027	Crash
3	2	0.018	0.027	Crash
4	2	0.018	0.027	Crash
5	3	0.018	0.027	Crash
6	1	0.025	0.036	Landing
7	3	0.018	0.027	Crash
8	2	0.060	0.083	Landing
9	-	-	-	-
10	2	0.030	0.083	Go-Around
11	3	0.018	0.027	Crash
12	1	0.020	0.048	Landing

The lower the parameter, the smaller the aileron or elevator deflection range and the more difficult to control the aircraft. The effect of the fault parameters, and therefore the fault severity, on the outcome of the approaches is evident. The elevator fault severity appeared to determine the outcome. No pilot could land the aircraft when the elevator parameter value was lower than 0.036. The pilot’s comments on the questionnaire also confirm the substantial difference in the situations. Table 3 shows the answers to Question A: “What do you think happened?” and Question B: “How sure are you about your previous answer?” In three cases, when the fault was not severe and a landing was possible, the abnormal behavior was blamed on “gusts” and “wind shear” (Pilot 1, 6 and 8). Seven pilots recognized to some extent a problem in the FCS.

Table 3 - Subjective questionnaire responses.

Pilot	Outcome	What do you think happened?	How sure are you?
1	Landing	Sort of abnormal gusts	1
2	Crash	Overshot the tunnel and tried to correct. Result was not realistic. I think a control problem occurred.	6
3	Crash	Steering failure	1
4	Crash	I'm really not sure. It seems like a malfunction of the control computer. I felt like the control wheel commands weren't properly transferred to the FCS anymore. I have the feeling that the FPA was still indicating correctly.	4
5	Crash	I turned a bit steep and tried to correct. At first, the a/c reacted, but then the roll channel did not correspond to my inputs	9
6	Landing	Wind shear from the left	7
7	Crash	I have no idea, some severe degradation of FBW.	7
8	Landing	Wind shear; engine failure	7
9	-	N/A	N/A
10	Go-Around	FCS failure	7
11	Crash	No reaction to my inputs, or with a very large delay	3
12	Landing	Flight control/ hydraulic problem. If aircraft roll rate error was ½ roll rate: sim fail. Pitch ok. Roll: more aileron needed for making the same turn	5

3.1.4 Summary

It is evident that the outcomes were dependent on the severity of the fault, both from the simulator data and from the subjective data. Pilot comments confirm that the situations were significantly different when aileron and elevator range restrictions were changed, although the results still represent the variation in perceptions. An analysis of the comments and the approach outcomes showed that pilots who managed to land the aircraft attributed the problem to external causes (windshear, gusts) in three out of four cases. On the other hand, all other cases in which the aircraft could not be landed were associated with system problems.

Another interesting aspect of the variations of responses is “how sure” they were of their answers. For example, pilot #1 landed the aircraft in what he thought were “abnormal gusts”, but he was just guessing. In contrast, pilot #6, who also managed to land the aircraft and blamed the problem to windshear, was “almost sure” about the cause.

3.2 Experiment #3 Results

3.2.1 Objectives

The objective of this experiment was, first, to understand how pilots respond to faults that are novel or are not detected by the standard alerting and monitoring systems. Understanding this response is essential to the design of systems, procedures and techniques that could aid the pilots in managing problems with the aircraft. Among the options to support the pilots in these situations are systems that could provide general information about the health of the aircraft. Therefore, the second objective of this experiment was to investigate how an HMS as described in 1.3 can help the pilots detect and manage the faults. In addition, the experiment was to investigate the effect of different methods for displaying HMS information to the pilot (alerting system vs. fault meter).

3.2.2 Collected Data

Of the planned 288 approaches, a total of 281 approaches were flown. One data set was lost, and six other runs were not flown because the experiment was delayed and the pilot had to leave at the originally scheduled time. However, this was anticipated and the six approaches not flown did not have faults.

As with all the other experiments, 76 aircraft parameters were recorded at 25Hz, including aircraft position and altitude, both with respect to the tunnel and to a reference frame centered in the runway touchdown zone.

Questionnaires were collected after each of the 281 approach was flown. Each included several questions regarding the fault, the alerting system and fault meter, and NASA TLX workload ratings.

3.2.3 Approach Outcomes

3.2.3.1 Analysis Method

The categories used to describe the outcomes of each approach of experiment #2 were used again in experiment #3. The four categories are:

1. Landing
2. Continued approach with later go around

3. Immediate go around
4. Others (crash, simulator problem, situation too ambiguous)

The “landing” category was the easiest to assign, based on a simple observation at the last position of the aircraft. The “continued approach” category included all situations in which the aircraft continued the tunnel tracking after the fault was fully developed, but ultimately conducted a go around or needed the simulator to be stopped. An “immediate go around” included all situations in which there is no evidence of intended tunnel tracking during or after the fault development. The “others” category included situations in which the outcome was influenced by known external factors, or when the pilot requested to stop the simulation without establishing a go around attitude. It was decided to keep this category included in the analysis because it can be argued that pilots’ performance or behaviors led to some of those outcomes.

Figure 9 shows how the situation was analyzed for a particular approach in this example. In this example, fault #1, an elevator problem, was triggered at about 10 km from the runway threshold. The pilot recognized the fault, disconnected the A/T as requested in the briefing and continued to fly the approach. However, as he approached the airfield, his tunnel tracking performance declined and became too unstable for the landing; he then decided to go around.

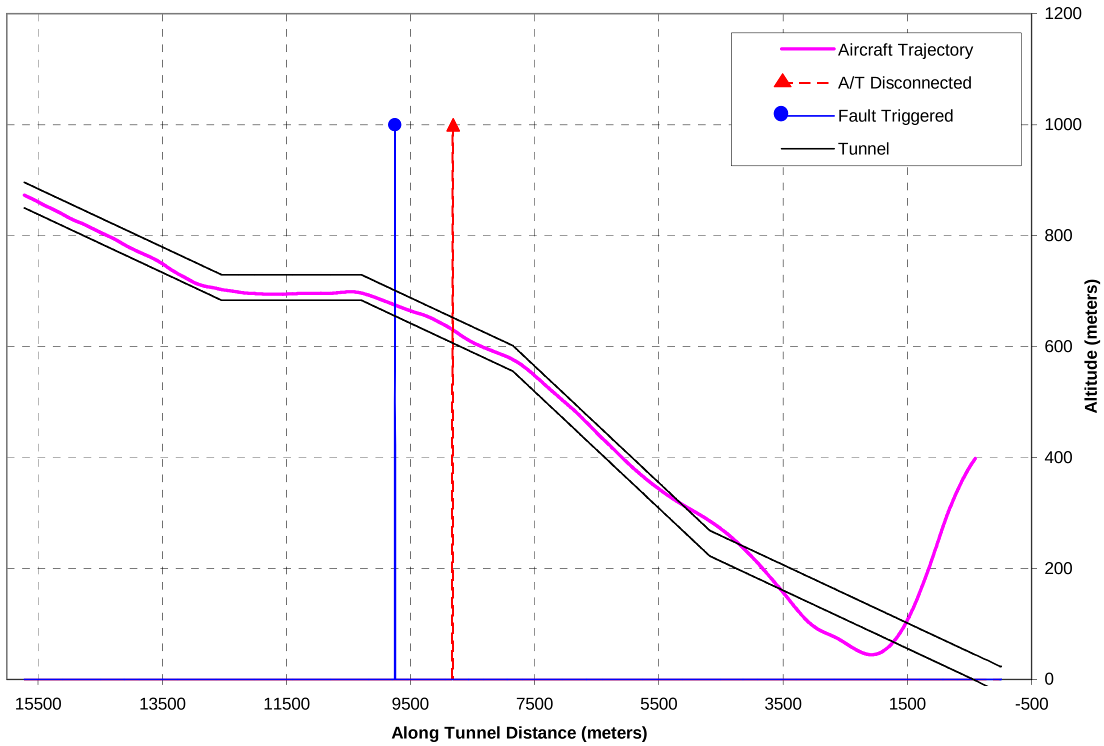


Figure 9 - Example of trajectory associated with "Continue with later go around".

The go around confirmed by a constant climb pitch attitude, full throttle, and the abandoning of the tunnel. (In some many cases, also the horizontal tunnel tracking provided useful information. Therefore, a plan view of the aircraft trajectory was also plotted for each approach.) The overall situation and the approach category assigned was also compared to the pilots' comments collected in the questionnaires for that particular run. In most cases, the comments are coherent with the observed position, attitude and performance parameters.

Initially, the A/T disconnection was used as means to determine when the pilot had detected the fault. It was later decided that in many cases pilots may have forgotten to disconnect the A/T, even if they recognized a problem with the aircraft and decided to continue the approach. For example, consider the situation shown in Figure 10: After the problem was triggered, the tunnel tracking performance seems to deteriorate but not enough for the pilot to consider going around. The A/T was disconnected at 500 ft, as briefed for a normal approach, and the aircraft landed without problem. From the information available, it can not be determined if the pilot was aware of the fault, and if so, when he became aware. Also affecting the A/T measure was the pilot's disconnection as a response to the alerting system or fault meter instead to the perception of a problem. This type of response can be observed in some approaches in which fault #5 was triggered, lowering the reference airspeed tracked by the A/T.

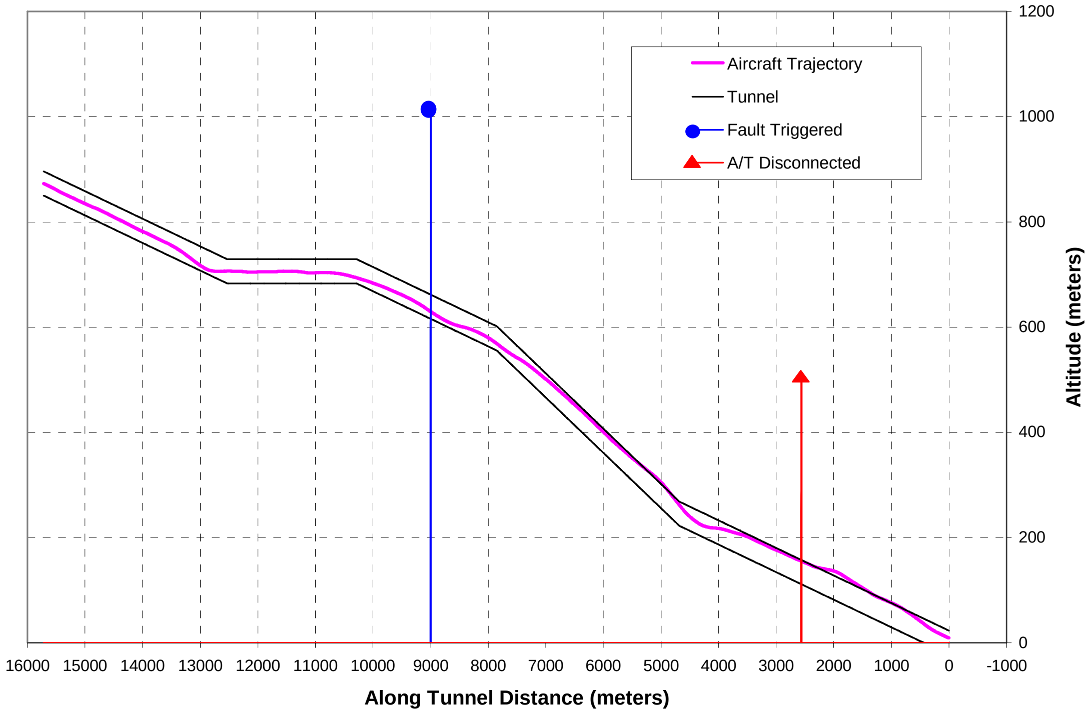


Figure 10 - Example of aircraft approach trajectory and flight path vector problem.

When this occurred, pilots reported having no idea about what triggered the alerts or even suggested a false alarm. Another issue that made it difficult to categorize the outcomes in greater detail was the possible experimenter's intervention in some cases when the simulator hardware could have been compromised by severe motion requirements. Many precautions were taken to avoid reaching full extension of the hydraulic actuators. If a pilot managed to put the aircraft in a situation of excessive and abrupt load factors (high or low g), the simulator was stopped automatically or by the operator.

3.2.3.2 Results

The complete approach outcome categorization of 143 runs for the twelve faults is shown in Figure 11. At least one pilot could land each fault with the exception of fault #8, in which an aileron deflection reduction fault was triggered with the Command-FPV FCS. This fault did not completely compromise the controllability of the aircraft, although maneuverability was very low. It is probable that landing was possible by disregarding the tunnel and aligning the aircraft with the runway using the navigation display, but it would have required several large radius turns taking several minutes. At least one pilot suggested or started to fly using this technique to return for a landing, but, since there was not useful data to collect from this maneuver and the experiments were tightly scheduled, the experimenter/copilot suggested stopping the run.

In contrast with fault #8, pilots landed the aircraft in 34 of 36 runs when presented with fault #3, #7 and #9, in which malfunction of sensors would cause a drift of the FPV, either up, down or to the left. The effects of this fault can be observed in pilots' tunnel tracking performance which deteriorated at some point during the approaches, such as the example shown in Figure 10. Evidently, when the discrepancy between the FPV indication and the aircraft's attitude was obvious, almost all pilots disregarded the FPV and flew the aircraft using other display references.

Without considering faults #3, #7 and #9, 107 approached in which a fault was triggered were flown. 35% resulted in landings, 36% continued the approach but did not land, 22% went around immediately and the remaining 7% was categorized as "other". For most of the other faults, responses were varied, both between faults and between pilots and no other universal trends were observed for the outcomes of the approaches.

3.2.4 Health Information Effect on Approach Outcomes

The impact of information about the health of the aircraft on the outcomes of the approaches was investigated. For these tests, faults #3, #7 and #9 (FPV drift) were excluded because 34 out of 36 pilots landed the aircraft, implying that the faults were easily recognized and the effect of the HMS information had little influence.

The hypothesis that HMS information could help the pilots with fault management was tested by examining the effect of different fault meter and alerting system combinations on the approach outcomes. A Chi-Square test for independence between the six fault meter and alerting system combinations was applied to the four outcome categories. As the test for independence failed to provide conclusions due to the low number of data points, the contingency table was reduced by combining some of the factors.

