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VALIDATION OF ADVANCED FLIGHT SIMULATORS FOR HUMAN-FACTORS OPERATIONAL EVALUATION AND TRAINING PROGRAMS

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CHAPTER I

USE OF ADVANCED FLIGHT SIMULATORS FOR HUMAN-FACTORS OPERATIONAL EVALUATION AND TRAINING PROGRAMS

INTRODUCTION

The increased speed with which new technologies are being introduced into the modern aviation operational environment has made it necessary to find new ways of evaluating certification, human-factors, operational, procurement and safety issues. We no longer have the luxury of an extended development program, followed by an evolutionary period of product maturation into more complex forms, with an extended useful life. Modern technology delivers fully formed products to the marketplace with rapid wide distribution and, in many cases, a limited operating life due to forced obsolescence caused by new advances, designs, and technologies. Aviation has always been a technology driver, and this has not changed, so the introduction of new communication, navigation, surveillance, and display technology is moving forward at a rapid pace. Aviation is also a very competitive business, and maximum benefit comes from the early implementation of innovative new products and applications. The emergence of Airbus as a viable competitor has extended this competition to the manufacturing arena. Airbus designs use the "fly-by-wire" (electronic) control as opposed to the more traditional designs used by the major US manufacturers. Being a relative newcomer to the scene (approximately 30 years), they have been able to start with a clean slate in so far as design and facilities are concerned, so they have been able to capitalize on the benefits of new technology on the flight deck and in the factory.

While some time elements of product life cycle have changed, critical requirements for validating safety, reliability, and system integrity in civil aviation have not. The process of operationally integrating a new technology into an existing, highly complex, costly, and potentially hazardous domain, such as the NAS, airports and aircraft cockpits, demands an exhaustive evaluation of their effects on the existing system, while maintaining safety and performance standards, support logistics, and affordability. To shorten the time required for equipment and procedural development, and operational implementation, the use of simulation has grown in importance. For simulators to be accepted for this application, it is necessary to mandate high-fidelity performance levels that can be validated by objective verification testing. While training requirements have established practical performance levels, it is necessary to validate the fidelity of other on-board systems that will be critical elements of an evaluation program.

Databases used to model advanced flight simulators can cost as much as $1 million, or more, so their use is restricted. Most laboratory simulators, even those flaunted as medium fidelity, lack the actual databases, and often use simulated aircraft instruments and controls that are of questionable accuracy. However, these devices can be useful, and often the mathematical calculations produced are highly accurate for limited purposes.

A normal sequence for applying the different types of simulation would be the use of numerical or mathematical modeling, part task simulation, followed by an unmanned integrated model with a high level of accuracy, to a human-in-the-loop flight training device, or cockpit procedural trainer, with part of the systems operating at a high fidelity, to, finally, a human-in-the-loop advanced full flight simulator approved under the advanced approval program with an extremely high level of fidelity. Because of cost, lack of knowledge, convenience, and limited access to advanced simulators there is a tendency to try to substitute the lower level devices for the simulators. This must be avoided. To be used to develop definitive results that accurately reflect the pilot's and the system's performance you must use the advanced simulators. Any program should, if at all possible, be finally tested in an actual aircraft as a final step.

SCOPE

This document is meant to deal with the process of validating advanced approved flight simulators as described in AC 120-40 for human-factors, procedural development, and operational evaluation programs. There are other levels of simulation available, and all have an appropriate application in the process of modeling, evaluating, and analyzing a procedure or an operational application. The term 'Approved" refers to the FAA's process of formally certifying, or approving, simulators for use in approved training programs. Approved simulators are all based on the use of actual aircraft databases derived from flight test data and qualified pilot-operators to ensure a high fidelity operating environment.

BACKGROUND - USES OF MODERN FLIGHT SIMULATORS

Flight Crew Training

The most widespread use of modern flight simulators is for flight crew training. The reason for this is the lower cost, safety for personnel and equipment, and more efficient use of resources. All of the major commercial air carriers have extensive simulator complexes, such as those of American at DFW, Delta in Atlanta, Alaska in Seattle and United in Denver. New training simulators that meet FAA Level C and D approval criteria can cost $15 million or more. Use of Level D devices can enable virtually a zero aircraft flight time transition for experienced pilots between aircraft types.

Operating large aircraft simulators costs approximately 10%, or less, than what it costs to operate an aircraft of the same type per hour, you don't endanger personnel and equipment, and the actual aircraft stay in revenue service. An added advantage is that the daily operating service time for simulators can be twice that of aircraft, up to 18 to 20 hours per day. In addition to the bottom line advantages, you get much more efficient transfer of learning in a simulator than in the actual aircraft. The possible faults and abnormal operational exercises are virtually unlimited, and it is possible to train to proficiency to accommodate the differing needs of different students.

Research and Operational Evaluation Programs

Simulators have been used for research for years by a number of organizations for human-factors studies, procedural development, equipment development, accident investigation, and design work. Some of the best known, of course, are NASA and the FAA, but the airlines now operate several hundred approved simulators all over the world. The aircraft manufacturers also build prototype simulators for new aircraft types for early crew training, and to support aircraft design activities. Many colleges and universities also maintain research devices in their laboratories, such as those at the Arizona State Williams Campus, Embry Riddle, Georgia Tech and others.

A more recent development has been the use of FAA approved training simulators for operational evaluation and test programs. Because of the constraints imposed on approved training simulators by the certifying officials, most operators are reluctant to do extensive changes, or modifications, to the equipment. We have learned in recent years that with the increased reliance on software based systems, as opposed to older hardware based architecture, however, that you can indeed make changes and modify the simulators, within these constraints, for evaluation programs, but you must provide provisions to return to the approved training software and hardware configurations when needed. Since most of the new systems are software based, you can load training software programs and return to training status in a short time. Working within the approval constraints, most training simulators can be returned to an approved status within 30 minutes, if changes are software only, but can require up to four hours or more if hardware must be replaced and checked out. Because of the approval requirements for advanced simulators used in FAA approved training programs, it is often fairly simple to validate simulator operations for a specific program.

Increased computer capacity and speed, coupled with more disk storage, and the capability to network simulators for data collection and joint exercises have further increased capabilities. There are research situations, of course, where it is necessary to keep changes or modifications in place for extended periods. In this case, approved training simulators may not be appropriate to use.

THE PROBLEM - FINDING LEVERAGED SOLUTIONS FOR COMPLEX PROBLEMS

The design, development and implementation of modern avionics systems is a costly and complicated process. It can take years before a new idea is selected for development and implementation. Once selected however, implementation can take place much quicker than could have been done a few years ago. Development of modern avionics systems is outrunning our ability to certify and deploy the new technology. Often a new technology, or application, is on the threshold even as we finish work on the predecessor system. Government officials that certify and approve the new systems are bound by regulation and federal law to ensure that any system approved for use meets stringent standards for reliability, operational safety, and accuracy. These standards cannot be drastically changed without significant effects on aviation safety.

Applying modern technology in a careful and scientific manner to the certification process itself can speed up the approval and certification process by incorporating human-factors evaluations in the early stages of development using subject pilots qualified for the intended use. Advanced flight simulators are currently used for complete training of airline pilots with little, or no, aircraft flight time required. Modern simulators offer advanced high fidelity performance, using actual aircraft avionics hardware, for aircraft aerodynamics and on-board systems. The Federal Aviation Administration Flight Operations Simulation Laboratory in Oklahoma City conducts a number of human-factors and equipment studies every year on critical safety issues that provide definitive results, in short time periods, to support installation of new avionics equipment, National Transportation Safety Board (NTSB) inquiries, procedures development, and airport infrastructure design decisions. Most of these evaluations result in decisions much quicker than conventional methods, and provide human-factors reviews of the equipment, or process, for the designers and approving officials much sooner than conventional processes. All these efforts require adequate validation and verification testing of the simulators and procedures.