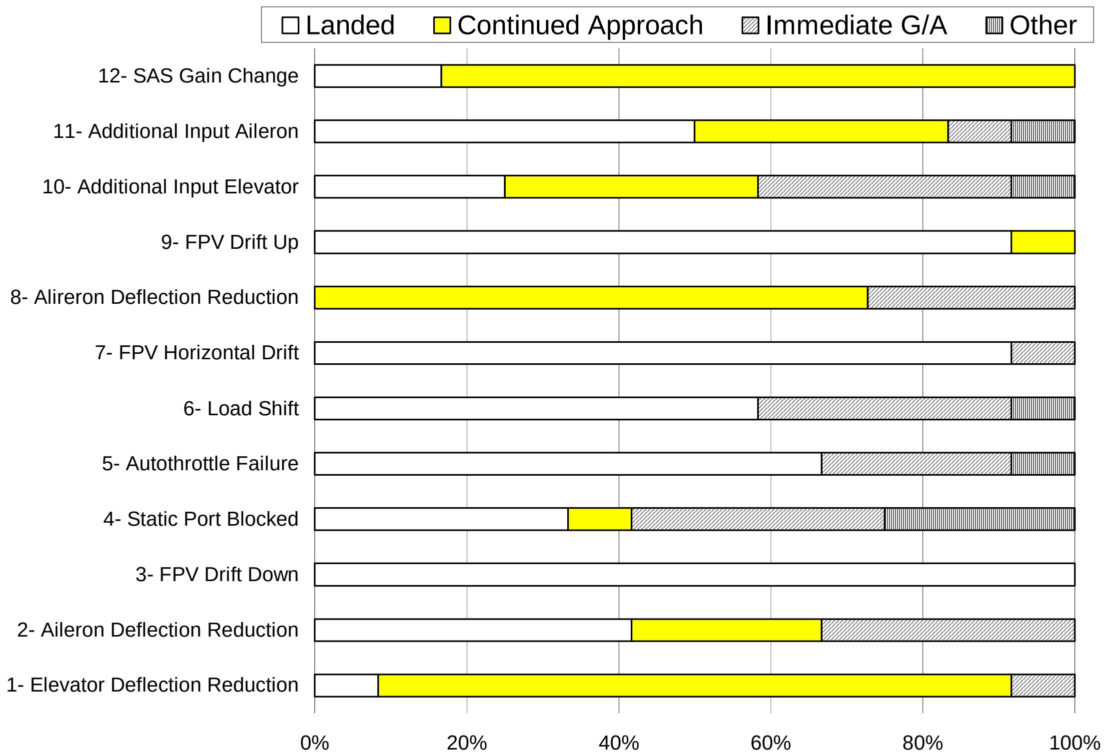


Figure 11 - Approach outcomes, pilot responses to faults and their outcomes.

Meaningful results were only achieved with two factors: A- No Information Available or B- Information available (either from the alerting system, fault meter or both). The corresponding contingency table is shown in Table 4.

Table 4 - Contingency table for two HMS information factors.

	Landed	Continued	G/A	Other	
A - No Information	8	7	3	0	
B - FM and/or A.S.	29	32	21	7	
Totals:	37	39	24	7	107

Table 4 contains 2 cells with expected counts less than 5, which is more than 20% of the total number of cells. But, since the P-Value of 0.497 is very large, the probability of finding any effect of the factors on the approach outcomes is very small. To further investigate the subject, another test on Table 4 was performed but the "other" column was discarded.

In this case, 16% of the cells have expected counts less than 5. Therefore, the P-Value can be used to accept the null hypothesis of independence. In other words, there is no evidence to conclude that the HMS information had any effect on the outcomes of the approaches.

3.2.5 Pilot Descriptions of the Faults

After each run, whether or not a fault was triggered, a questionnaire was presented to the pilot by the experimenter/copilot. The first question was "What do you think happened?"

In 100% of the approaches in which no fault was triggered, pilots answered "Nothing". In a few cases pilots added some comments regarding their performance or the aircraft's behavior. When faults were triggered, a mixture of answers was given which was sorted into the following categories with respect to how well they described the fault:

1. Wrong answer (non existent fault description).
2. No idea (pilot declared having no answer).
3. Acceptable comment (comments that are not incorrect but do not describe the problem symptom).
4. Recognition of symptom (comment precisely describes the symptom of the problem).
5. Mention possible cause or detailed description of symptoms (comments not only describe the symptom but also propose possible causes of the problem).

These categories are also organized in an increasing order of pilot's understanding of the problem, ranging from 1 for "Wrong answer" to 5 for "Attempt to explain cause of problem or detailed description of symptoms".

The categorization showed that in 11% of the approaches the pilots did not have a correct understanding of the fault. In at least 76% of the runs, the pilots recognized the symptoms. If the "acceptable comments" are considered as an indication that the pilot was aware of the problem, the pilots of 89% of the runs can be considered to have had awareness of the degradation of health of the aircraft. The results of categorizing all answers are summarized in Figure 12 and in Figure 13 by pilots. It is interesting to note that the distribution of these answers is relatively uniform between pilots and faults, with one exception: Pilot #2 seemed to have made less effort than the rest in answering the questionnaire, as can be observed in Figure 13. With respect to the faults, only one of them caused more confusion than the others: the static port blockage which affected indications not only of attitude and airspeed, but also the presentation of the tunnel display.

The following question on the questionnaire was: “How sure are you about your previous question?” The answer was requested on a 9 step scale from 1 (Just Guessing) to 9 (Very Sure). The responses for the categories Wrong Guess, Acceptable Comment, and Mention Possible Cause were centered on the mid-point, while Recognition of Symptom and Mention Possible Causes tended to have higher ratings. A Wilcoxon Rank Sum test found that pilots that correctly identified the symptoms showed a higher confidence in their answers than pilots who attempted an even more detailed explanation of the situation or attempted to explain causes for the recognized symptoms ($p<0.01$).

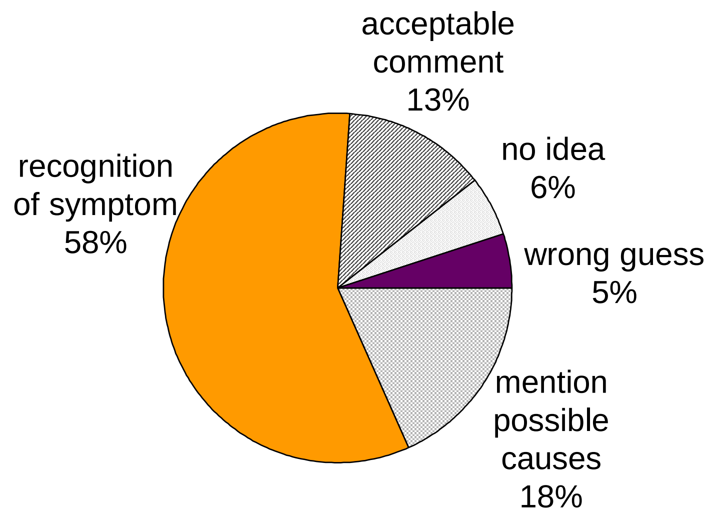


Figure 12 - Categorization of the correctness and detail of fault descriptions.

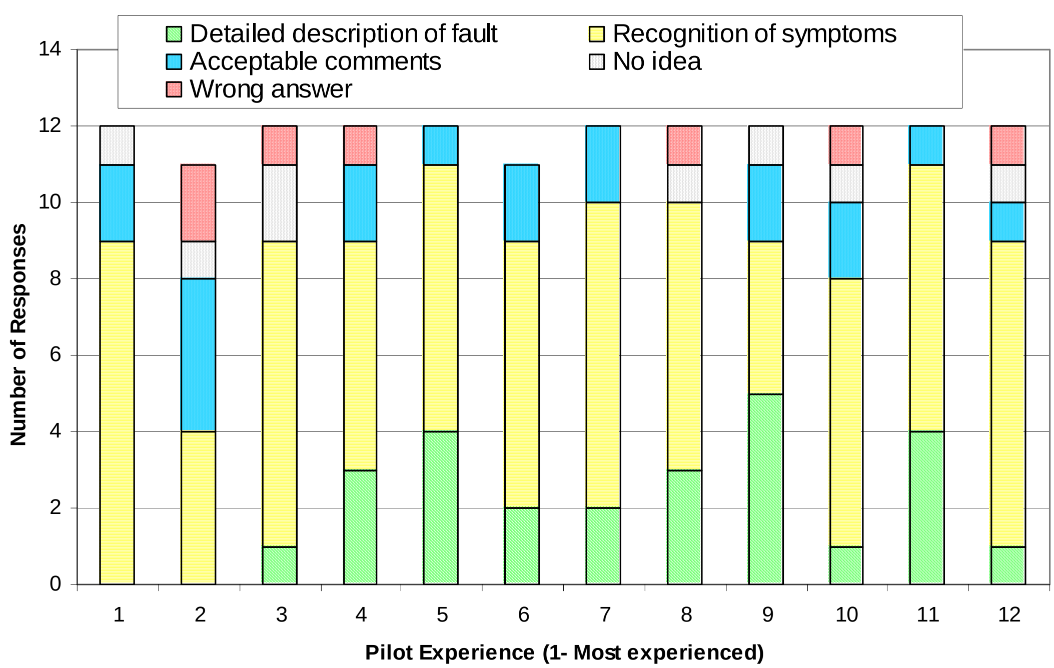


Figure 13 - Correctness and detail of pilot descriptions of the fault by pilots.

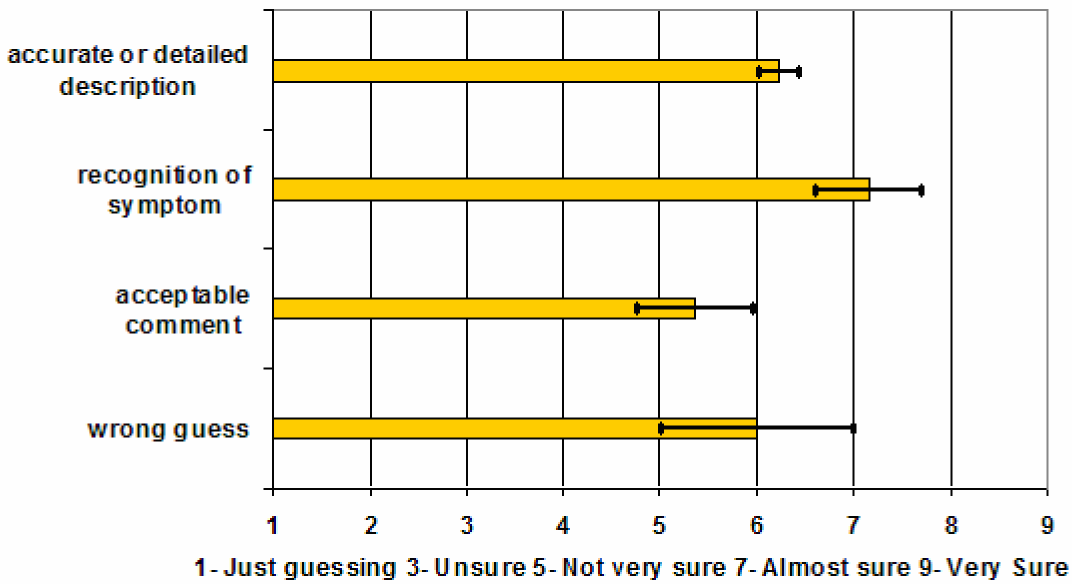


Figure 14 - Pilot's confidence on their answer to "What do you think happened?"

3.2.6 Pilots' Experience

Other measures for which pilot experience could have had an effect were approach outcomes, tunnel tracking performance, TLX measures, and fault meter and alerting system use and ratings. No correlation between any of these measures and the pilots' experience was found. Similar conclusions were obtained in a study by Davis and Pritchett (1999), in which twelve helicopter pilots with experiences ranging from 440 to 6800 hours were presented with faults and failures while flying a UH-60 helicopter simulator equipped with an experimental alerting system. The authors did not find any indications that pilot experience affected on use of a novel alerting system.

3.2.7 Pilot Comments on Fault Meter and Alerting System

At the end of all runs in which faults were triggered, pilots were asked to rate the statement "The fault meter and/or alerting system helped to detect the fault". Pilots provided an answer by rating the statement on a scale from 1 (Strongly Disagree) to 9 (Strongly Agree). The mean of the numeric value associated with their answer and the standard error was calculated for four different categories: the first two are in reference to the alerting system or fault meter when each was the only source of information. The other two are in reference to the alerting system or fault meter when both sources where available in the cockpit. The mean was calculated from the post run questionnaires corresponding to the 117 approaches with these systems present and a fault. The results from this analysis were compared with the answers of similar questions asked to each pilot at the end of the experiment.

When only the fault meter was present, its mean rating was 5.5 (Neutral - Slightly Agree). When only the alerting system was present, pilots rated its usefulness higher, with a mean rating of 6.4 (Slightly Agree – Agree). Having both systems available did not significantly change their ratings of each. Figure 15 shows the results for the fault meter and alerting system when rated individually (AS and FM) and when rated simultaneously (AS+[FM] and FM+[AS]). These same results are shown in Figure 16 for each pilot. Nine pilots ranked the alerting system as more useful than the fault meter and only pilots #6, #7 and #11 gave the opposite rating.

An analysis of the ratings given after each fault showed that 11 out of 12 pilots were consistent in their answers in the questionnaires given after each run and at the end of the experiment. On the other hand, pilot #11 contradicted himself by repeatedly rating the alerting system higher after each approach but giving the opposite rating at the end of the experiment; this pilot may have misinterpreted the question on the final questionnaire. Assuming this was the case, 10 out of 12 pilots preferred the alerting system over the fault meter.

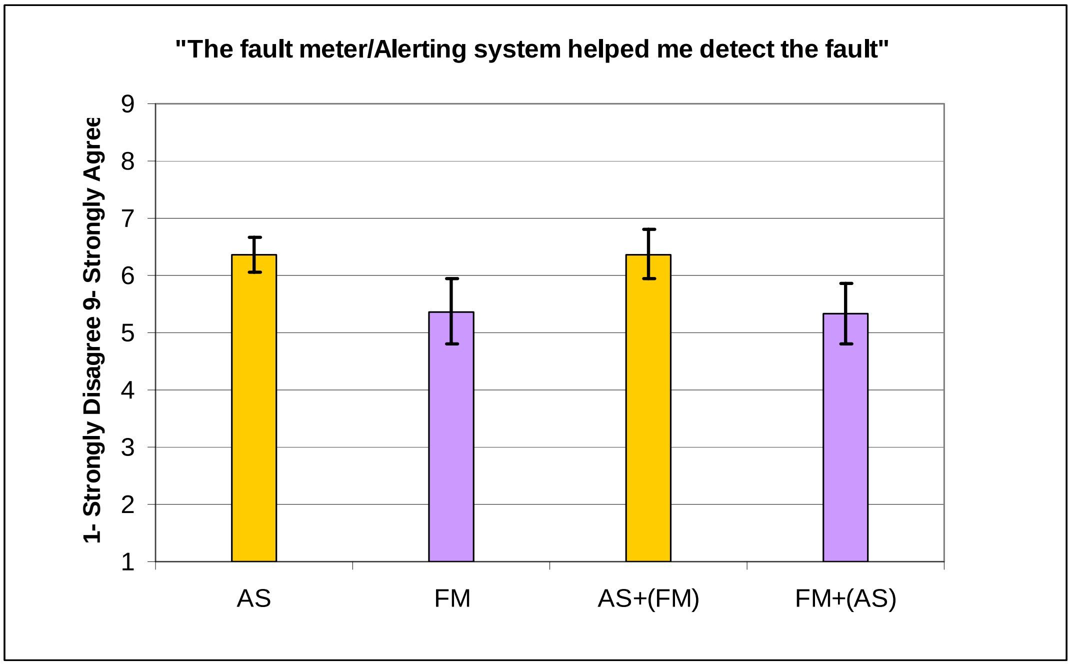


Figure 15 – Fault meter and alerting system end of run questionnaire answers.

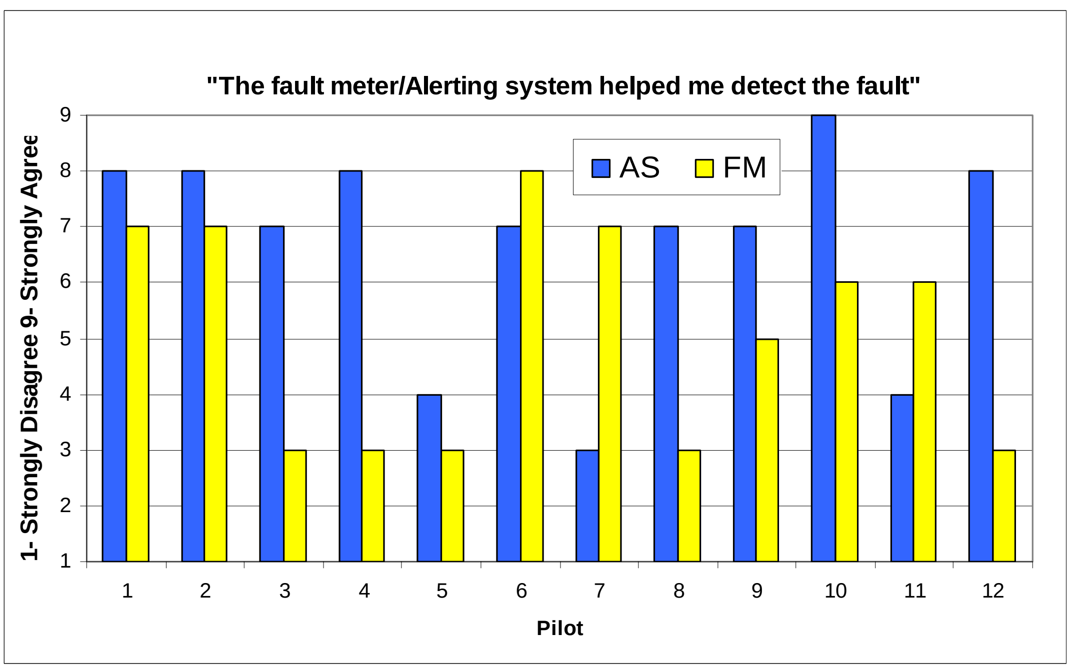


Figure 16 - Fault meter and alerting system overall ratings by pilot.

3.2.8 Use of the Fault Meter

The use of the fault meter was investigated from the use of the “Push to See” button by which the pilot made the fault meter visible. It is assumed that each time the button was pressed and the fault meter became available, the pilot scanned the instrument. The use of the fault meter was analyzed at three different phases: before, during and after the fault. Since the faults were implemented such that they would gradually develop, the “during” phases included the 15 seconds after the faults were triggered; after this period of time, the faults were fully developed. The measures obtained from the fault meter use were the number of times the button was depressed and the total time the button was pressed. The second measure, total time the button was depressed, divided by total number of button presses gives an indication of how much time the pilot had the display available each time he wanted to see it. The same measures used for the approaches with faults were also taken from all approaches in which no fault was triggered. This allowed obtaining measurements in the same conditions and time period: one full approach.

The fault meter scans/time per pilot before, during and after the fault was triggered, is shown in Figure 17. Only pilot #6 and #7 used the fault meter at a higher rate before than during the fault, corresponding with their questionnaire answers and fault meter and alerting system ratings.

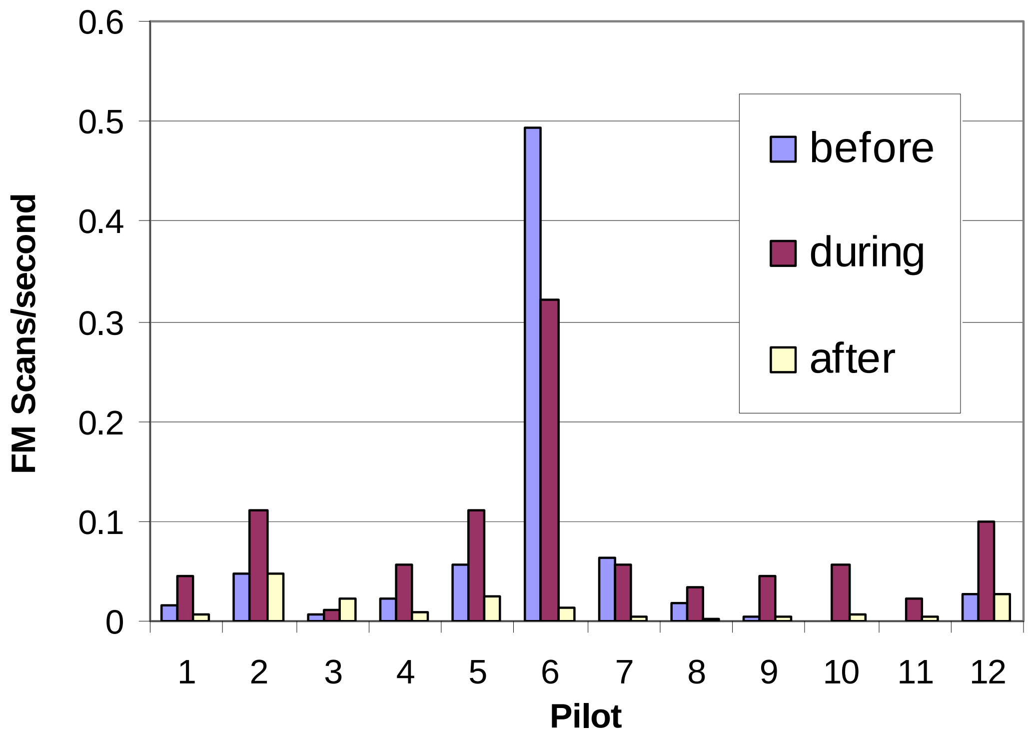


Figure 17 - Fault meter scans by time per pilot, before during and after the fault.

Six pilots (50%) used the fault meter at higher rates before the fault than after the fault. Three (25%) pilots did not change the rate of scans of the fault meter before and after, and the other 3 used the fault meter more during and after the fault than before. Nine (75%) pilots used the fault meter at higher rates during the 15 seconds in which the fault was developing.

The total time the fault meter was held down by each pilot during approaches with no faults is shown in Figure 18. The average total time was less than 5 seconds for 66% of the pilots, and less than 10 for 92% of the pilots. The exception is Pilot #6, with an average of 37 seconds, confirming his unique behavior of fault meter use. It is also interesting to consider the fault meter availability in the context of the total duration of each approach, usually around 3 minutes and 30 seconds. In average, the fault meter was visible approximately between 2% and 5% of the approach time by 11 of the pilots, while for pilot #6, the fault meter was visible during 20% of the time. The fault meter was available in 6 of the 12 faults seen by a pilot. In four of these approaches, the alerting system was present and gave alerts as described in 2.3.4. Table 5 lists the number of scans of the fault meter on all approaches where no fault occurred, in two main categories: with alerting system, and without. The presence of an alerting system did not seem to affect the number of scans of the fault meter, indicating their independent use of the instrument. Pilot #1 did not fly some of the placebo runs due to a schedule problem, thus he only flew one run with fault meter and alerting system.

Table 5 - Scans of fault meter with and without alerting system.

Pilot	1	2	3	4	5	6	7	8	9	10	11	12
Without AS	4	14	3	6	18	105	6	5	0	0	1	8
	4	24	3	5	6	85	10	2	2	1	1	16
With AS	3	0	3	2	13	86	6	4	0	1	0	7
	n/a	18	3	4	7	90	7	3	2	0	1	13
	n/a	2	1	6	8	67	10	2	0	2	1	7
	n/a	22	1	4	11	86	13	1	0	0	0	11

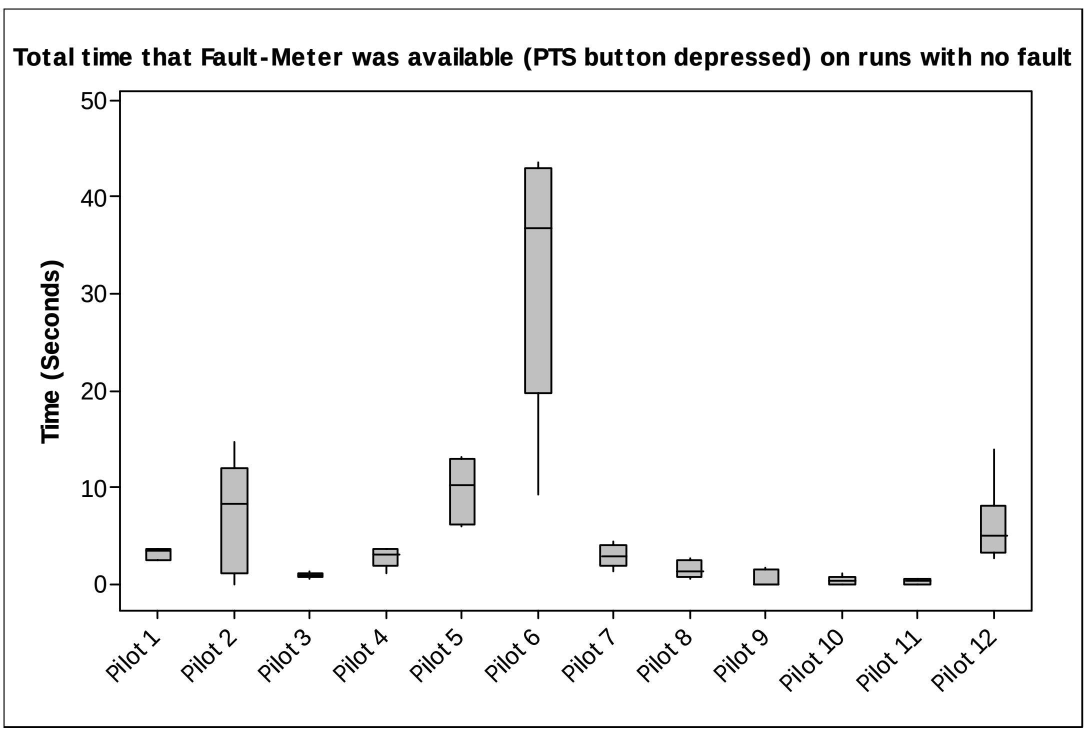


Figure 18 – Total time of fault meter available to pilot

3.2.9 Pilot Workload Rating

At the end of each run, pilots also described their workload using the 0-100 NASA TLX workload rating for each of the following measures:

a. physical demand
b. mental demand
c. temporal demand
d. performance
e. effort
f. frustration

Appendix D includes the questionnaire in which these measures were presented to the pilot. These six workload ratings were examined effects of different factors with an Analysis of Variance (ANOVA). The factors investigated were “pilot”, “fault”, “run” (run order), “FCS”, “alert” (alerting system) and “fault meter”. Observations with standard residuals greater than 3.5 were discarded.

The two different Flight Control Systems had effects on all measures except for Frustration, although P-value was marginal (0.066). The fault meter and alerting system did not have any effect on the TLX measures. The only other factor that affected any of the measures was “Frustration” (P=0.008), which diminished with run order, meaning that as pilots flew more approaches and encountered new faults, the reported “Frustration” diminished. The main effect plot from the ANOVA is shown on Figure 19.

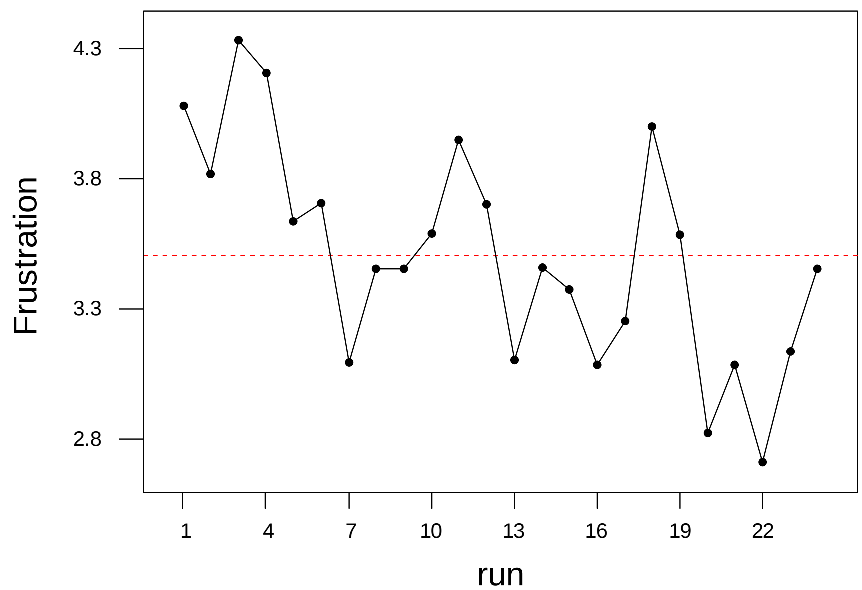


Figure 19 – Main effect plot from ANOVA analysis for "Frustation".

3.2.10 Pilot Performance at Tracking the Tunnel

3.2.10.1 Analysis Methods

The approaches to the fictitious airport were flown using the primary flight display shown in Figure 4, a three-dimensional ego-centric presentation in which a ground-referenced tunnel was displayed over a presentation of the outside world. The width and height of the tunnel was 45m x 45m and the pilot had to fly the aircraft flying as close as possible to the center of the tunnel until reaching the runway. The tunnel tracking error was defined as the distance in meters at any given time from the aircraft's cockpit to the tunnel's "walls", "ceiling" or "floor". The error was automatically measured by the simulator at 25 Hz, in two dimensions, horizontal and vertical. The Root Mean Square (RMS) of the errors was calculated for each dimension. An ANOVA was done on the tunnel tracking error for the approaches without faults only to investigate the effect of the following factors: Run (run order), FCS, fault meter (presence of) and alerting system (presence of).

As expected, the tunnel tracking performance was found to be affected by the different flight control systems. However, this effect was only observed in the horizontal error. The two flight control systems helped the pilot to better track the center of the tunnel. There is no evidence that the presence of the alerting system, fault meter or the run order had any effect on the tracking error.

The horizontal tunnel tracking error for each pilot and FCS is shown in Figure 20. Fifty percent of the pilots clearly performed better with the Command-FPV system, although considering the width of the tunnel the difference does not have any impact in the accomplishment of the task. Figure 21 shows the vertical tunnel tracking error, in which 3 pilots did better with FCS 3 and 4 pilots did better with FCS1. The data for the remaining 5 pilots did not show significant difference between the two FCS due to the overlapping standard errors.

The effect of the faults on tunnel tracking performance is shown in Figure 22. The analysis was performed only on runs in which the outcome was a landing or the aircraft reached the end of the tunnel, at about 200 ft of altitude and 3500 ft from the touchdown zone. Out of 144, 79 approaches met with this requirement. Faults of the FPV (#3, #7 and #9) showed particularly low impact on the tracking performance. On the other hand, the fault reducing aileron deflection with FCS 3 (Fault #8) severely affected tunnel tracking and no pilot could continue the approach.