Many new equipment manufacturers, or those not familiar with commercial aviation requirements, do not understand the FAA’s certification and approval processes on new avionics equipment. This can lead to extensive delays and redesign efforts before a system or procedure is finally approved and placed in revenue service. Increasingly, the design engineers have little or no flight background, and have no, or limited, access to professional pilots during the design process.

The software and hardware designers become totally familiar with a product as it is developed, and are dismayed when the end users, the pilots, complain about poor design, or functionality, and the FAA starts placing extensive testing and evaluation requirements on the products for which the manufacturer, or customer, are often ill prepared. Pilots often do not understand, or are not informed, of design limitations imposed for various reasons, and may have expectations based on their own mental models of what to expect. Operators may purchase new technology without fully understanding the risks and costs of introducing and maintaining the new system in their fleet operations.

USING ADVANCED SIMULATION EFFECTIVELY

Modern flight simulators with proper validation for the intended purpose can provide an effective tool for facilitating the early involvement of everyone that will eventually have a stake in approving and using new equipment or procedures. This requires "thinking out of the box" since most simulators are built specifically for training applications. In most cases, the limitations on what can be accomplished are self-imposed, either through lack of knowledge and understanding by the technical support staff, or a strict management focus on using devices only for training.

The normal process for bringing a new piece of equipment into the cockpit involves lengthy development using extensive laboratory evaluations and testing, then time for flight testing, gaining certification approval from the FAA, and, finally, operational approval. The use of simulators can shorten the process after a piece of equipment leaves the design laboratory; however, airworthiness and environmental testing cannot be compromised for safety reasons. A system can be installed in an advanced flight simulator where professional pilots, designers, and certifying and approving officials can evaluate and use the new equipment under realistic operational conditions with confidence that observed performance will mirror the actual aircraft installation and operation.

The steps discussed above will still have to be completed, but now the stakeholders have prior knowledge and experience with equipment, and the manufacturer is already aware of most human-factors and operational problems. This allows those problems to be corrected before entering or during the certification process. Realistic operational evaluations can be conducted on new avionics and display systems, modification to existing systems, proposed operational procedures, accident investigations, and weather related issues in a controlled scientific manner that will yield valid results.

There is a constant, on-going effort to streamline the regulatory approval process without jeopardizing the ever-present need to improve operational safety. Because human operators are involved, in fact, required, human-factors concerns must be addressed at the design, manufacturing, installation and operational phases of the process. Any method used for evaluating the resulting system must be highly realistic compared to the final utilization, must be cost competitive, and must provide timely and accurate results.

STATEMENT OF HYPOTHESIS

Modern flight simulators offer an approach that meets all the above requirements. The only comparable method is to use actual aircraft, which is not practical due to safety, costs, and logistical constraints. Using the FAA's advanced simulator approval process as a discriminator to select a test bed provides the most cost effective, timely, and accurate equipment in which to conduct the evaluations. The approval requirements imposed by the program ensure a high fidelity, realistic, and operationally accurate environment. Modern simulators can be modified to accept new systems with relative ease, and pilot operators can operate in an environment identical to the final installation.

Data collection and analysis are relatively easy to implement with modern computers and interfacing techniques. The test environment is stable, controllable, repeatable, and adaptable. Simulators are available twenty-four hours a day, seven days a week, for use, and pilot test subjects are normally not too difficult to find, especially in an evaluation that has safety implications, or is introducing new technology into the cockpit. Simulators are costly to operate, but are much lower in cost than actual aircraft, and much more readily available.

CAPABILITIES

The use of advanced simulators for conducting human-factors and operational evaluation programs has the potential to save considerable time and cost, and reduce the redundancy present in most currently used approaches. There is no better way to involve the actual end-user in the development process, and to evaluate the design for potential human-factors flaws, than to let the system be evaluated under actual operational conditions. Any new equipment that requires pilot interpretation or operation must be evaluated with live pilots in the process. The use of non-piloted evaluation tools, especially Mote Carlo type processes, without actual pilots in the loop cannot provide valid results for final operational implementation.

Most commercial pilots have spent their careers having to maintain proficiency, and having to adapt to new systems and procedures in a very dynamic environment. Anytime they fail to meet requirements, either mentally or physically; their career is at jeopardy. They are also selected for their intelligence, leadership and personality traits, which means that they are willing to provide candid observations and opinions that are well founded.

Using advanced simulators with qualified pilots as test subjects can provide a more efficient manner of developing new products and procedures, and can deliver a better, more complete, system to the users. Regulatory officials will also be better judges of the product based on their early and continued involvement in the development process. Simulators can also offer evaluation under adverse conditions that one could never do in the actual aircraft, such as windshear, wake vortices, compound systems failures, and fault introduction. It is also possible to evaluate the systems impact on the overall cockpit environment, and any integration issues encountered.

Based on the information available from cockpit voice recorders, it is possible to replicate aircraft accidents very accurately. The failures, weather conditions, crew procedures and resulting aircraft performance can be duplicated with great accuracy. Using distributed simulation, multiple simulators can be connected to reconstruct, or evaluate, multiple aircraft operations and procedures. Including the pilots and regulators at an early stage aids in building a consensus prior to actual system deployment.

LIMITATIONS

Try as we may, using the latest in technology and procedures, we are still operating in a "simulated" environment. While this offers many benefits, such as cost, time, access and manipulation, it is still a manufactured environment. This offers substantial challenges to those modeling an operational environment. While hardware systems are generally well defined, especially in the aviation or military environment, you still have those pesky humans to deal with. While we do our best to 'dehumanize' their behavior through training and the use structured environments, they still can make decisions on their own and those decisions often lead to unpredictable results. We continually work to mitigate this annoying human trait through automation and design limitations, it continues to surface.

One approach, and the one we use, is to try to develop the highest fidelity models possible for equipment and the elements of the operating environment, and allow the humans in the process to function as they would in the 'real world'. The results of this are then used to improve training, procedures or equipment design that will help recognize behavioral patterns that can lead to problems, or mitigate the results. Humans will make mistakes, and that will never change, but what we can do is design error tolerant systems that can compensate for human mistakes. Given sufficient time and resources, our models will continue to evolve and improve to near perfection, but it is still a simulated environment and we should always view it that way and recognize the realistic limitations that can exist. While it may be fairly easy to model a hardware component, modeling dynamic entities, such as humans or weather, will always carry some level of risk. Recognizing that limitations do exist ensures that we will always strive to improve modeling and fidelity to enhance the quality of simulation activities.

RISKS ASSOCIATED WITH THE USE OF ADVANCED FLIGHT SIMULATORS

The risks associated with using advanced flight simulators to conduct operational evaluation and test programs are typically controllable. The include the use of low-end equipment, using simulated instrument or other avionics equipment, poor test plan, use of unqualified test subjects and not allowing sufficient time to properly complete the work.

As we mentioned before, there are several levels of simulators available that are suitable for addressing various fidelity requirements. The danger is to try to force low-end equipment to perform in ways they weren't designed to do. If such devices are used, then the specific systems that are critical to the tests being conducted should be rigorously validated prior to the tests.

Current trends in advanced simulators have allowed the use of 'simulated' displays and other avionics in place of actual aircraft equipment. There are several reasons for this, but cost is the biggest driver. With the conversion to electronic display system, it is much cheaper to use non-aircraft hardware and develop your own software.

There are generally two approaches to this. One is a complete simulation of the systems including hardware and software. The other, on the most preferred, is rehosting. Rehosting allows the use of non-aircraft hardware, avoiding the cost of airworthy equipment, but still use actual aircraft software. There are many advantages to this, including being able to keep simulator equipment current with aircraft hardware levels and easier access to the equipment for modification. Rehosting preserves the integrity of the actual systems while allowing substantial cost savings.

Development of poor test plans usually reflects the inexperience of those conducting the tests, or trying to apply a 'one size fits all' approach. The test plan should very carefully and explicitly address the issues being addressed. Generally, short-cuts don't work.