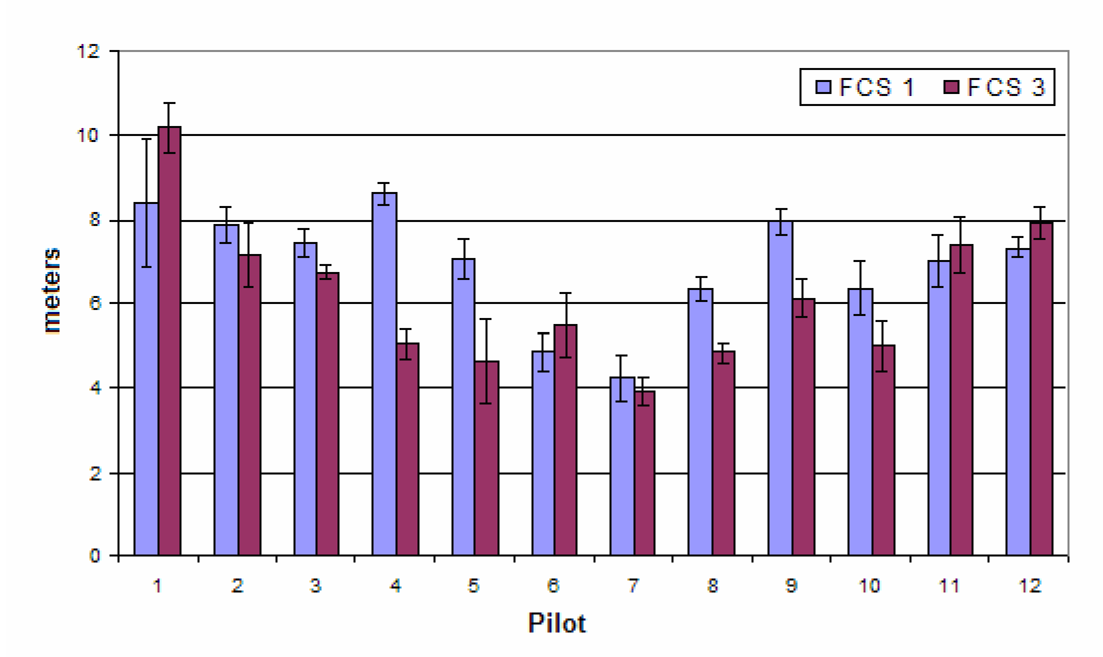


Figure 20 – Horizontal tunnel tracking error (RMS, meters).

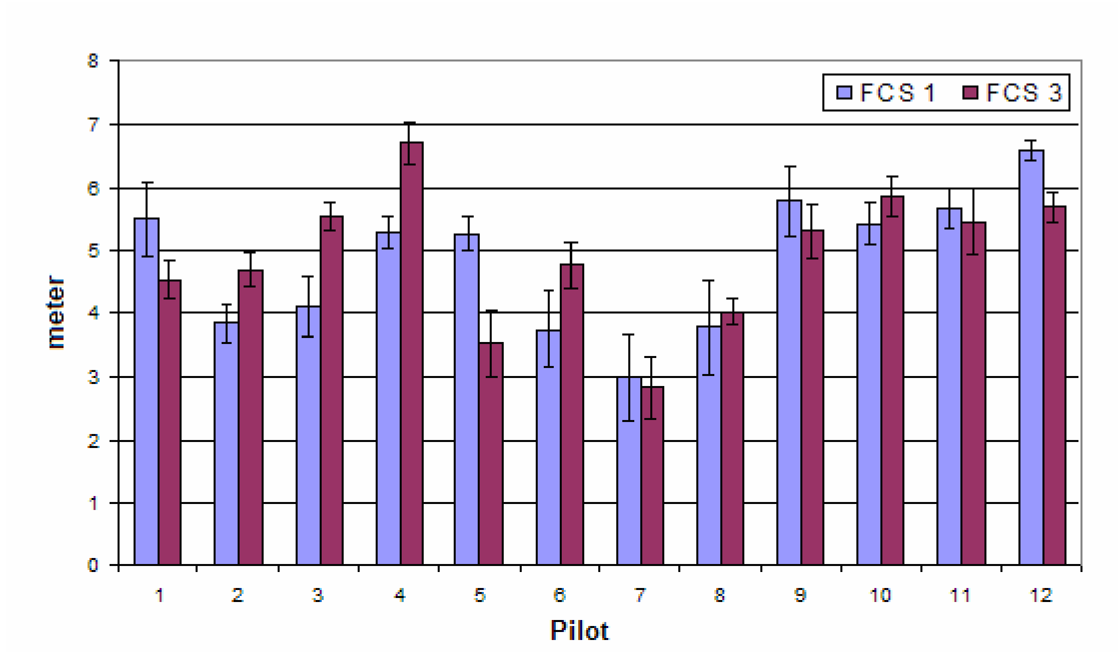


Figure 21 – Vertical tunnel tracking error (RMS, meters).

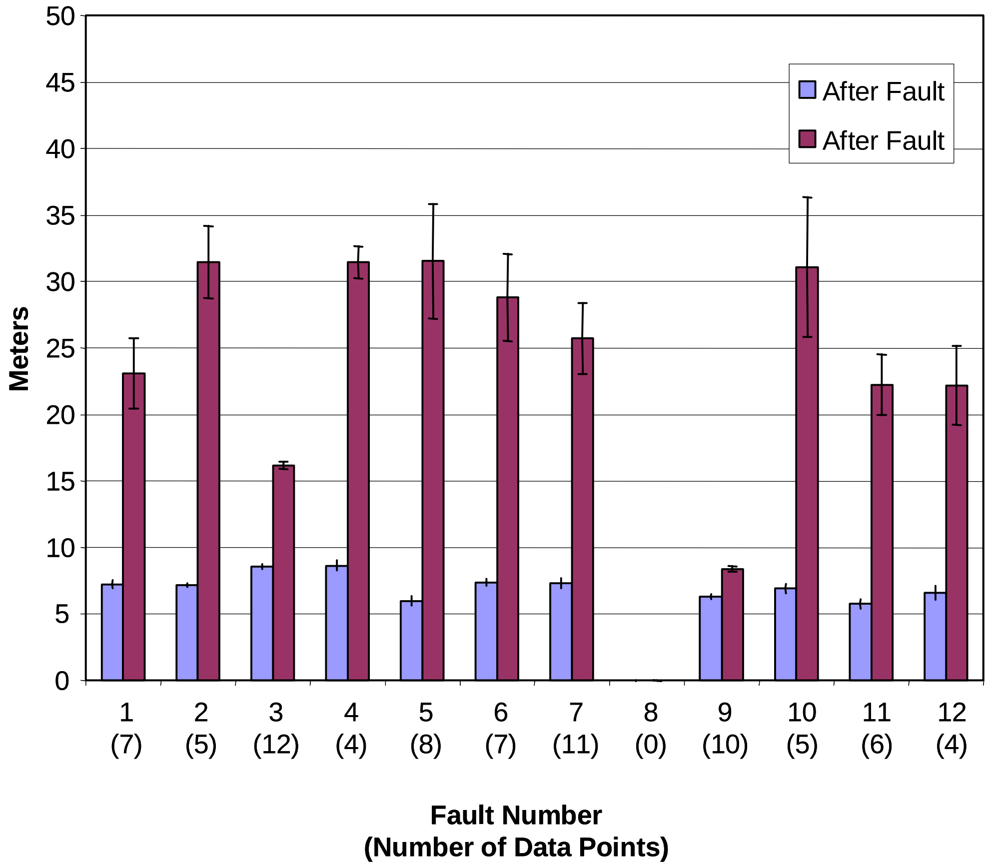


Figure 22 – Tunnel tracking error before and after the fault.

3.3 Experiment #4 Results

3.3.1 Objective

In this experiment responses to a false alarm were investigated. The hypothesis was that the use of the HMS during experiment #3 would induce automation bias on the system, affecting fault management and tunnel tracking performance.

3.3.2 Pilots' Responses to False Alarms

Ten out of twelve of the originally planned approaches were flown for experiment #4, all resulting in landings. After the run pilots were asked, as in all previous approaches with faults, "what do you think happened?" The responses are categorized in Table 6, indicating that at least 50% of the pilots could not identify any problem, however, indicated that something was wrong.

To investigate the effects of the fault meter and the alerting system on tunnel tracking performance, a comparison between the tracking error during the placebo runs of experiment #3 and the error on the runs of experiment #4 was performed. Figure 23 and Figure 24 show the Root Mean Square for horizontal and vertical error. An ANOVA found a marginally significant difference in tunnel tracking error before and after the false alarm ($p=0.1$ for 10 data points).

Table 6 - Pilot descriptions after the false alarm.

# of Pilots	Description
5	"Something is wrong" but couldn't identify what
2	"False Alarm"
2	"Don't Know"
1	Described a non-existent fault

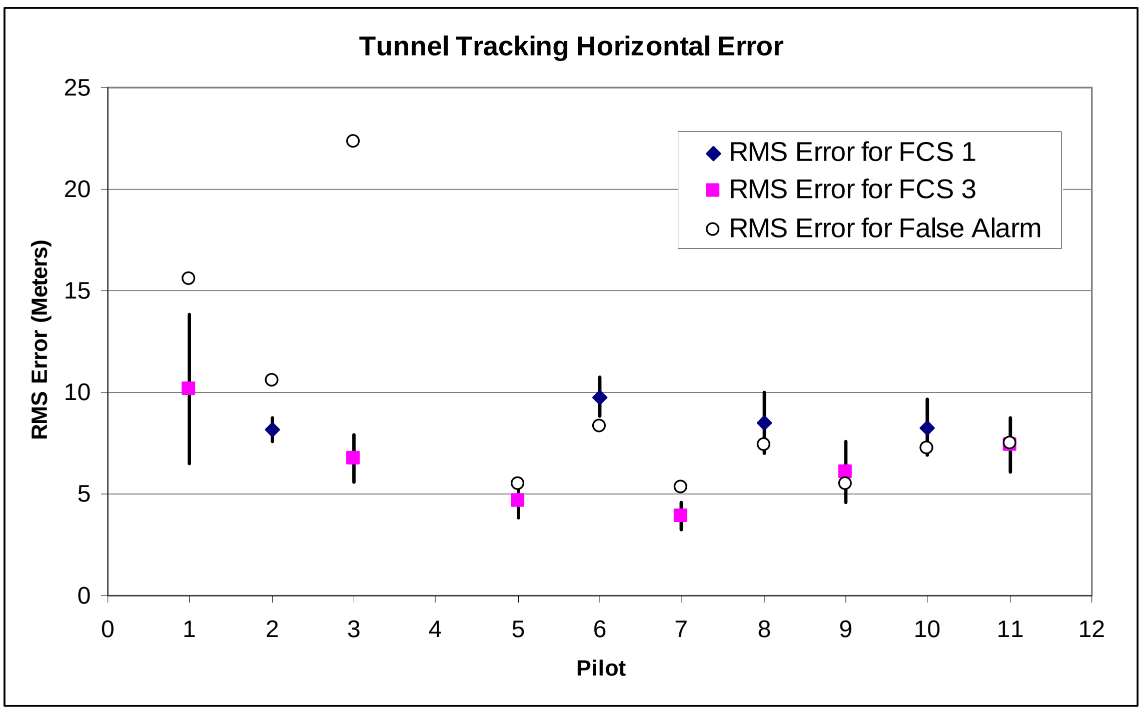


Figure 23 - Tunnel tracking horizontal error.

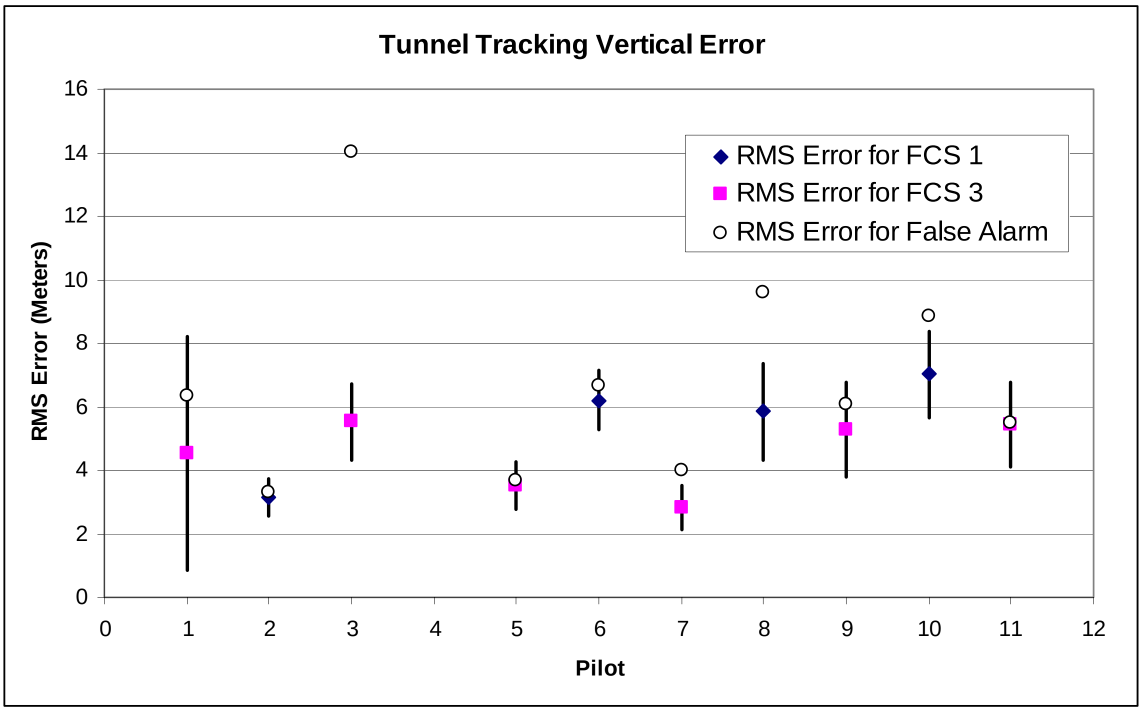


Figure 24 - Tunnel tracking vertical error.

4 Discussion and Conclusions

The experiments described in this dissertation provide an insight into pilot fault management, including the role of a proposed new health monitoring system. The discussion covers two main topics: fault management and the role, problems and potential uses of the alerting system and fault management system.

4.1 Fault Management

Fault management is modeled as four operational tasks: detection, diagnosis, prognosis, and compensation. These four tasks were shown in Figure 1, superimposed on Rasmussen's "decision ladder". In addition, fault management can occur at three different operational levels: systems, aircraft and mission. In the context of this fault management model, these experiments did not provide the pilots means to respond to faults in the systems operational level. Instead, faults would have to be compensated for at the aircraft level, and, in many cases, they would trigger fault management at the mission level. It was observed nevertheless that pilots also attempted fault management at the systems level. Immediately after the approach, pilots were asked "What do you think just happened?" 18% of the pilots not only described the problem symptoms, but attempted to explain the causes. These answers clearly show that pilots may start their fault management at the system level, without being able to compensate at that level.

Likewise, a significant percentage of pilots that could not precisely define the fault symptoms, admitted having "no idea" of what the problem was, or provided wrong descriptions of the faults. The answers categorized as "wrong guess" have to be interpreted with prudence, since some pilots may have recognized the symptoms but provided a wrong explanation of possible causes. The “no idea” answers are self explanatory. But, when pilots answered with an “acceptable” comment, it could not be determined if their situation awareness was sufficient to compensate for the fault. In summary, at least 19% of the answers showed the pilot’s difficulties describing, recognizing or identifying the problem.

Of the three operational levels, pilots had the most complex task at the aircraft level. All faults were designed to affect flight control and required a response to continue tracking the tunnel. The type of response corresponds to three different categories of faults. The first category corresponds to the four faults manifested in the cockpit flight displays. Three of them affected the displayed flight path vector and could be compensated for by ignoring the displayed discrepancy and tracking the tunnel using other primary flight display cues. The fourth display fault was caused by a blocked static port. Compensation for this fault required the pilot to completely disregard the primary flight display and fly the aircraft visually, managing airspeed based on pitch and power performance experience. (This fault also affected the mission level since pilots had to visually find the airport.)

The second category corresponds to two faults which could be completely compensated for by using aircraft systems. First, the weight shift could be compensated by the use of elevator trim to reduce the forward pressure needed to keep the aircraft in the tunnel, although pitch remained unusually unstable. Second, the autothrottle failure could be compensated by disconnecting it and regaining manual throttle control. (This is the only fault in which the response partially occurs at system level.)

The third category corresponds to the rest of the faults, in which compensation required new “stick and rudder” strategies to maintain control of the aircraft. These faults required a constant effort from the pilot because their effect on flight control could not be eliminated.

Just as pilots’ descriptions of the faults give an insight of the fault management at the system and aircraft level, the outcome of each approach during experiment #3 shows how the responses of the fault happened at the aircraft level or cascaded into the mission level.

Results show that pilots were cautious in evaluating the possibility of aborting the approach. For example, faults affecting the FPV did not seem to have affected the approach at the mission level, since in 34 out of 36 runs the pilots landed, even when the alerting system or fault meter was indicating a problem. However, considering the rest of the faults, 35% of the runs resulted in landings, and in another 36% pilots did not immediately abort the approach and continued to track the tunnel. Only in 22% of the runs an immediate go around was initiated. If landing a with certain fault proved to be possible as demonstrated by some pilots, why did other pilots decide to abort the approach? These results confirm that this decision is highly subjective

Finally, examining experiment #2, it is interesting to note how pilots described a sometimes almost unnoticed, sometimes catastrophic problem. In all cases in which pilots loss control of the aircraft or managed to go around, their comments directly point to the FCS failure. However, in the four cases where severity was low and pilots had little difficulty in landing, three comments referred to windshear. This contrast with the results of experiment #3, in which faults were attributed to aircraft system problems and not to environmental or operational factors such as windshear, icing or deficient load management (center of gravity problems). Pilots' briefings to expect faults may have affected their answers.

4.2 Fault Meter and Alerting System

What was the role of HMS information in the fault management process? First, subjective data shows that pilots generally agreed that the fault meter and alerting system helped them somewhat to detect the fault. In addition, 10 out of 12 pilots scanned the fault meter before the faults, using it as a monitoring tool aiding in detection. The presence of the alerting system did not affect the use of the fault meter, suggesting that pilots could have thought of both systems as independent, instead of considering them as complementary.

In general, most pilots preferred the alerting system over the fault meter. This preference was not only expressed in the questionnaires after each approach but was also confirmed when a similar question was asked at the end of the experiments. These pilots also had the fault meter uncovered, on average, about 5% of the approach duration. All pilots scanned the fault meter at much higher rates during the period of 15 seconds after the faults were triggered. This trend was observed in the 10 out of 12 pilots who used the fault meter the most before the fault, even for pilots #10 and #11 who did not use the fault meter at all before the fault.

However, two pilots preferred the fault meter over the alerting system and were seen to use it more before the faults. One of the pilots may have developed a strategy to take advantage of its continuous presentation of the aircraft health information; he had the fault meter uncovered about 20% of the total approach duration.

Did the presence of the HMS information affect the pilot's workload? NASA's Task Load Index ratings used in the post run questionnaires did not show any effect by the fault meter or alerting system. The only workload effect was with "frustration", which was found to diminish with run order. It is believed that, as the pilots got used to the experiment scenarios, dealing with the faults became an interesting challenge instead of a frustrating experience. Likewise, tunnel tracking performance (TTP) was analyzed in experiment #3 and #4 to investigate the effects of the fault meter and alerting system. ANOVA found no effects due to the presence of HMS information in the approaches without faults in experiment #3. However, ANOVA of tunnel tracking performance in experiment #4's false alarm cases finds the difference "before" and "after" to be marginally significant, ($p=0.1$, $n=10$). This difference may be attributed to two different reasons. First, the fault meter may have triggered a fault management process, increasing cognitive workload to deal with the new situation and taking resources shared with the tunnel tracking task, consequently affecting the performance. Second, it can be conjectured that the observed deterioration in the measure may have been caused by the pilot purposefully testing out the aircraft controllability, thus deviating from the tunnel temporarily.

In the questionnaires during and after the experiments, pilots repeatedly "complained" about the under-specific information provided by the fault meter or alerting system (e.g. "I need to know WHAT is wrong"). Their comments suggested that at least which axis (pitch, roll or yaw) was affected may be more helpful. Although the pilots' comments are valid, they put in evidence that the briefing may not have provided sufficient guidance for using the HMS, suggesting that pilot training would be required.

Potentially, procedures may be developed to help pilots use HMS information. It is a natural tendency for pilots to operate at a rule-based level, although the use of rule-base processing applied in the wrong context could present serious disadvantages. Thus, procedures may best serve to partially structure and encourage knowledge based reasoning by suggesting diagnostic processes to consider, rather than exactly specifying actions to be performed by rote.

Could the HMS initiate fault management at the mission level? The fault meter and alerting system had little effect on the approach outcomes with the faults used here (although the scenarios already allowed for an immediate landing whether the false alarm was believed or not). However, responses at the mission level may be independent of the HMS information, but dependent on the outcome of fault management at aircraft level. For example, a false alarm may trigger fault management at systems and aircraft level, but should the crew fail to find any problem, they may decide to abort the flight as a precautionary measure.

The results obtained from experiment #4 give significant insight into the pilots' responses to a false alarm (or a case when the fault symptoms remain invisible to the crew). The tendency toward automation bias is clearly seen in the pilots' responses to the post flight questionnaires. More than 50% of the pilots declared "something is wrong"; one pilot even described a non existent fault. Only 2 pilots out of 11 recognized the false alarm. This result has to be considered in context: experiment #3 had just provided 20 approaches in which the reliability of the fault meter and alerting system was 100% and pilot detection of the fault was very high. Thus, remains open the question of how pilots would respond to the fault meter during normal operations when faults are rare.

4.3 Overall Insights

The experiments provided valuable insight into the fault management processes in the cockpit environment. The results confirm the hypothesis that responses to faults degrading flight control will vary significantly between and within pilots. The response variation was observed not only at the mission level, where decisions proved to be highly subjective, but also at the aircraft level, where responses needed to compensate for the fault were specific.

The HMS information proved to be helpful in several ways. Both the alerting system and the fault meter played a role in the detection process. In addition, the fault meter was used to confirm a problem detected by other means or as a source for feedback of the compensation strategy. Both uses support the hypothesis that HMS information can help pilots in the fault management.

Pilots' preferences of HMS interfaces were not uniform, suggesting that some pilots did develop scanning strategies to take advantage of the fault meter. This supports the notion that training and procedures may be necessary to assure pilots' effective use of the HMS information.

None of the six NASA TLX workload measures appear to be affected by the presence of the fault meter or alerting system. Likewise, tunnel tracking performance seemed to be momentarily affected after the trigger of an alarm, but this could be attributed to the pilot trying to detect or diagnose the fault by changing his control behavior. Finally, the triggering of a false alarm showed the existence of automation bias induced after a small number of interactions with the HMS.

4.4 Further Research

The Health Monitoring System concept has never been applied in the cockpit. Could this system actually provide the information as assumed in this study? Further issues with the technical feasibility of the health monitoring system may drive research required into its role in the fault management processes. How sensitive could be the system to external disturbances? Could the system offer additional information about health degradation, such as which axis or system is affected?

The integration of the HMS with other aircraft systems presents several open questions. To which extent does the HMS complement or supplement current alerting systems? At another level, the conclusions suggest that procedures designed to respond to the HMS detected faults could help the pilots in the fault management process. How could these be designed and integrated with emergency and abnormal aircraft's procedures? Likewise, the training associated with the implementation of the HMS should be explored and defined to assure the pilot correctly interprets the information and applies it correctly during fault management processes.

Appendix A – Simulator Flight Parameters

	Name		Name
1	line number	41	Y_wind_v
2	time	42	Y_wind_w
3	stick-elev	43	Y_gust_u
4	stick-aileron	44	Y_gust_alpha
5	stick-rudder	45	Y_gust_beta
6	throttle	46	Y_gust_udot
7	flap	47	Y_gust_alphadot
8	Y_p roll rate	48	Y_gust_betadot
9	Y_q pitch rate	49	Y_gust_ug_asymm
10	Y_r yaw rate	50	Y_gust_ag_asymm
11	Y_vtas	51	Y_udot X accelerations
12	Y_alpha	52	Y_vdot Y accelerations
13	Y_beta sideslip	53	Y_wdot Z accelerations
14	Y_phi euler roll	54	Y_pdot angular accel.
15	Y_theta euler pitch	55	Y_qdot angular accel.
16	Y_psi euler heading	56	Y_rdot angular accel.
17	Y_h altitude	57	Y_h_disp
18	Y_x	58	Y_hdot_displayed
19	Y_y	59	Y_vias_disp
20	Y_hdot	60	Y_vtas_disp
21	mass	61	Y_vg_disp
22	Y_vias	62	Y_engine1_Tn Thrust
23	Y_n load factor	63	Y_engine1_FF
24	Y_gamma FPV pitch	64	Y_engine1_N1
25	Y_chi FPV Heading (ground track)	65	Y_engine1_N2
26	Y_gammadot	66	Y_engine2_Tn Thrust
27	Y_chidot	67	Y_engine2_FF
28	Y_bank angle	68	Y_engine2_N1
29	Y_vg ground speed	69	Y_engine2_N2
30	Y_de elevator def	70	trim pitch
31	Y_da aileron def	71	FM button
32	Y_dr rudder def	72	A/T Disconnect
33	Y_dte trim elev	73	experiment events
34	Y_df flaps	74	along track distance
35	Y_pla throttle??	75	x - track error
36	Y_gammacmd cmd=commanded	76	y - track error
37	Y_chicmd	77	track angle error
38	Y_phicmd	78	flight path angle error
39	Y_AT_vtas_ref for A/T	79	column moment on elev. (80 cm)
40	Y_wind_u	80	yoke moment on aileron (31 cm)

Appendix B – Pilot Briefings

TUDelft – Georgia Institute of Technology

Multi-Objective Experiment – Delft, August 2002

Schedule

Thank you very much for coming, your time is very valuable to us. If all goes well, we are hoping to follow the schedule shown below.

8:00 – 8:30	briefing
8:30 – 11:40	about 28 approaches, including practice and break in middle
11:40 – 12:00	debriefing on morning runs
12:00 – 12:40	lunch
12: 45 – 1:10 PM	briefing
1:10 – 4:50	about 26 approaches, including a break in the middle
4:50 – 5:10 PM	debriefing on afternoon runs

It will be a busy day. However, please know that we welcome any request you may have for explanations, and it is your choice when to take breaks. You are also free to end the simulation runs if you feel it is necessary.

Overview

The experiment's objective is to study and compare different tunnel-in-the-sky displays, flight control systems and motion models in the new SIMONA simulator. To test these different configurations, we will be flying curved approaches to a fictitious airport using the tunnel displays. The aircraft flight model is based on a Cessna Citation II; however the cockpit and displays are experimental.

Even though the simulator is not perfect, please use your best pilot judgment to fly the aircraft. Do your best to act naturally, as if you have passengers on board. This will give us an idea whether it is realistic to fly curved approaches with these tunnel displays.

An experimenter will be flying with you as first officer. After each approach and at the end of each set of approaches with each Flight Control System he will ask you to answer a short questionnaire. He will also brief you before each run and will answer any question you may have at any time.

During the experiment, please feel free to verbalize your thought process for him to record. We are particularly interested in your thoughts on the tunnel display. In addition, let the experimenter know if you find any unexpected situations or problems.

Simulator

You will notice that there are no rudder pedals in the simulator, but this should not have an impact on flying the tunnel because the yaw damper takes care of side slip.

You will also notice that the control column is a little too high. We are aware of this issue and will be corrected in the future.

The simulator requires following a few initialization and safety procedures. There will be an intercom for communications with the control room. For emergencies, you will find a red button on your left panel. This button turns off all systems, but does not connect the bridge. Please, follow the simulator operator commands for fastening and unfastening the seat belts or leave the cabin. Also, follow his commands for engaging the flight control loading system. After this procedure, the control column requires a calibration. Please make sure that you can stay clear of the column during calibration.

The operator will initiate each experiment run when you reply “Ready”. To help reduce the possibility of motion sickness or other related problems, the operator will stop the simulator by counting 3 – 2 – 1 – “Stop”. The operator will stop the simulator after touchdown, since the aircraft model has no brakes. Also, the operator may stop the simulator at any time if he believes that the motion system safety limits may be exceeded.

Morning Approaches

The morning block has several practice approaches and as many data approaches as we can fit in by lunch. The practice approaches will give you a chance to get familiar with the simulator, and we will not move on if you don't feel comfortable or you still have questions.

Each simulation run will last no more than 5 minutes and will start with the aircraft situated at the beginning of a curved approach presented as a Tunnel-in-the-Sky on the PFD. Your task is to manually fly the approach and land. IMC conditions will prevail until about 200 ft AGL. You may notice that different motion system models will be tested during the experiment.

Your tunnel tracking performance will be recorded. We will only record data until you descend to 100 ft. above ground. Data about the flare and landing will not be used in the analysis.

Autothrottle:

You are requested to fly the approaches using the autothrottle, until you reach 500 ft AGL. At this altitude, you should disconnect the autothrottle and start to reduce your speed to 115 – 120 knots as you see fit during the final approach.

IMPORTANT: However, if you have any problems controlling the aircraft at any point during the approach, you should disengage the autothrottle.

Additional remarks:

The landing gear will be always down, and the flaps will be set by default to 25 deg. Your F/O will not do anything except for the following call outs: "500 ft" for A/T disconnect, "Runway in Sight", and "100, 60, 40, 20" before touchdown.

No additional tasks, such as checklists or ATC commands, will be asked of you.