Test subjects should be representative of those generally expected to use the systems being tested. Efforts to use inexperienced pilots generally will provide poor results, and can call the credibility of the entire test program into question. Examples are using general aviation pilots or college students as test subjects for issues related to commercial aircraft just because they are available, or cost less, can yields inaccurate results.

You must allow sufficient time to complete the study. This is a chronic difficulty and normally driven by people that either doesn't understand the concepts of risk analysis or have little interest in the success of a program. Simulator time is a valued commodity, and while scheduling can be difficult, you should always strive to get sufficient time to conduct a study properly. Obtaining enough data to show statistical significance is difficult in real-time human-in-the-loop studies.

DEFINITIONS AND ACRONYMS

For purposes of this document we will use the definition used by the FAA for airplane simulator. That is: an airplane simulator is a full-sized replica of a specific type or make, model, and series of airplane cockpit, including the assemblage of equipment and computer programs necessary to represent the airplane in ground and flight operations, a visual system providing an out-of-the-cockpit view, and a force cueing system which provides cues at least equivalent to that of a three degrees-of-freedom motion system; and is in compliance with the minimum standards of a Level A simulator.[1] An Approval Test Guide (ATG) is a document prepared to validate that the performance and handling qualities of a simulator match those of the aircraft within the specified limits and tolerances of the AC. Convertible simulators are simulators in which hardware and software can be changed to match the characteristics of another model aircraft. Details of the requirements for the different levels of approved simulators are contained in Chapter II.

Anytime you deal with aviation topics there are a number of acronyms used. Following is a list of the ones used in this document:

AC	Advisory Circular
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ATC	air traffic control
ATIS	Automatic terminal information service
CRM	Crew resource management
DH	decision height
DME	distance measuring equipment
EFIS	electronic flight instrument system
EGPWS	Enhanced ground proximity warning system
FAA	Federal Aviation Administration
FMS	Flight Management System
GPWS	Ground proximity warning system
GS	Glide slope
HCI	Human-computer interaction
IFR	Instrument flight rules
IM	inner marker

[1] AC 120-40B - Airplane Simulator Qualification, Department of Transportation, Federal Aviation Administration, 1993.

MAP	missed approach point
MDA	minimum descent altitude
MM	Middle marker
NAVAID	navigational aid
ND	navigation display
NDB	none-directional beacon
NM	nautical miles
NOAA	National Oceanic and Atmospheric Administration
SAE	Society of Automotive Engineers
STAR	standard terminal arrival route
TACAN	tactical air navigation
VFR	Visual flight rules
VOR	very high frequency omnidirectional range
VORTAC	co-located VOR and TACAN NAVAIDs

CHAPTER II

REVIEW OF V&V RELATED REFERENCES AND BACKGROUND MATERIALS

To understand the nature of conducting operational evaluation programs, it is necessary to understand the operating environment of commercial pilots. This means understanding the role and capabilities of the pilot, human-factors considerations, the use of automation in aircraft, and understanding the operation of the National Airspace System (NAS).

Most accidents are still attributed to human error, and usually the pilot becomes the human that is identified as making the error. In truth, the pilot is only one element in a highly complex and demanding operational environment. The aircraft equipment designers, the aircraft manufacturers, the operating environment, the infrastructure, the regulatory structure, the professional culture of the crew, and the culture of the operating organization all contribute to the overall environment. When we speak of human error, we must consider whether it is the pilot, the designer that designed faulty or overly complex equipment, or failed to fully understand the operational environment in which it would be used or the airline manufacturer that selected a suite of instruments based strictly on cost factors.

Every accident is a chain of events. Intervention at any stage can prevent, or change, the nature of an accident. The Flight Safety Foundation Report on Approach and Landing Accidents (1999) shows an average of 6.9 crew factors for each accident. The pilot was flying in most cases examined, and in all cases the crewmembers had undergone extensive training, but failed to recognize and mitigate the unfolding disaster.

The first reaction to a need to improve aviation safety is to try to train the errors out of the human operators. The second reaction, when the first fails to completely solve the perceived problem, is to try to automate the human out of the loop. Neither approach will work by itself. We must find ways to improve training, of course, but the human can only be trained to a point. We are already selecting the most intelligent, stable, and physically fit individuals that can be identified for pilots. There is no profession that has more stringent, and on-going, performance requirements than professional pilots that work in the air carrier industry. And we cannot remove the human operator from the cockpit, at least not yet. We still cannot come close to matching the versatility, judgment, and cognitive abilities of the human across all activities, especially in unorthodox or unexpected situations.

The answer lies somewhere in the middle, with contributions from all these factors. We must continue to select and maintain flight crewmembers from the most capable individuals and train those selected to proficiency, but we must also find ways to design better aircraft systems. Human-factors design considerations must be evaluated in all certification, operational approval, and procedural implementations. Apply automation to those areas where humans are most vulnerable, and let the human operators continue to do what they do best.

With the proliferation of new technology, the ability to data link virtually any, and all, information available in the national airspace system to the aircraft cockpit is here. We must continue to closely evaluate all new systems to the same rigorous standards as previously used, but strengthen our standards for human-factors design requirements. Not every new innovation should go onto the flight deck, and not every effort to stack more airplanes into already crowded airspace should be implemented. We must continue to evaluate proposed systems for good human-factors design, and consider all applications with the pilot's job performance requirements in mind. Human centered design, a valid need, a verified improvement in operations efficiency or safety, and valid economic benefits must be considered in all future systems approvals.

HISTORICAL BACKGROUND

The National Airspace System (NAS) was built to operate within a well-defined airspace and terminal infrastructure using equipment, procedures and policies designed to provide maximum efficiency within stringent safety constraints. Any change to any component within the system will invariably force changes elsewhere in the system to accommodate those changes. Free Flight[2] and other initiatives offer substantial changes, but whatever develops from these initiatives, the developers will have to consider the existing infrastructure because of costs, attrition of existing facilities, and public safety.

The FAA and the commercial aviation industry have promoted increased usage of advanced real-time flight simulators to meet the requirements for the majority of commercial pilot training programs. With the establishment of the Advanced Simulator Approval Program in the early 1980's, described in Advisory Circular 120-40B (FAA, 1993), improvements in the operational fidelity of flight simulators has steadily improved. The program covers Levels A through Level D simulators, but this discussion will focus on the Level C and D equipment. Along with the improvements have come increases in the capability of Level C and Level D simulators to support operational evaluations of numerous aviation related issues including pilot performance, avionics, and human-factors issues at a much lower cost, and in a more timely manner, than could be done previously. Driven by safety and cost issues, and the need for more timely results, recognition of these developing capabilities has led to increased utilization of commercial flight simulators for operational evaluation programs to obtain data to support regulatory development and operational evaluations of new technologies.

In the past, issues identified by the FAA and/or the civil aviation industry were generated by the need to consider specific regulatory changes, or the need to implement new technology into the National Airspace System (NAS). With the increased capabilities of commercial simulators, it has been possible to effectively evaluate a number of issues, including those related to pilot performance, pilot aging, advanced avionics, runway and taxiway design criteria, proposed airport lighting and signage, head-up display characteristics, flight automation, navigation system performance, weather phenomena, low visibility weather criteria, wake vortices, cockpit display of traffic information, and air traffic control criteria (Dillard, 1998).

In all of these cases it has been necessary to validate elements of equipment used to conduct an evaluation program. However, to provide the necessary fidelity, particularly for pilot and system interface evaluations that have been used for establishing criteria or approval of new systems, the level of simulation has most generally required an FAA Approved Level C or Level D simulation device.