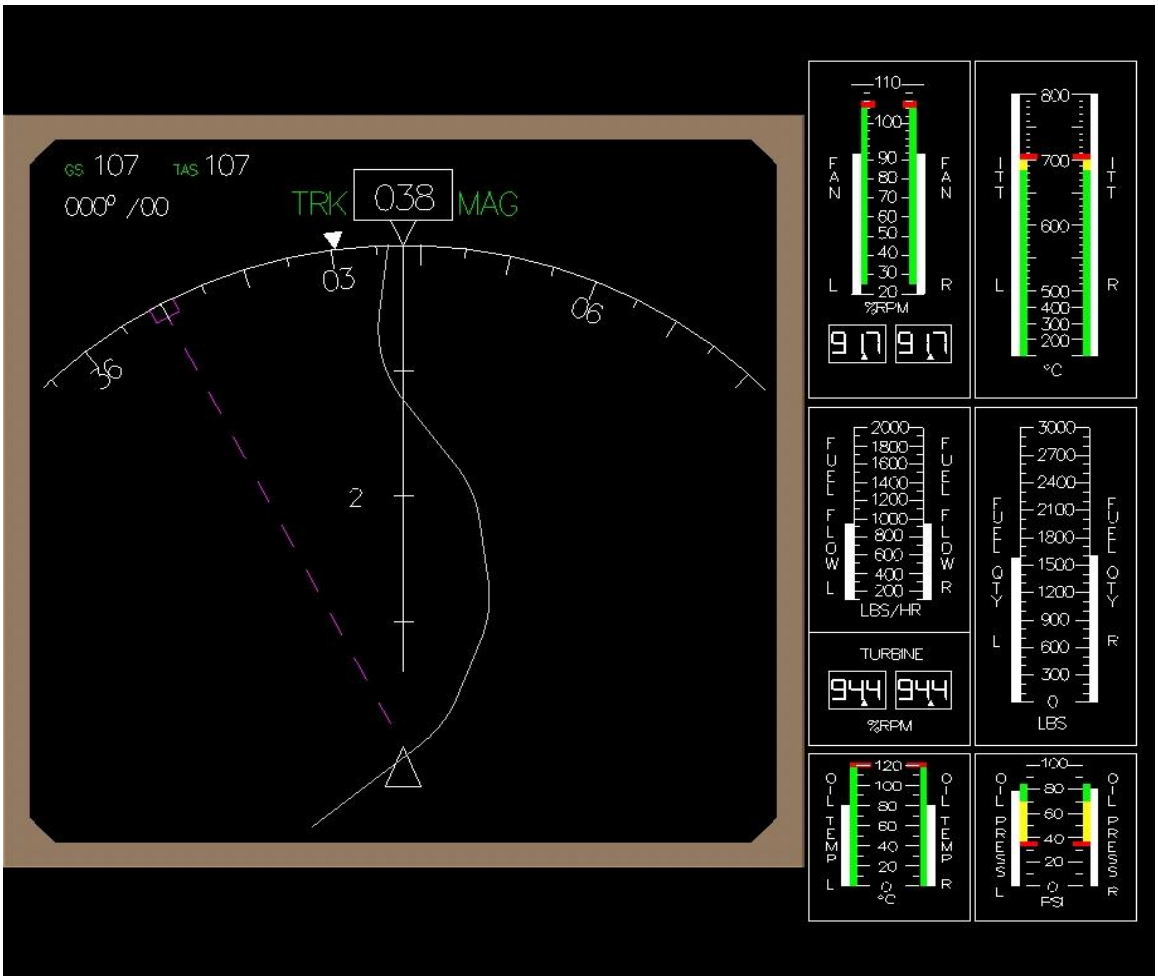
Cockpit Displays

The Primary Flight Display will be based on a “Tunnel-In-The-Sky” concept.

1- Pitch Attitude
2- Bank Angle
3- IAS
4- Altitude
5- Heading
6- Vertical Speed
7- Flight Path Vector
8- Guidance Information: Tunnel-In-The-Sky
9- AutoThrottle Message

Navigation Display Engine Instruments and Systems Annunciation Display

A second screen will be used to display a Navigation Display combined with engine instruments and additional displays used for the afternoon approaches.



Flight Control Systems (FCS) and Primary Flight Displays

During the experiment, we will be testing 3 different types of FCS:

Basic: Conventional Control, based on the standard Citation manual control system. Your control column controls the aileron and elevator. The aircraft will start the approach trimmed for a flight path angle of -3 deg.

RC/AH: Airbus Type Control. This FCS is based on the Airbus A320.

Your column inputs will produce rates of roll and pitch. When you center the column, the aircraft will maintain the current attitude, so you shouldn't need to use pitch trim.

FP-Command: Flight Path Vector is a new type of control where the control column directly controls the desired direction of flight relative to the ground by producing rate of change of track and flight path angle. When you center the column, the aircraft will maintain track and flight path angle. To help portray the effect of your inputs, the "commanded Flight-Path Vector" on your tunnel display moves in response to your control inputs.


fp–command 0
+1.68
+2.10
+0.25
+1.62
2500
2000
1000
1560
150
160
140
24
041

Afternoon Approaches

Sorry for the surprise on the last run, it was intended to see how pilots react to unexpected faults. This afternoon, we will be studying how different displays and alerting systems, and may help you detect and react to faults or problems that may impact the flying quality of the aircraft. Problems may occur in some runs, but not in all of them. The problems may be with the aircraft, the Flight Control Systems, the sensors or with the displays.

The following approaches are similar to the morning approaches except for the differences listed below:

- We will be flying in VMC.
- You may expect light to moderate turbulence.
- We will only use FCS1 (Basic) and FCS3 (Flight Path Command)
- We will only use one motion model for all approaches.

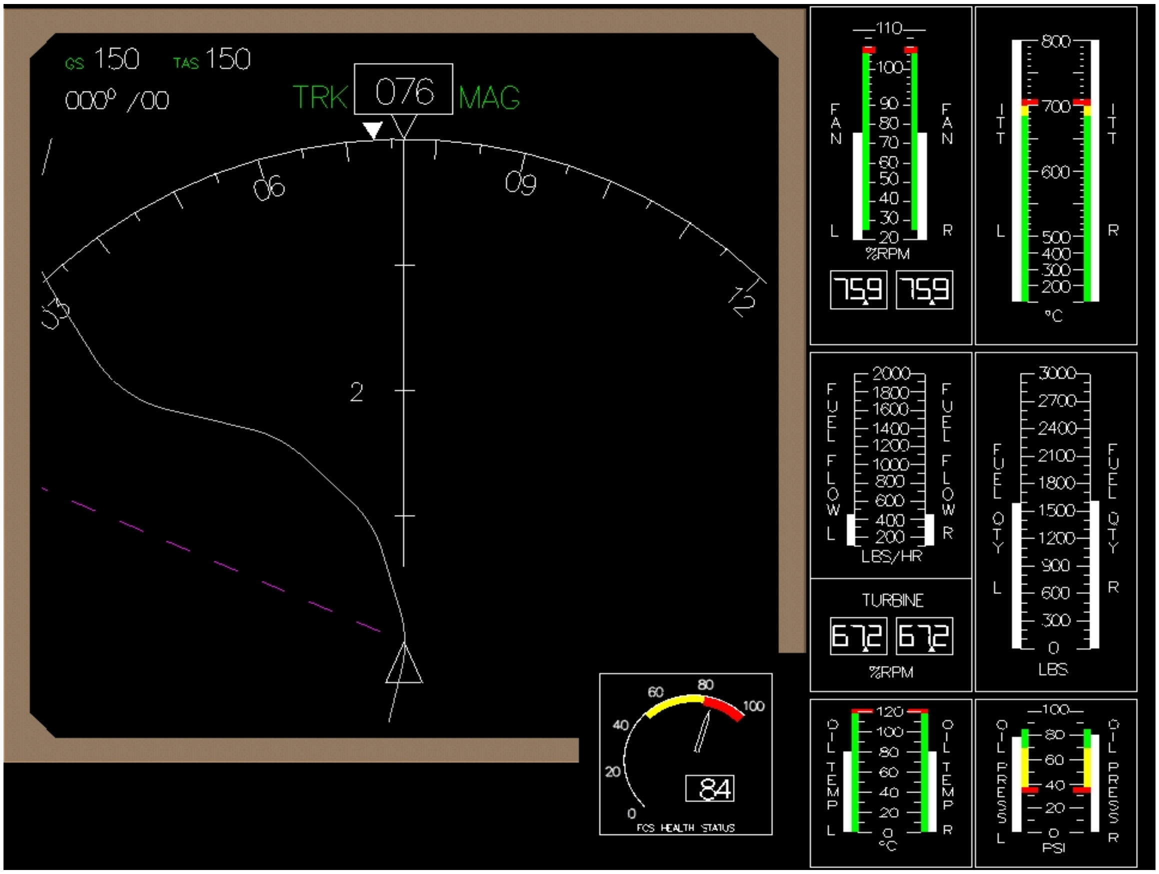
Test Conditions

In random order, we will be testing a new instrument and an alerting system. The instrument is called the “fault meter” and provides information about the health of the aircraft handling qualities. The alerting system will give aural and text alerts when the health of the system has deteriorated to critical levels.

Fault Meter

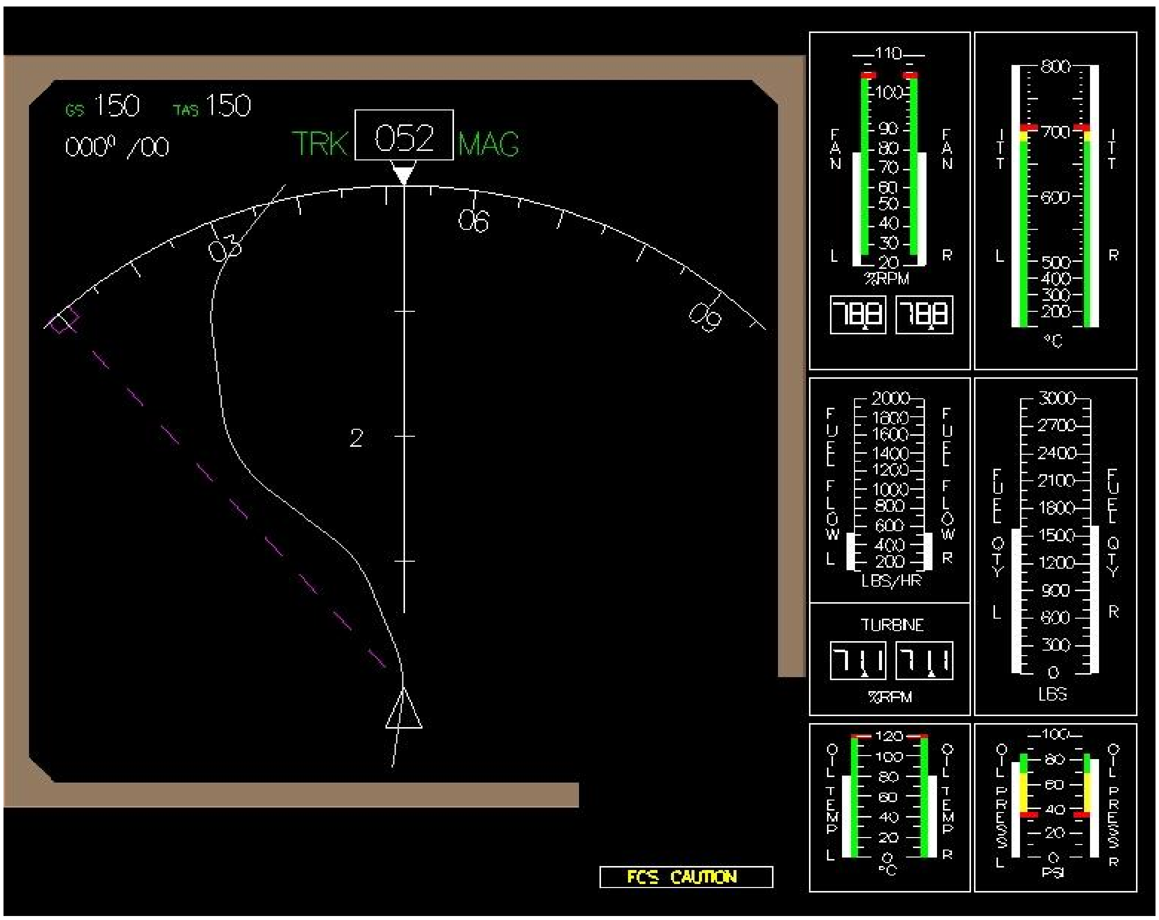
In half of the runs, an instrument (called the Fault Meter) will display the (lack of) health on a scale from 0 to 100. The higher the value, the worse is the severity of the problem. Any indication in the white arc range is normal. The yellow arc, starting at 60%, is considered a Caution, and the red arc, starting at 80% is considered a Warning.

So that we can measure how and when you use the Fault Meter, you will need to press a button in the yoke to see it: “Push To See”. Please use this instrument as you find it helpful to you.


GS 150 TAS 150
000° /00
TRK 076 MAG
06
09
33
12
2
FAN L
FAN R
110
100
90
80
70
60
50
40
30
20
%RPM
75.9 75.9
ITT L
ITT R
800
700
600
500
400
300
200
°C
FUEL FLOW L
FUEL FLOW R
2000
1800
1600
1400
1200
1000
800
600
400
200
LBS/HR
TURBINE
67.2 67.2
%RPM
FUEL QTY L
FUEL QTY R
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
LBS
0
20
40
60
80
100
84
FCS HEALTH STATUS
OIL TEMP L
OIL TEMP R
120
100
80
60
40
20
0
°C
OIL PRESS L
OIL PRESS R
100
80
60
40
20
0
PSI

Alerting System

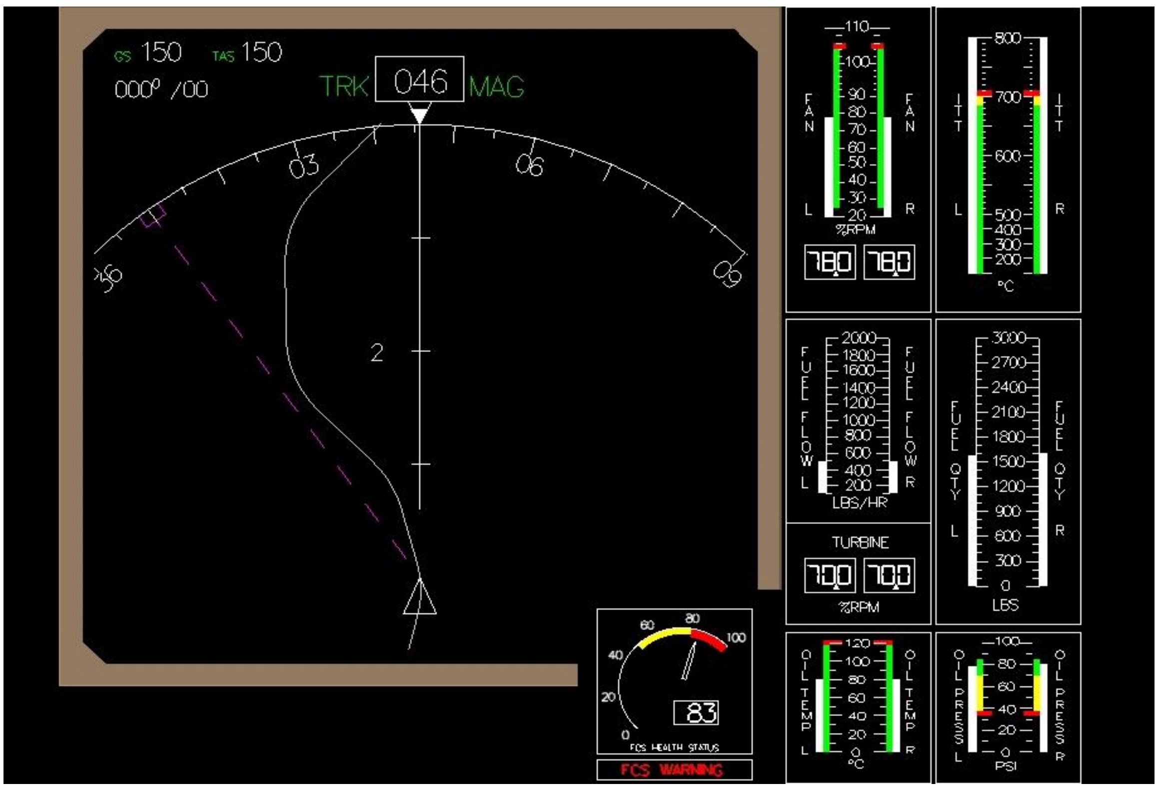
The alerting system will provide caution and warning alerts based on the same information source as the Fault Meter. A caution aural alert will sound and a message will be displayed in yellow when the fault value is over 60%. If the fault continues to deteriorate and the fault value goes over 80%, a warning alert will sound and a warning message will be displayed in red. In some runs, the alerting system will only give Warning alerts, while on other runs, both Caution and Warning alerts will be given. Before each run, the experimenter will let you know which alerting system configuration you will be flying with.