Simulators and other facilities at remote sites can now be linked to simulator facilities at different sites to accomplish specific evaluation objectives. We can also connect and dynamically exchange data from differing operational domains, such as between a simulator flight deck and an air traffic control center. We have even integrated simulator and real aircraft data for display on air traffic control displays for examination of issues such as those associated with air traffic control or capacity at specific airports. This arrangement, referred to here as a

[2] Free Flight is the concept whereby the pilot will be able to navigate and operate the aircraft through all phases of flight with a minimum of live contact with the ground, including air traffic control.

simulator network, allows extended flexibility in obtaining participation from the aviation industry to assist in the resolution of issues of common interest.

With the scope and number of operational and aircraft-specific evaluation needs expanding, and becoming more commonplace, the need to expand the evaluation efforts undertaken to include the use of simulators at other sites has also increased. As a result, the capabilities have been developed to conduct distributed, real-time simulation studies using a number of sites simultaneously, and provide real-time data to other locations for analysis and implementation. Where this involves remote site simulators, any modification to be used by theses simulators should generally be limited to software changes to facilitate data output, data recording, radio aids implementation and generation of control pages for the instructors station. There are cases where simulator hardware modification may be needed and, if so, it must be done on test specific software modules so as not to affect simulator approval. Networking to remote sites also introduces a number of validation issues concerning network latency, data integrity and differing levels of fidelity for different devices.

HUMAN-FACTORS

In a simpler time, systems design and integration inherently considered human-factors considerations as part of the basic design. The primary driver for this was economic. If a product was not easily used, or required extensive adaptation for the human operator, it would not sell. Aviation products were no exception.

The human operator has evolved to recognize and cope with a relatively low speed, simple, linear, and mostly predictable environment. Piloting modern aircraft is a complex process involving adaptations of the senses to myriad colors, situational displays, communication and navigation equipment controls, and performing complicated aircraft control and management tasks. The skies are steadily becoming more crowded, with aircraft forced ever closer together. Pilot workload has multiplied with the addition of new technology and procedures. This has created an environment that is no longer simple, low speed, linear or predictable, even though human behavior and performance has not changed. The increased use of automation in air traffic control and on the flight deck have complicated the human-factors issues involved.

Modern aviation involves many players. The commercial and general aviation pilots and flight crews are the most obvious, but there are also air traffic controllers, mechanics, regulatory agencies, aviation management groups to recognize, and more recently, security. All have vital roles in the operation of today's aircraft. The nature of aviating, communicating and navigating an aircraft from one point to another is largely unchanged. But the process and infrastructure have changed immensely. Demands for efficiency, increased productivity, more economical operations, and competitive advantage, while maintaining and improving safety, have created a stressful environment further complicated by the flood of new technology onto the modern flight deck.

While there have always been some human-factors considerations in designing and building aircraft, such as pilot reach, strength and comfort, the applications of serious human-factors, or ergonomic, design concepts did not start until the late 1940's, a mere 55 years ago. Many of the problems recognized during the Second World War, such as pilot fatigue, pilot error and poorly designed cockpit equipment, began to be addressed. At one point in World War II, the chances of surviving 30 flight missions was less than 10% (Edwards, 1999).

Aviation human-factors considerations have their roots in earlier similar efforts in the areas of factory production, education, and equipment design. Prior to World War II there had not been enough activity in aviation to reveal human-factors problems. Early efforts to identify the reason for neurotic symptoms in pilots found that they were generally caused by (1) flying stress, (2) non-flying stress, such as domestic, and marital problems, and (3) mostly by a person's predisposition, or low resistance, to stress (Symonds and Williams, 1943). Considerable emphasis was then placed on methods of selection for pilot candidates. Efforts were also made to limit the combat tours of pilots, and to try and identify the early development of neuroses (Reid, 1979). By the end of the war, problems were greatly diminished.

In the context of most aviation issues, use of the terms ergonomics and human-factors are interchangeable. Human-factors is problem oriented, rather than discipline centered, and is aimed at the practical solution to problems, not just hypothesis. No arrangement of hardware, software, and liveware[3] exists in a vacuum, but operates in the context of an environment made up of physical, economic, political and social factors. This relationship is sometimes referred to as the SHEL[4] model (Edwards, 1972). A total system normally contains several layers of these components. Any change to any component within the system may require adjustment of other components. One link, the liveware to liveware, has been emphasized in recent years with the industry interest in crew resource management training. The human-human link is the one most prone to failure, and one of the most difficult to repair.

Aircraft display and avionics systems are designed around a very specific environment. Anything that appears on the flight deck must “buy” its way onto there through improved efficiency, safety or profitability. Economic payback from the larger airlines is now three to five years, and sometimes less. There is limited real estate[5] available to install equipment, especially displays. The pilot and aircraft are operating at near their performance limits in critical situations, so human cognitive behavior becomes a limiting factor. There are a number of definitions for human-factors, but I will just list a couple here to put the topic in context.

> Human-Factors: A multidisciplinary field devoted to optimizing human performance and reducing human error. It incorporates the methods and principles of the behavioral and social sciences., engineering, and physiology. Human factors is the applied science which studies people working together in concert with machines. Human factors embraces variables that influence individual performance and variables that influence team or crew performance. It is recognized that inadequate system design or inadequate operator training can contribute to individual human error that leads to system performance degradation (FAA, AC 120 51B, 1995).

And:

> Human-Factors: The technology concerned with optimizing the relationships between people and their activities by the systematic application of the human sciences, integrated within the framework of system engineering (Edwards, 1988).

I generally prefer the first definition, the term “technology” doesn’t make sense to me in the content of human-factors, but the second raises the concept that the cockpit, and everything in it, including the human operator, is a system, and that to introduce or modify anything in the domain will affect every other component in it. It is critical that a systems approach to design be taken when changing any component on the flight deck. That means gaining a thorough

[3] Liveware is a term, used by some, for the human in the loop.
[4] The term SHEL stands for software, hardware, the operational environment, and liveware.
[5] Real estate refers to panel space in the cockpit.

understanding of the environment, and the function of all existing elements, including crewmembers, before introducing changes.

Engineers are the largest group of practitioners of systems theory, followed by the operations researchers (Sheridan, 1988). Unfortunately, these groups can be the least schooled and sympathetic to the human sciences, preferring the much more defined and controlled domains of their technical fields. Anytime you introduce a human, you introduce uncertainty, and the need for accommodating human limitations. This complicates life immeasurably.

To err is human. Regardless of the amount of training, experience, intelligence or desire, people still make mistakes. And apparently always will. An important element in improving aviation safety is the development of systems designs that are error-tolerant and mitigate, or compensate, for inherent human weakness. Errors can be reduced with proper equipment and system design, improved training, correct selection of personnel, and experience. But the costs can be high, so there can be resistance to implementing the proper processes.

Situational awareness[6] of the aircraft condition, position and systems function is essential for proper crew control. Anytime manual reversion is necessary, the crew must be able to intervene in a seamless manner to assume physical operational control of the aircraft with a minimum of effort and adjustment. The aircraft must keep the pilot informed at all times of aircraft state and systems status. One of the primary dangers of excessive automation is isolating the flight crew from the aircraft so that they lose situation awareness.

A Systems Approach

In general, a systems approach is a way of separating a defined piece of the real world into identifiable pieces, and looking at how those pieces interact with each other. We must bound a problem and analyze it in specific component pieces, or we can end up being too vague and ambiguous. A balanced subjective judgment must be made by competent and responsible people about the performance, dollar costs, safety, and benefit of any proposed system, or systems, change. Objective measures can then be applied to the component pieces as appropriate. For operational evaluation programs, you are working with equipment that is generally beyond basic design and development, so evaluations must take a pragmatic approach to dealing with the intended function and constraints of the new system.

The elements taken to represent system components must be specified in terms of their independent, or input variables, their dependent, or output variables, and the formal or mathematical relationships between the two. The system is then defined by the configuration of interconnects between the elements. It is this interrelationship between elements that is important in analyzing the system. Many of the variables may not be known with certainty, so they must be treated as random variables with some margin of error, or probability. Even if variables are known, relationships with other variables may not be linear, or time varying. Sometimes assuming a degree of linearity makes it easier to make approximations. Fine-tuning can be applied later.