The aural alerts are 3 beeps for Caution, and 6 beeps for Warnings. The warning beeps will be at higher tempo and pitch.

In random order, we will test different combinations of the alerting system and fault meter:

- No Fault Meter and No Alerting System
- Aural Alerts and Text Messages Only
- Fault Meter Only
- Fault Meter + Aural Alert and Text Messages



Autothrottle:

IMPORTANT: You are requested to fly the approaches using the autothrottle; however, if you suspect that the aircraft has a problem or failure, you should disengage the autothrottle. This will both give you total manual control of the aircraft and also serve as a measure to us of when you detect the fault. To achieve manual control of the throttle, you have to press the disengage button, the throttle levers will not override the A/T. After disengaging, use your best judgment to continue or abort the approach, and let your first officer know your intentions.

Appendix C – Experiment Design

Experiment #1: Runs 1-18   Experiment #2: Run 19

Run: T = Training   Motion: 0 = Off 1=On   Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
1	T1	1	2	0	0	0	1	0
1	T2	2	1	0	0	0	1	0
1	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
1	T4	1	2	0	0	0	1	0
1	T5	1	1	0	0	0	1	0
1	1	1	2	0	0	0	1	0
1	2	1	1	0	0	0	0	0
1	3	1	1	0	0	0	1	0
1	4	1	2	0	0	0	0	0
1	5	1	1	0	0	0	0	0
1	6	1	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
1	T6	2	1	0	0	0	1	0
1	T7	2	2	0	0	0	1	0
1	7	2	1	0	0	0	1	0
1	8	2	1	0	0	0	0	0
1	9	2	2	0	0	0	1	0
1	10	2	2	0	0	0	0	0
1	11	2	1	0	0	0	1	0
1	12	2	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
1	T8	3	1	0	0	0	1	0
1	T9	3	2	0	0	0	1	0
1	13	3	1	0	0	0	1	0
1	14	3	2	0	0	0	0	0
1	15	3	1	0	0	0	1	0
1	16	3	1	0	0	0	0	0
1	17	3	2	0	0	0	0	0
1	18	3	2	0	0	0	1	0
1	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Fault	FM	Alert
1	T10	1	2	0	1	2
1	1	1	1	2	0	2
1	2	1	2	0	1	1
1	3	1	2	5	1	2
1	4	1	1	0	0	1
1	5	1	1	6	1	1
1	6	1	2	0	0	2
1	7	1	1	0	0	0
1	8	1	2	4	0	0
1	9	1	2	1	0	1
1	10	1	1	0	1	0
1	11	1	2	3	1	0
1	12	1	2	0	1	2
1	13	3	1	10	1	2
1	14	3	1	11	0	0
1	15	3	2	0	1	1
1	16	3	2	9	0	2
1	17	3	1	7	1	0
1	18	3	2	0	0	0
1	19	3	2	12	1	1
1	20	3	1	0	0	2
1	21	3	1	0	1	0
1	22	3	2	8	0	1
1	23	3	1	0	0	1
1	24	3	1	0	1	2
1	25	3	2	0	1	2

Experiment #1: Runs 1-18   Experiment #2: Run 19

Run: T = Training   Motion: 0 = Off 1=On   Visual: 0 = IMC 1= VMC

2	T1	1	2	0	0	0	1	0
2	T2	2	1	0	0	0	1	0
2	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
2	T7	2	2	0	0	0	1	0
2	T6	2	1	0	0	0	1	0
2	1	2	1	0	0	0	0	0
2	2	2	2	0	0	0	0	0
2	3	2	2	0	0	0	1	0
2	4	2	1	0	0	0	0	0
2	5	2	1	0	0	0	1	0
2	6	2	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
2	T8	3	1	0	0	0	1	0
2	T9	3	2	0	0	0	1	0
2	7	3	1	0	0	0	0	0
2	8	3	1	0	0	0	1	0
2	9	3	2	0	0	0	0	0
2	10	3	1	0	0	0	1	0
2	11	3	2	0	0	0	1	0
2	12	3	1	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
2	T5	1	1	0	0	0	1	0
2	T4	1	2	0	0	0	1	0
2	13	1	1	0	0	0	1	0
2	14	1	2	0	0	0	0	0
2	15	1	2	0	0	0	1	0
2	16	1	1	0	0	0	0	0
2	17	1	2	0	0	0	0	0
2	18	1	2	0	0	0	1	0
2	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
2	T10	3	2	0	1	2
2	1	3	2	7	1	1
2	2	3	2	0	1	1
2	3	3	1	0	1	2
2	4	3	1	0	1	0
2	5	3	2	12	1	2
2	6	3	1	0	0	0
2	7	3	2	9	1	0
2	8	3	2	11	0	2
2	9	3	1	0	0	2
2	10	3	2	8	0	0
2	11	3	1	0	0	1
2	12	3	1	10	0	1
2	13	1	2	0	0	0
2	14	1	2	5	0	1
2	15	1	1	4	0	2
2	16	1	2	0	0	1
2	17	1	1	0	0	2
2	18	1	1	0	1	1
2	19	1	2	2	1	0
2	20	1	1	3	1	1
2	21	1	1	1	0	0
2	22	1	2	6	1	2
2	23	1	1	0	1	0
2	24	1	2	0	1	2
2	25	1	2	0	1	2

Experiment #1: Runs 1-18   Experiment #2: Run 19

Run: T = Training   Motion: 0 = Off   1=On   Visual: 0 = IMC   1= VMC

3	T1	1	2	0	0	0	1	0
3	T2	2	1	0	0	0	1	0
3	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
3	T9	3	2	0	0	0	1	0
3	T8	3	1	0	0	0	1	0
3	1	3	1	0	0	0	1	0
3	2	3	2	0	0	0	0	0
3	3	3	1	0	0	0	0	0
3	4	3	2	0	0	0	1	0
3	5	3	2	0	0	0	0	0
3	6	3	1	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
3	T5	1	1	0	0	0	1	0
3	T4	1	2	0	0	0	1	0
3	7	1	1	0	0	0	0	0
3	8	1	2	0	0	0	0	0
3	9	1	2	0	0	0	1	0
3	10	1	1	0	0	0	1	0
3	11	1	2	0	0	0	0	0
3	12	1	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
3	T6	2	1	0	0	0	1	0
3	T7	2	2	0	0	0	1	0
3	13	2	1	0	0	0	0	0
3	14	2	2	0	0	0	1	0
3	15	2	1	0	0	0	0	0
3	16	2	2	0	0	0	0	0
3	17	2	1	0	0	0	1	0
3	18	2	1	0	0	0	1	0
3	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
3	T10	1	2	0	1	2
3	1	1	2	0	0	2
3	2	1	1	0	0	1
3	3	1	2	0	0	0
3	4	1	1	0	1	2
3	5	1	2	6	0	0
3	6	1	1	1	1	0
3	7	1	1	3	0	1
3	8	1	2	0	1	1
3	9	1	1	4	1	1
3	10	1	2	0	1	0
3	11	1	1	2	1	2
3	12	1	2	5	0	2
3	13	3	2	0	0	2
3	14	3	1	9	1	2
3	15	3	2	8	1	0
3	16	3	2	7	0	1
3	17	3	1	0	1	1
3	18	3	2	0	0	0
3	19	3	1	0	0	1
3	20	3	2	0	1	2
3	21	3	1	10	0	2
3	22	3	1	12	0	0
3	23	3	2	11	1	1
3	24	3	1	0	1	0
3	25	3	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
4	T1	1	2	0	0	0	1	0
4	T2	2	1	0	0	0	1	0
4	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
4	T4	1	2	0	0	0	1	0
4	T5	1	1	0	0	0	1	0
4	1	1	2	0	0	0	0	0
4	2	1	2	0	0	0	1	0
4	3	1	1	0	0	0	1	0
4	4	1	1	0	0	0	0	0
4	5	1	2	0	0	0	0	0
4	6	1	1	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
4	T8	3	1	0	0	0	1	0
4	T9	3	2	0	0	0	1	0
4	7	3	2	0	0	0	0	0
4	8	3	1	0	0	0	0	0
4	9	3	1	0	0	0	1	0
4	10	3	2	0	0	0	0	0
4	11	3	1	0	0	0	1	0
4	12	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
4	T6	2	1	0	0	0	1	0
4	T7	2	2	0	0	0	1	0
4	13	2	2	0	0	0	0	0
4	14	2	1	0	0	0	1	0
4	15	2	1	0	0	0	0	0
4	16	2	2	0	0	0	1	0
4	17	2	2	0	0	0	1	0
4	18	2	1	0	0	0	0	0
4	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
4	T10	3	2	0	1	2
4	1	3	2	0	1	2
4	2	3	2	9	0	1
4	3	3	1	11	1	2
4	4	3	1	8	1	1
4	5	3	2	0	0	0
4	6	3	2	0	0	2
4	7	3	1	12	0	2
4	8	3	2	0	1	1
4	9	3	1	0	0	1
4	10	3	2	7	0	0
4	11	3	2	10	1	0
4	12	3	1	0	1	0
4	13	1	1	0	0	0
4	14	1	2	3	0	0
4	15	1	2	1	1	1
4	16	1	1	0	0	1
4	17	1	1	0	1	0
4	18	1	2	0	0	2
4	19	1	1	6	0	2
4	20	1	2	5	1	1
4	21	1	1	0	1	2
4	22	1	2	0	1	1
4	23	1	1	4	1	2
4	24	1	1	2	0	1
4	25	1	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
5	T1	1	2	0	0	0	1	0
5	T2	2	1	0	0	0	1	0
5	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
5	T7	2	2	0	0	0	1	0
5	T6	2	1	0	0	0	1	0
5	1	2	2	0	0	0	1	0
5	2	2	2	0	0	0	1	0
5	3	2	1	0	0	0	0	0
5	4	2	2	0	0	0	1	0
5	5	2	1	0	0	0	0	0
5	6	2	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
5	T5	1	1	0	0	0	1	0
5	T4	1	2	0	0	0	1	0
5	7	1	1	0	0	0	1	0
5	8	1	1	0	0	0	1	0
5	9	1	2	0	0	0	0	0
5	10	1	1	0	0	0	0	0
5	11	1	1	0	0	0	1	0
5	12	1	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
5	T8	3	1	0	0	0	1	0
5	T9	3	2	0	0	0	1	0
5	13	3	2	0	0	0	1	0
5	14	3	1	0	0	0	0	0
5	15	3	2	0	0	0	1	0
5	16	3	1	0	0	0	1	0
5	17	3	2	0	0	0	0	0
5	18	3	1	0	0	0	0	0
5	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
5	T10	1	2	0	1	2
5	1	1	2	2	1	1
5	2	1	2	1	0	2
5	3	1	1	0	1	0
5	4	1	2	0	0	1
5	5	1	1	5	0	0
5	6	1	1	0	0	2
5	7	1	2	0	1	1
5	8	1	1	0	0	0
5	9	1	2	6	0	1
5	10	1	2	4	1	0
5	11	1	1	0	1	2
5	12	1	2	3	1	2
5	13	3	2	7	1	2
5	14	3	1	8	0	2
5	15	3	1	0	0	0
5	16	3	2	10	0	0
5	17	3	1	0	1	1
5	18	3	1	9	1	1
5	19	3	2	0	0	2
5	20	3	2	12	0	1
5	21	3	1	0	1	2
5	22	3	1	0	1	0
5	23	3	2	0	0	1
5	24	3	1	11	1	0
5	25	3	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
6	T1	1	2	0	0	0	1	0
6	T2	2	1	0	0	0	1	0
6	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
6	T9	3	2	0	0	0	1	0
6	T8	3	1	0	0	0	1	0
6	1	3	1	0	0	0	0	0
6	2	3	1	0	0	0	1	0
6	3	3	2	0	0	0	1	0
6	4	3	2	0	0	0	0	0
6	5	3	1	0	0	0	1	0
6	6	3	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
6	T6	2	1	0	0	0	1	0
6	T7	2	2	0	0	0	1	0
6	7	2	1	0	0	0	0	0
6	8	2	2	0	0	0	1	0
6	9	2	1	0	0	0	0	0
6	10	2	2	0	0	0	0	0
6	11	2	1	0	0	0	1	0
6	12	2	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
6	T5	1	1	0	0	0	1	0
6	T4	1	2	0	0	0	1	0
6	13	1	1	0	0	0	0	0
6	14	1	1	0	0	0	1	0
6	15	1	2	0	0	0	0	0
6	16	1	1	0	0	0	1	0
6	17	1	2	0	0	0	1	0
6	18	1	2	0	0	0	0	0
6	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24   Experiment #4: Run 25