Advantages of a systems approach include the requirement to bound a problem, and it demands that independent variables be identified. Another advantage is that the system model, once formulated, can be processed on a computer, or similarly manipulated, to simulate the system behavior under various inputs, parametric changes, and conditions. Once you are in a position to run a simulation, you have the ability to make a quantitative prediction of information

[6] The definition of situational awareness is: A continuous perception and understanding of one's self and the aircraft in relation to the dynamic environment in which you are operating.

to be used by researcher, planners, and designers. Other advantages include the advantage of having an accounting framework to track all variables and relationships considered, and a resulting archival description that shows an orderly relationship between all elements.

The ultimate goal of systems analysis is to make the system perform better. The process allows you to see all the variables associated with the system and how they interrelate. Manipulating the variables, and performing tradeoffs (Wierzbicki, 1982), allows the analyst to optimize the system. Because of the structure, a computer can be used for most of the work once subjective bounds have been established. The idea of control allows an on-going decision process that can respond continuously to improve performance (Rouse, 1980).

A close relationship exists between the design of electronic (computer) systems and human physiology (Wiener, 1948). This includes the model of supervisory, or hierarchical, control for low level autonomic functions such as heartbeat, breathing and postural reflexes. Intermediate level behavior is for such things as recognizing sensory patterns, and triggering responses. At the highest level, stimuli require conscious thought, planning, and measured response. These levels of information processing have been identified as skill-based, rule-based, and knowledge based (Rasmussen, 1986).

One area that requires careful consideration above all other possible variables is system safety. One contemporary definition of system safety is " the integration of skills and resources, specifically organized to achieve accident prevention over the life cycle of an air vehicle system" (Miller, 1965). Aviation safety has improved immeasurably since the 1940s. In 1943, approximately 5,000 aircraft were lost in domestic operations compared to 3,800 in combat (Stewart, 1965). The Flight Safety Foundation was founded in 1954 to improve aircraft safety through better human engineering on the flight deck (Miller, 1954), and has made tremendous contributions to improving safety, worldwide. Beginning in the 1960s, system safety principles and practices began to appear in industries beyond aviation.

Certain accident prevention fundamentals must be recognized. These include the following:

- The known precedent is that there are rarely new causes for accidents.
- Some of the biggest problems are the timely and accurate dissemination of information, and implementing remedial action.
- Accidents are always a sequence of events. If the causal chain can be broken, accidents can be prevented. All factors must be identified and analyzed. Studies by Airbus Industries show that most of these causal chains can be logically recognized, and on-board systems are capable of identifying the sequence of events involved. Hopefully, this will lead to better error-tolerant designs.
- Statistics do not always give a clear picture of the safety situation if the data is taken in raw form. It must be translated to numbers of victims to be in perspective. The public has a reaction threshold that allows a certain level of risk associated with commercial air travel, somewhere around 10^8 probability, where it is acceptable. To increase the risk beyond that causes a drastic reaction.
- Any accident investigation should always conclude with recommendations for corrective action (Miller, 1988).

The role of human-factors in system safety can be approached in many ways, including:

- Personnel planning, selection, assignment, and performance assessment.
- Safety-related interface considerations

- Design and test in terms of human engineering principles.
- System biomedical considerations.
- Procedures and training.
- Operational personnel situational awareness and motivation.

MIL-STD-882B, Paragraph 4.4, describes the principle of "System safety precedence". This means following an order of precedence for satisfying system safety requirements and resolving identified hazards. The priority order is as follows:

- Design for minimum risk.
- Incorporate safety devices.
- Provide warning systems.
- Develop procedures and training.

Human Performance

The human performer is designed with finite limitations on both their physical and mental abilities. The human evolved in a world where, until a hundred years ago, speed was defined in terms of how fast the human, or his domesticated animals, could move. Human vision is designed for detecting relatively close, slow moving objects, and visual information is processed as either recognition or orientation (Leibowitz, 1988, Sekular & Blake, 1985). Our binocular foveal, or focused, field of view, as is our color vision, for all practical purposes, is only 15 degrees, and our nose even gets in the way of part of that (Woodson, Tillman & Tillman, 1992).

Instead of using cue reliability, or importance, as a basis for focusing our attention, we focus most heavily on those cues that are physically demanding, such as those that are loud, bright, recent, centrally visible, and easy to interpret, or those that fit our preconceived mental models more closely (Wallsten & Barton, 1988). A human can process information at about 10 times a second, but this decreases significantly under stress (Wickens & Flach, 1988), or in unfamiliar situations. Our memory is atrocious. We can typically remember no more than 5 to 9 items in a sequence in working memory (Miller, 1956). A human has great difficulty in generating physical responses at more than 1 to 1.5 hertz. Table 2.1 shows some response times for common stimuli.

Sensory Input	Time (s)
Hearing	0.16s
Touch	0.17s
Sight	0.2s
Cold	0.2s
Warmth	0.22s
Smell	0.3s
Pain	0.7 s
Stimulus detection and neural transmit time	0.1s
Brain recognition time	0.4s
Decision-making time	Up to 4.0 s
Motor response time (minimum)	6.0s

Table 2.1 - Sensory Input and Reaction Times (Woodson, Tillman & Tillman, 1992)

Pilot Selection

Regardless of the advances in technology that permit us to go higher, further, and faster, the human element remains largely unchanged. It is possible to improve performance to some extent with training and experience, but basic human performance remains fixed. One method used to match a high level of performance with advanced systems, including aircraft, has been to select only the top candidates, physically and mentally, for flight training. The military has used this approach since they started using aircraft, and the commercial airline industry continues the practice today. Not only are pilots in the top few percentile mentally and physically, but they have to maintain their physical and mental edge throughout their careers in order to keep their jobs. A failure in either area is cause for ending their career. In general, NAS infrastructure is designed and built to accommodate what was determined to be an "average" pilot. For the commercial world, this is fairly straight forward since all pilots receive training that essentially yields the same level of proficiency. This early pilot model was based on former military pilots with lots of large aircraft time. The world today is changing in that most new pilots are not experienced ex-military pilots with their extensive training and knowledge. For our studies, we try to use a mix that reflects the age distribution and experience level of pilots operating in the commercial fleet.

Human-factors engineering is based on knowledge of the fundamentals of our sensory, perceptual, memory, and motor systems, and an understanding of their performance limits. The human-machine interface must recognize and accommodate these limitations to be successful. Fortunately, man is bright enough to design and control systems that can extend, or compensate for, human limitations. Microscopes, aircraft, automobiles, telephones, computers and hand tools all fill this need.

Vision

One of our primary senses in aviation is vision. Vision is possible because the retina reacts to an image that stimulates the light sensitive rods and cones. The optical lens and cornea focus the image on the retina for processing (Sekular & Blake, 1985). Functionally, the cones provide superior detail, color, and motion perception, while the rods work better in low light conditions. The foveal region, or region of focused viewing, is only a few degrees in width, but contains the focused detail we see. Under low illumination, the center, or foveal region, becomes almost blind, which necessitates a scanning action for the eyes. The rods and cones also have different sensitivity to color. The use, or overuse, of color in aircraft display systems is a growing problem. In general, there are 8 or 9 colors available for use on displays. The reason for restricting the number of colors is to permit sufficient discrimination between adjoining or overlapping colors. For adequate discrimination, even under adverse conditions, there must be approximately a 20 to 30 nanometer difference in wavelength between adjacent colors.

Human vision operates in two modes. One is concerned with pattern recognition, the other with visual guidance. It is possible for pilots to lose spatial orientation in low visibility conditions if they rely only on the vestibular systems for orientation. To compensate for this pilots are provided with an artificial horizon on the instrument panel. Motion sickness can result if there is a mismatch between the visual and other sensing systems (Benson, 1978). Vision is not always reliable in flight for detecting other aircraft and assessing accurate ground movement.

The way we perceive and process information is based on closed-loop goal seeking behavior. Human behavior has often been presented as analogous to servo-mechanisms and computers (Wiener & Curry, 1980). The stages in a closed-loop system include sensing a stimuli and comparing it to sensory stores to identify the type, such as light. Pattern recognition is then applied to compare to learned experiences. Decision and response is based on recognition, response to the stimuli, and finally, feedback to complete the loop. When faced with a new task, we first compare the situation to earlier established responses using mental models.

Auditory

Another form of perception involves hearing and understanding auditory information. Auditory information should be presented in context with the event that is occurring (Bransford & Johnson, 1972). Logical reversals, where a pilot has to logically reverse the meaning of a statement, hinders comprehension. Critical information should always be presented in a positive format. Humans react better when instructions are presented in a logical, ordered sequence. Presenting critical information out of order or context can lead to errors. We develop mental models of an event, and things that do not fit that model may be overlooked of misinterpreted.

Memory

We sample the environment appropriate to the speed at which an event is occurring to establish the statistical properties of the situation (Senders, 1966). Human memory is imperfect, so pilots tend to sample cockpit displays frequently to maintain situational awareness and appropriate responses. Human performance and sampling improve if pilots are presented with situations in training prior to actual in-flight experiences. High stress affects the accuracy of visual information and can lead to errors in execution. To help compensate for these problems, critical displays should be positioned near the center of the field of view, and close together.

Information that is perceived, interpreted, and comprehended usually results in action. Such information is processed in working memory. Working memory is quiet limited, so every effort must be made to relieve the workload. Information processed in working memory is processed in two different codes. Verbal information is processed using an acoustic-phonetic rehearsal. Spatial information regarding locations, orientation, and velocities is normally maintained using a visual code. Visual codes are less easily rehearsed than verbal codes (Goettl, 1985). The maximum number of unrelated things that can be maintained in working memory ranges from about 5 to 9. Exceeding this limit will result in lost information. Some ways to avoid overloading short-term memory is distributing material over time, reducing similarity between items, eliminate redundancy, and eliminate within-code interference.

Long-term memory uses two classes of information, semantic and episodic. Semantic memory represents memory for meaning. Episodic memory represents knowledge about specific events. It is assumed that ability to locate and use information will be more efficient if the systems knowledge database is organized in a manner consistent with the operator's (Durding, Becker & Gould, 1977). How we remember an event is strongly influenced by our expectations and previous experiences. Decision-making and responses are guided by our use of long-term memory. Stimulus sequencing and dual-task performance can greatly influence response time.

Task Loading

Variables that will increase task difficulty are shown in Figure 2-2:

TASK	VARIABLE
Memory	Number of items retained, Phonetic and semantic confusa Retention duration.
Response	Response frequency, Response complexity, Degree of c Stimulus-response incompatibility, Degree of precision.
Continuous Control	Control order, Control bandwidth, Gain, System time-dela

Figure 2-2: Variables That Will Increase Task Difficulty

We have discussed the probability of errors increasing as the number and complexity of tasks increases. In modern aviation we are forcing pilots and aircraft to operate at near the limits of performance. The pilots must react in ways that are dependent on memory and training for proper responses, and aircraft are allowed small margins of error. Pilot workload has been controlled by the use of multiple pilots in commercial cockpits, and by the use of the latest in advanced avionics and automation. Pilot decision-making and performance is augmented by the use of air traffic control and stringent operating procedures. As we push pilots further toward the limits of performance, the solution has been to further automate the cockpit.

Automation was envisioned as the cure for excessive pilot workload. In fact, it has only added to the problem in many cases. As aircraft are forced closer together in a more congested environment, the automatic systems often make decisions without pilot input. This problem has led to a sharp philosophical division in the industry. There is a danger that pilots will lose the situational awareness that is so critical to maintaining safe operations. There is an ongoing debate about the allocation of functions to either the crew or the automatic systems. At the present time the prevailing attitude is that automatic systems should provide alerting and guidance to be executed and carried out by the pilot after assessing the situation. While concern is growing about pilot workload under high stress conditions, economics has forced the removal of the third crewmember from many cockpits.

Crew Resource Management

The necessity to create better teamwork between crewmembers has led to extensive retraining and emphasis on crew resource management, CRM (FAA, AC120-51B). All of the major carriers now include CRM as an integral part of all training programs. Most pilots are selected because of their high stress tolerance, intelligence and decision making abilities. This does not always contribute to a strong team player unless the corporate culture precisely defines it. We still need the type of individual that can assume control or assist in critical, or incapacitating, situations, but crew discipline and procedures must be maintained. The seniority system and work environment sometimes influences team dynamics. Many studies have shown that strong leadership abilities often occur in individuals that are also good group members, and that this attribute should be fostered and strengthened (Helmrich, 1982).

The Ideal Pilot

Characteristics of the ideal pilot include high levels of interpersonal skills with a task-oriented personality (Helmrich & Wilhelm, 1989). They are the type of person that can be expected to take control at any time and be able to continue operations, even under stressful situations. Most commercial pilots have survived an extensive selection and testing process to ensure selection of the brightest, most capable, and physically fit persons available. The military normally took care of the culling process; so former military pilots have always enjoyed an advantage in gaining airline work. At any time in their career that they fail to meet physical or mental requirements, they are removed from the system. Each commercial pilot undergoes a flight physical and recurrent training at least once a year, and most captains get training twice a year. The pilot seldom acts as an individual, but instead is a member of a team, or flight crew, that must function as a unit to properly operate the aircraft.

Pilot Training

Once suitable pilot candidates are selected, training is used to strengthen native skills, and to teach operational procedures. Commercial pilots are probably the most trained professionals in the world. Commercial pilots undergo continuing training in initial and recurrent programs. Captains are required to prove proficiency at a minimum of once a year, and in some cases every six months, while first officers and flight engineers must do so annually. The training consists of classroom instruction on critical systems, followed by cockpit procedural training devices, and finally, flight simulators. The pilots are exposed to the most common operating procedures, as well as emergency training for more critical aircraft failures. They also receive extensive training in wind shear, unusual attitude, and low weather minima operating environments. Following each training course, the pilots must pass a check ride to demonstrate proficiency and currency. Included as part of all training sessions, the pilots execute a line-oriented flight training session to show proficiency throughout all flight regimes. Recent innovations include the growing use of computer-based instruction.

Modern flight training has its roots in World War II. Heavy losses associated with human-factors during the war led to the recognition that flight operations had unique behavior requirements, and to the development of more formalized training programs. It also led to closer screening of pilot candidates.

Training is often seen as the cure for all human-factors errors in flight operations. In fact, training can only go so far, and it certainly cannot compensate for poor equipment design, or poorly designed crew procedures. While training is a valuable tool for improving flight safety, it is not the cure-all that people would like to believe that it is. There is a tendency to try over-simplify solutions to complex problems. The number of fatalities for commercial aircraft has remained relatively stable for the past 20 years despite the increased emphasis on flight crew training, increased government regulation, and new technology in the cockpit (Flight Safety Foundation, 1999), despite the increase in aviation operations. While training can improve performance, its effects tend to level off after a period of time. Any attempt to quantify aviation related fatalities must consider an average over several years to be accurate.

Despite all the training, practice, and explicit operating procedures, planes still crash. The most common reason given is human error. But, even with the growing number of accidents, the accident rate continues to drop as the growth in aviation accelerates (Flight Safety Foundation, 1998). The improving accident rate is attributed to better equipment, better operating procedures, and better training. With the projected growth in worldwide aviation, accident rates must be reduced further. One of the limiting factors at this point is human performance (Billings & Reynard, 1984). A primary means of improving crew performance is to rely more and more on automatic sensing and alerting in cases of failure and emergency. We have the technology to augment virtually any human activity or response, so we must be more discriminating in how we apply automation, and augment those areas that offer the greatest benefits.