FM: 0=Absent 1=Present   Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
6	T10	3	2	0	1	2
6	1	3	2	10	1	1
6	2	3	1	0	0	0
6	3	3	2	0	1	2
6	4	3	2	0	0	1
6	5	3	1	9	0	0
6	6	3	2	0	1	0
6	7	3	1	8	1	2
6	8	3	1	7	0	2
6	9	3	2	12	1	0
6	10	3	2	11	0	1
6	11	3	1	0	0	2
6	12	3	2	0	1	1
6	13	1	2	1	1	2
6	14	1	1	0	1	1
6	15	1	1	0	1	2
6	16	1	2	0	0	0
6	17	1	1	6	1	0
6	18	1	2	4	0	1
6	19	1	1	3	0	2
6	20	1	2	0	1	0
6	21	1	1	2	0	0
6	22	1	1	5	1	1
6	23	1	2	0	0	2
6	24	1	1	0	0	1
6	25	1	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
7	T1	1	2	0	0	0	1	0
7	T2	2	1	0	0	0	1	0
7	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
7	T4	1	2	0	0	0	1	0
7	T5	1	1	0	0	0	1	0
7	1	1	2	0	0	0	1	0
7	2	1	1	0	0	0	0	0
7	3	1	2	0	0	0	0	0
7	4	1	1	0	0	0	1	0
7	5	1	2	0	0	0	1	0
7	6	1	1	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
7	T6	2	1	0	0	0	1	0
7	T7	2	2	0	0	0	1	0
7	7	2	1	0	0	0	1	0
7	8	2	2	0	0	0	0	0
7	9	2	1	0	0	0	1	0
7	10	2	1	0	0	0	0	0
7	11	2	2	0	0	0	1	0
7	12	2	1	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
7	T8	3	1	0	0	0	1	0
7	T9	3	2	0	0	0	1	0
7	13	3	1	0	0	0	1	0
7	14	3	2	0	0	0	0	0
7	15	3	2	0	0	0	1	0
7	16	3	1	0	0	0	0	0
7	17	3	2	0	0	0	1	0
7	18	3	2	0	0	0	0	0
7	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
7	T10	1	2	0	1	2
7	1	1	2	2	1	0
7	2	1	2	4	0	1
7	3	1	1	0	0	1
7	4	1	2	0	1	2
7	5	1	1	5	1	1
7	6	1	2	0	1	1
7	7	1	1	6	1	2
7	8	1	1	0	0	2
7	9	1	2	0	0	2
7	10	1	1	3	0	0
7	11	1	2	0	1	0
7	12	1	1	1	0	2
7	13	3	1	0	0	1
7	14	3	2	8	0	0
7	15	3	2	0	0	0
7	16	3	1	0	1	2
7	17	3	2	11	0	2
7	18	3	1	0	1	0
7	19	3	1	12	1	0
7	20	3	2	0	1	1
7	21	3	1	7	0	1
7	22	3	2	10	1	1
7	23	3	1	0	0	0
7	24	3	2	9	1	2
7	25	3	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
8	T1	1	2	0	0	0	1	0
8	T2	2	1	0	0	0	1	0
8	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
8	T7	2	2	0	0	0	1	0
8	T6	2	1	0	0	0	1	0
8	1	2	1	0	0	0	0	0
8	2	2	1	0	0	0	1	0
8	3	2	2	0	0	0	1	0
8	4	2	2	0	0	0	0	0
8	5	2	1	0	0	0	1	0
8	6	2	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
8	T8	3	1	0	0	0	1	0
8	T9	3	2	0	0	0	1	0
8	7	3	2	0	0	0	1	0
8	8	3	1	0	0	0	0	0
8	9	3	2	0	0	0	1	0
8	10	3	1	0	0	0	0	0
8	11	3	2	0	0	0	0	0
8	12	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
8	T5	1	1	0	0	0	1	0
8	T4	1	2	0	0	0	1	0
8	13	1	1	0	0	0	1	0
8	14	1	1	0	0	0	0	0
8	15	1	2	0	0	0	1	0
8	16	1	1	0	0	0	1	0
8	17	1	2	0	0	0	0	0
8	18	1	1	0	0	0	0	0
8	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
8	T10	3	2	0	1	2
8	1	3	2	0	1	0
8	2	3	1	10	1	0
8	3	3	1	0	1	1
8	4	3	2	12	0	2
8	5	3	1	11	0	0
8	6	3	2	0	0	2
8	7	3	2	0	0	1
8	8	3	1	8	0	1
8	9	3	1	0	1	2
8	10	3	2	9	1	1
8	11	3	1	0	0	0
8	12	3	2	7	1	2
8	13	1	1	5	0	2
8	14	1	2	0	1	2
8	15	1	2	6	1	0
8	16	1	1	3	1	2
8	17	1	2	0	0	0
8	18	1	1	4	1	1
8	19	1	2	0	0	1
8	20	1	1	0	1	1
8	21	1	2	0	1	0
8	22	1	2	2	0	0
8	23	1	1	1	0	1
8	24	1	1	0	0	2
8	25	1	2	0	1	2

Experiment #1: Runs 1-18   Experiment #2: Run 19

Run: T = Training   Motion: 0 = Off 1=On   Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
9	T1	1	2	0	0	0	1	0
9	T2	2	1	0	0	0	1	0
9	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
9	T9	3	2	0	0	0	1	0
9	T8	3	1	0	0	0	1	0
9	1	3	1	0	0	0	1	0
9	2	3	2	0	0	0	0	0
9	3	3	2	0	0	0	1	0
9	4	3	1	0	0	0	0	0
9	5	3	2	0	0	0	1	0
9	6	3	1	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
9	T5	1	1	0	0	0	1	0
9	T4	1	2	0	0	0	1	0
9	7	1	1	0	0	0	1	0
9	8	1	2	0	0	0	0	0
9	9	1	1	0	0	0	0	0
9	10	1	2	0	0	0	1	0
9	11	1	1	0	0	0	0	0
9	12	1	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
9	T6	2	1	0	0	0	1	0
9	T7	2	2	0	0	0	1	0
9	13	2	1	0	0	0	1	0
9	14	2	2	0	0	0	0	0
9	15	2	1	0	0	0	1	0
9	16	2	2	0	0	0	1	0
9	17	2	2	0	0	0	0	0
9	18	2	1	0	0	0	0	0
9	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
9	T10	1	2	0	1	2
9	1	1	2	3	0	2
9	2	1	1	0	1	0
9	3	1	2	6	0	1
9	4	1	2	1	1	0
9	5	1	1	0	1	1
9	6	1	2	0	1	2
9	7	1	1	0	0	0
9	8	1	1	2	1	1
9	9	1	2	0	0	2
9	10	1	1	5	1	2
9	11	1	2	4	0	0
9	12	1	2	0	0	1
9	13	3	1	0	1	2
9	14	3	2	0	0	0
9	15	3	1	9	0	1
9	16	3	1	7	0	0
9	17	3	2	0	1	0
9	18	3	2	10	1	2
9	19	3	1	0	0	2
9	20	3	2	11	1	0
9	21	3	1	0	0	1
9	22	3	1	0	1	1
9	23	3	2	8	0	2
9	24	3	1	12	1	1
9	25	3	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
10	T1	1	2	0	0	0	1	0
10	T2	2	1	0	0	0	1	0
10	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
10	T4	1	2	0	0	0	1	0
10	T5	1	1	0	0	0	1	0
10	1	1	1	0	0	0	1	0
10	2	1	2	0	0	0	0	0
10	3	1	1	0	0	0	0	0
10	4	1	2	0	0	0	1	0
10	5	1	2	0	0	0	0	0
10	6	1	1	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
10	T8	3	1	0	0	0	1	0
10	T9	3	2	0	0	0	1	0
10	7	3	1	0	0	0	1	0
10	8	3	2	0	0	0	0	0
10	9	3	1	0	0	0	1	0
10	10	3	2	0	0	0	1	0
10	11	3	2	0	0	0	0	0
10	12	3	1	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
10	T6	2	1	0	0	0	1	0
10	T7	2	2	0	0	0	1	0
10	13	2	1	0	0	0	1	0
10	14	2	2	0	0	0	0	0
10	15	2	1	0	0	0	0	0
10	16	2	2	0	0	0	1	0
10	17	2	2	0	0	0	1	0
10	18	2	1	0	0	0	0	0
10	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
10	T10	3	2	0	1	2
10	1	3	1	0	1	1
10	2	3	2	0	0	1
10	3	3	1	11	1	1
10	4	3	1	8	1	0
10	5	3	2	0	1	2
10	6	3	1	7	0	2
10	7	3	1	9	0	0
10	8	3	2	0	0	0
10	9	3	1	10	0	1
10	10	3	2	12	1	2
10	11	3	1	0	1	0
10	12	3	2	0	0	2
10	13	1	2	0	0	2
10	14	1	1	0	0	0
10	15	1	2	5	1	0
10	16	1	1	0	0	1
10	17	1	2	4	1	2
10	18	1	2	0	1	2
10	19	1	1	0	1	1
10	20	1	1	6	1	1
10	21	1	2	2	0	2
10	22	1	1	3	0	1
10	23	1	2	0	1	0
10	24	1	2	1	0	0
10	25	1	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
11	T1	1	2	0	0	0	1	0
11	T2	2	1	0	0	0	1	0
11	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
11	T7	2	2	0	0	0	1	0
11	T6	2	1	0	0	0	1	0
11	1	2	2	0	0	0	1	0
11	2	2	1	0	0	0	1	0
11	3	2	2	0	0	0	0	0
11	4	2	1	0	0	0	0	0
11	5	2	2	0	0	0	1	0
11	6	2	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
11	T5	1	1	0	0	0	1	0
11	T4	1	2	0	0	0	1	0
11	7	1	1	0	0	0	1	0
11	8	1	1	0	0	0	0	0
11	9	1	2	0	0	0	1	0
11	10	1	1	0	0	0	0	0
11	11	1	2	0	0	0	1	0
11	12	1	2	0	0	0	0	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
11	T8	3	1	0	0	0	1	0
11	T9	3	2	0	0	0	1	0
11	13	3	1	0	0	0	1	0
11	14	3	1	0	0	0	0	0
11	15	3	2	0	0	0	0	0
11	16	3	1	0	0	0	1	0
11	17	3	2	0	0	0	1	0
11	18	3	1	0	0	0	0	0
11	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
11	T10	1	2	0	1	2
11	1	1	1	6	0	2
11	2	1	2	0	0	1
11	3	1	2	0	0	2
11	4	1	1	5	0	0
11	5	1	2	0	1	1
11	6	1	2	3	1	1
11	7	1	1	1	1	2
11	8	1	2	0	0	0
11	9	1	1	0	1	2
11	10	1	2	0	1	0
11	11	1	1	2	0	1
11	12	1	1	4	1	0
11	13	3	2	0	1	0
11	14	3	1	12	0	0
11	15	3	1	0	0	1
11	16	3	2	11	0	1
11	17	3	2	7	1	1
11	18	3	1	8	1	2
11	19	3	2	10	0	2
11	20	3	1	0	1	2
11	21	3	2	0	1	1
11	22	3	2	9	1	0
11	23	3	1	0	0	0
11	24	3	1	0	0	2
11	25	3	2	0	1	2

Experiment #1: Runs 1-18 Experiment #2: Run 19

Run: T = Training Motion: 0 = Off 1=On Visual: 0 = IMC 1= VMC

Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
12	T1	1	2	0	0	0	1	0
12	T2	2	1	0	0	0	1	0
12	T3	3	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
12	T9	3	2	0	0	0	1	0
12	T8	3	1	0	0	0	1	0
12	1	3	2	0	0	0	0	0
12	2	3	1	0	0	0	0	0
12	3	3	1	0	0	0	1	0
12	4	3	2	0	0	0	0	0
12	5	3	1	0	0	0	1	0
12	6	3	1	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
12	T6	2	1	0	0	0	1	0
12	T7	2	2	0	0	0	1	0
12	7	2	2	0	0	0	0	0
12	8	2	1	0	0	0	0	0
12	9	2	2	0	0	0	1	0
12	10	2	2	0	0	0	1	0
12	11	2	1	0	0	0	0	0
12	12	2	2	0	0	0	1	0
Pilot	RUN	FCS	Tunnel	fault	FM	Alert	motion	visual
12	T5	1	1	0	0	0	1	0
12	T4	1	2	0	0	0	1	0
12	13	1	1	0	0	0	0	0
12	14	1	2	0	0	0	0	0
12	15	1	1	0	0	0	1	0
12	16	1	2	0	0	0	0	0
12	17	1	2	0	0	0	1	0
12	18	1	1	0	0	0	1	0
12	19	3	1	?	0	0	1	0

Experiment #3: Runs 1-24 Experiment #4: Run 25

FM: 0=Absent 1=Present Alert: 0=Absent 1=One Phase 2=Two Phase

Pilot	RUN	FCS	Tunnel	Surp	FM	Alert
12	T10	3	2	0	1	2
12	1	3	2	0	1	1
12	2	3	1	7	1	0
12	3	3	1	9	0	2
12	4	3	2	0	1	2
12	5	3	1	0	1	0
12	6	3	2	0	0	0
12	7	3	1	0	0	1
12	8	3	1	12	0	1
12	9	3	2	0	0	2
12	10	3	1	11	1	2
12	11	3	1	10	0	0
12	12	3	2	8	1	1
12	13	1	1	0	0	1
12	14	1	2	3	1	0
12	15	1	1	1	1	1
12	16	1	2	6	0	0
12	17	1	2	0	1	0
12	18	1	1	0	1	2
12	19	1	2	2	1	2
12	20	1	2	0	0	0
12	21	1	1	4	0	2
12	22	1	2	0	0	2
12	23	1	1	0	1	1
12	24	1	2	5	0	1
12	25	1	2	0	1	2

Appendix D – Questionnaires

Experiment #1 FCS Block Questionnaire

With this FCS, it was easy to fly the tunnel with an adequate level of accuracy.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

What display features did you rely on the most?

Are there any features that you would like to see in this display?

How would you describe your strategy in flying with this FCS?

The simulation felt accurate and realistic.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

NASA TLX Ratings Questionnaire

Pilot: ____ Run No. T1 T2 T3 1 2 3 4 5 6 7 8 9 10 11 12 13 15 16 17 18 TLX Morning Experiment

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

TLX

Experiment #2 Questionnaire

Last Run (Fault)

What do you think happened?

How certain are you about your previous answer?

Just Guessing		Unsure		Not very Sure		Almost Sure		Very Sure

What was the first thing that made you think something was wrong?

What other things showed there was a problem?

How did you diagnose or confirm the problem?

General Questions

1. Overall, the simulator was realistic.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Please comment on suggest modifications or additions to the experimental setup:

2. The aircraft dynamics and controls were accurate and realistic.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

3. The different motion models had an effect in your flying quality and control behavior.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

Experiment #3 and #4 Post Run Questionnaire

What do you think happened?

How certain are you about your previous answer?

Just Guessing		Unsure		Not very Sure		Almost Sure		Very Sure

What was your first indication of malfunction?

What did you look at next to verify the malfunction?

How did you confirm the malfunction?

The alert system helped to detect the fault.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

The Fault Meter helped to detect the fault.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

End of Experiments Questionnaire

The alerting system was useful.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

How did you use the alerting system? Did you develop any scanning strategies?

The Fault Meter was useful.

Strongly Disagree	Highly disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Highly Agree	Strongly Agree

Comments:

How did you use the Fault Meter? Did you develop any scanning strategies?

Could extra information have been useful? What information and when?

Do you have any comments or suggestions to improve the alerting system or Fault Meter?

Have you ever experienced in actual operations, problems that impacted the flying qualities of the aircraft? (Severe icing, hydraulic problems, FCS problems, etc)

Name and age:

Total Flight Hours:

Current Aircraft type and hours:

Captain or F/O:

Initial pilot training: Civil or Military:

Additional post high-school Technical or University degree, not including pilot training:

Previous experience: Aircraft – Hours

Total Flight Hours in Glass Cockpit:

Previous experience that may be relevant:
(Tunnel in the Sky displays, relevant experiments, flight testing, Fly by Wire, etc)

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