Modeling Human Behavior

Human behavior is complex. Many efforts to model this behavior have produced models so complex that they cannot be applied to actual behavior in a meaningful way. Many of the theories take an academic approach that fails to recognize and address real-world problems (Rouse & Rouse, 1984). Any model that ultimately proves accurate must include consideration of the way we acquire, process and exchange information, the way we make decisions, and finally, the way we implement and act on our decisions in a realistic environment (Nagel, 1986).

Reducing Design Errors

Errors can be reduced in a system through the careful and informed design of displays, controls, and procedures, continued careful selection and training of pilots, and designing systems that are error tolerant. Error tolerant systems can recognize and correct inadvertent errors by the human operator, and allow easy correction of mistakes.

The approach to landing phase of flight is one of the highest workload periods, with demanding time constraints, communications demands, and outside visual cue loading. At times of increased stress and time pressure, pilots tend to drop normal visual scan, and develop a tunnel perception of the operational environment.

One major factor contributing to pilot performance is fatigue and circadian rhythm. Most commercial crews operate in a three to four day duty cycle. Errors tend to increase as they move further into the duty cycle (Lyman & Orlady, 1980). The problem is attributed to the biological clock that drives our alertness and behavior. This is a biological characteristic that gives us normally high and low activity periods within a 24-hour period. Anytime we change our patterns our body must be allowed to respond to the change. Our clock determines when we are tired, hungry, sleepy and alert. The number of time zones crossed determines the extent of our clock phase shift. Fatigue in flight crews can result in increased reaction time, reduced attention, diminished memory function, and, sometimes, social withdrawal (Greaber, 1986).

Experience

Studies have shown that accident rates drop in professional pilots with increased recency and total flying experience, with recency being the more important of the two (Golaszewski, 1991). The average commercial pilot flies something more than 500 hours a year, but by federal law, a commercial pilot hauling passengers, is limited to a maximum of 1000 hours per year flight time.

Flight Hazards

Some of the environmental hazards that have been identified are air turbulence, precipitation, ground obstacles, airborne objects, atmospheric debris, and electromagnetic radiation. Attempts to alleviate the threat of these and other hazards, has led to the installation of more automation, additional sensors, and new crew procedures. Requirements to maintain safe flight while monitoring and analyzing data from these systems have increased the pilot workload.

Situational Awareness

Many aircraft accidents are associated with a loss of situational awareness. This loss of awareness can be due to poorly designed automation is too complex, not properly coupled, operates in an autonomous manner, and provides inadequate feedback (Woods, 1996). It is essential that the human operator remains the primary focus of systems design, and any automation remains a tool to assist with carrying out the mission. This concept is identified as human-centered design.

Monitor Functions

It should be recognized that the human is not good at monitoring activities on a long-term basis, but machines, in particular computers, are very good at this function. Any automation must capitalize on the strengths of human operator, as well as those of the automation. There is a misconception that humans and machines can be created as equivalents. Machines are no more intelligent than the intelligence programmed in by their human developers. Machines can only perform comparative reasoning with the information with which they are provided. Rational thought is not yet a machine capability, and people that are good at designing machines may not great at communicating with other people, and they obviously cannot know everything about a task as complex as flight, so it would be normal to expect their machines would have the same failings.

Human Factors In Aircraft Design

Operating an aircraft, either in military service, general aviation, and commercial aviation, is a goal-oriented human activity. It involves assessing the operational environment, reaching sound decisions based on available information, and then executing the flight. All of this is done in a closed-loop environment with the pilot closing the loop with the machine. An aircraft operates in a three-dimensional space with six-degrees of freedom of movement including lateral, longitudinal, vertical, and angular rotation about three separate axes; pitch, roll and yaw, and all related cross-coupling. Movement within this space is a function of pilot control inputs. Pilot control inputs must be easily accomplished from the crew position under all phases of operation. All aural alerting and visual information must be clear and concise. Control order refers to the number of integration steps necessary for the control input to take effect. The higher the control order, the longer it takes for a control input to cause a response, and the more complicated the required control, the more input time increases to generate an output response.

Because the human pilot is flexible and adaptive, and strongly influenced by their surroundings, many factors affect closed-loop flight control performance. These variables are generally separated into four different categories: task variables, environmental variables, procedural variables, and pilot-centered variables (McRuer & Krendal, 1974). Task variables include the aircraft and related system dynamics that the pilot must directly interface with. Environmental variables include temperature, ambient lighting, noise, vibration, and acceleration, which normally have no direct effect on control. Procedural variables affect performance via the procedures imposed on the pilot in conducting normal flight duties. Pilot centered variables encompass those personal characteristics that a pilot possesses.

Commercial Pilots are highly skilled and trained professionals that develop an in-depth understanding of the aircraft; it's subsystems, and the entire operational environment surrounding flight operations. Pilots tend to optimize their response to a given situation by developing predictive compensation based on consistency and regularities in an aircraft's performance. Three aspects are of particular importance: prediction of the effects of system dynamics, input signal prediction, and preprogrammed responses. If events do not occur as a pilot expects, based on these factors, it will interfere with pilot performance, and can lead to more frequent errors and lowered performance.

Environmental variances such as noise, undue time delays, and bandwidth limitations can also affect pilot performance. It is essential that a pilot be acutely aware of the operational status of the aircraft at all times. This is referred to as situational awareness. To maintain this awareness a pilot relies on ambient noise, aircraft performance, crew communications, external communications, the visual out-the-window scene, and visual displays. All aircraft systems must be design recognizing this reliance on awareness, and must serve to clarify and strengthen these characteristics. Inherent limitations to human performance must be considered at all times. For instance, a human has great difficulty in generating physical responses at more the 1 to 1.5 hertz, which affects the ability to respond in a sustained manner to input requirements, so augmentation may be needed to compensate under certain conditions.

Critical to maintaining situational awareness is the pilot's reliance on cockpit display systems. As aircraft grow more complex and technology provides the capability to offer more and more information, the pilot's senses can become overloaded with information (Statler, 1984). Information must be displayed in a manner that avoids this overloaded condition. Displays are typically viewed as either command displays or situation displays. Command displays become more important as aircraft become larger, more complex, and more sluggish. Control is normally maintained by responding to predicted error, based on the pilot's mental model, rather than current error. Some displays, such as acceleration, are not perceived well by the human eye (Fuchs, 1962). Some of this inherent human weakness is compensated for by the use of quickening and predictive displays. Predictive displays can add clutter and increase visual workload by providing the pilot with too much information (Yeh & Wickens, 1984), so care must be exercised in their application.

Human-Centered Design Principles

The following principles (Billings, 1996) are the basis for a human-centered design:

- The pilot bears the responsibility for safety of flight.
- Air Traffic controllers bear the responsibility for traffic separation.
- Pilots must remain in command of their flights.
- Controllers must remain in control of air traffic.
- The pilot and controller must be actively involved.
- Both human operators must be adequately informed.
- The operators must be able to monitor the automation.
- The automated system must be predictable.
- The automated system must also monitor the human operator.
- Every intelligent system element must know the intent of all other intelligent elements.

Modern technological development is out-pacing our ability to learn and apply innovations. New systems are forcing the obsolescence of existing systems in a very short time. The airline industry is saying that any new system must buy its way onto the flight deck with payback in a short time, generally three to five years. Airlines are also in a fight for survival where any innovation that promises to save fuel, manpower, or can increase efficiency and utilization, is readily embraced.

Modern designers are so preoccupied with keeping up with technological development that they often fail to properly consider human-factors issues. Historically, aircraft systems, as with any high capital cost investment, evolved over an extended period of time allowing normal human usage to drive cockpit design improvements. Today a manufacturer will not survive if they take too long to bring a product to market, and the product must prove competitive from initial implementation.

The aviation system is a technologically intensive, spatially distributed system in which highly skilled human operators fly people and freight from place to place, worldwide, utilizing complex, automated machines, in a culturally diverse, and an increasingly congested, environment. There is no other undertaking, except maybe warfare, in which technology has been brought to bear in a more effective and timely manner than in aviation. On the other hand, no undertaking, except possibly warfare, has had a bigger effect on advancing technology than aviation. The requirement for reliable, efficient, compact, high speed processing in a rugged environment has pushed innovations now commonplace in many other fields.

Between 65% and 80% of the aircraft accidents in jet aircraft are attributable, at least in part, to human error (Wiener, 1989). Accident records over the past 20 years show two seemingly contradictory trends (Khatwa & Helmrich, 1999). There have been sharp declines in certain types of accidents that are attributable to the introduction of new automatic monitoring and warning systems on the flight deck. There is also clear evidence that the application of the new technologies has not had a noticeable affect on other areas, and may even isolate the flight crew from operation of the aircraft. The presence of automation has changed the role of the pilot from that of an operator to that of a systems manager. It also has become clear that automation does not eliminate human error, but only changes its nature and possibly increases the severity its effects (Wiener, 1993) by delaying its manifestation.

Error Management

What emerges from the study and applications of human-factors is that no matter how well trained or competent human performers become, they will still make mistakes. Fortunately these seldom are cause for major concern, but in critical situations it can be deadly. Mitigation of these mistakes through efforts to design and build error tolerant systems continues. The ability of computer systems to recognize the emerging patterns and detect key elements of an error as it develops offers hope that eventually improved alerting and recognition can prevent many accidents.

COCKPIT AUTOMATION

Concerns about cockpit automation have increased significantly with the availability of on-board computer systems, and growing usage of multifunction display systems. A couple of quotes are in order here:

> "The rapid pace of automation is outstripping one's ability to comprehend all the implications for crew performance. It is unrealistic to call for a halt to cockpit automation until the manifestations are completely understood. We do, however, call for those designing, analyzing, and installing automatic systems in the cockpit to do so carefully; to recognize the behavioral effects of automation; to avail themselves of present and future

guidelines; and to be watchful for symptoms that might appear in training and operational setting" (Wiener & Curry, 1980).

And:

" automation does not eliminate human error, but rather changes it's nature and possibly increases the severity of its consequences" (Wiener, 1993).

Many of the more notable experts were concerned about automation over 20 years ago, and the ability to automate has advanced beyond even their wildest dreams since then. The development of compact digit computers has made it possible to automate virtually any facet of the modern aircraft flight deck. Manufacturers that have technology to sell are beating the bushes in an attempt to adapt and market their version of the future of aviation. However, the design philosophy of most major aircraft manufacturers remains that the only acceptable design requires a human operator, or pilot, to control, monitor, and, if required, assume flying control, of the aircraft. Automation is seen as an aide, and complementary to human control.

The use of cockpit automation in modern aircraft is controversial. There is an ongoing effort on the part of equipment manufacturers to market additional automation. At one extreme, automation is considered as the perfect solution to pilot workload, and as a way to compensate for inherent human limitations. At the other extreme, it is viewed as reducing the status of the human operator, and degrading pilot involvement in flying the aircraft. Automation will decrease pilot workload for manual control inputs, but adds substantial cognitive workload in monitoring their operation. Pilots are not good monitors for extended periods, so they tend to lose awareness.

When considering the use of automation, one must remain cognizant of the negative aspects. Automation capable of augmenting human behavior in complex situations is very costly. In any system, there will be false positives, or false alarms. These may improve as a system matures, but their too frequent use can destroy credibility for the operator, and even prevent their use. Automation is not normal for human operators. We have only had aircraft for a hundred years, so use and understanding of mechanical automation is not an inherited trait. Any implementation must try to replicate human performance to facilitate human intervention. Eight principal reasons have been cited for increased cockpit automation:

- Availability of technology
- Safety
- Economy, reliability
- Perceived workload reduction
- More precise flight maneuvering
- Display flexibility
- Cockpit space
- Special requirements

Notice that many of these reasons are intended to extend the range of performance beyond existing human limits. Any implementation must be designed to optimize the human-machine interface. Some principals that have been applied to computer interaction apply equally well to aircraft instruments. These are:

- Compatibility
- Consistency
- Memory

- Structure
- Feedback
- Workload
- Individualization

Following these principals will negate some of the inherent interfacing problems. Two of the most critical are compatibility and consistency. The display must be compatible with existing on-board systems to the extent possible, and they must perform consistently in a manner that the aircrew expects.

Since man has only limited performance abilities, it follows that the proper approach is to design systems around inherent human frailties. Computers can do a much better job at memory, and we can design sensors that are infinitely better than us at detecting systems status. But, since man is the operator and controller, we must be cautious when we automate. Since man may be required to intervene at any time, and must monitor the operation of the automation, he must stay apprised of the state and status of the automation. Nowhere is this more critical than in aviation where safety of the public is at stake. Once most designers realize that human performance can be improved only within inherent limitations, the tendency is to start trying to design the human out of the process with automation. The problem is that the human operator is still responsible for the overall operation of the aircraft (Billings, 1997), and is still the only totally self-contained component with sensors, motor skills, information processing, and decision making abilities, in the entire system.

Automation can either enhance or diminish situational awareness, and there is a need for the designers, operators and management to understand the risks associated with its use. For automation to truly enhance the task of a pilot, the design must be predictable, consistent, contextually correct, and provide adequate feedback for the pilot to maintain situational awareness at all times (Curran, 1992). Such an approach requires a knowledge of what has worked before, what hasn’t, and why.

The latest aircraft built by Boeing, the 777, used a flight deck that was designed to incorporate a human-centered design and automation (Kelly & Greaber, 1992). The Boeing flight deck design philosophy include the following key points:

- Pilot's role and responsibility
  - The pilot is the final authority for the operation of the aircraft.
  - Both crewmembers are responsible for safe operation of the aircraft.
  - Decision-making is based on a goal hierarchy.
- Pilot's limitations
  - Expected pilot performance must recognize human performance limitatio
  - Individual performance by different crewmembers must be accommodate
  - Flight deck design must apply error tolerance and avoidance techniques.
  - Flight decks should be designed based on past practices and intuitive oper
  - Workload should be balanced appropriately.
- Pilot's needs
  - When used, automation should aid the pilot
    - Hierarchy.
  - The flight deck should be a comfortable work environment
  - Flight deck automation should be managed to support the pilot's goal.

Figure 2-3: Boeing Human Factors Philosophy for the B777 Aircraft

Economic and market issues will ultimately be the deciding factor on many automation issues, and should be considered by the designers. Just because it is "doable" doesn't automatically justify its inclusion on the flight deck.

There can be a disconnect between the design engineers, the pilot operators, and the company management on what automation can and should do in the aircraft. Automation is perceived as being able to solve all of the operational problems without due consideration of the costs in terms of human performance. Design engineers are so busy coping with ever changing technology that they seldom have the time to consider something like human-factors unless it is explicitly mandated. Previous generations of designers had a strong appreciation for the need to include human-factors considerations in their designs. Today people tend to be so specialized that younger designers may not even be aware of the limitations, and why they exist.

Human-centered design is the concept of placing humans at the center of the environment, and then building, or molding, the environment around them. It recognizes that the human retains supervisory control and management of the automatic systems, and may be required to intervene in the systems at any time. It also means designing aircraft cockpit systems so that the human operator is always aware of what the automation is doing, and that automation is best applied when used in those areas not performed well by humans. Seven general principles to consider in human–machine interfaces are as follows (Williges, Williges, & Elkerton, 1987):

- Compatibility: Minimize the amount of information decoding required.

- Consistency: Minimize the differences in dialogue both within and across various interfaces.
- Memory: Minimize the amount of information that the user must maintain in short-term memory.
- Structure: Assist the user in forming a mental image of the structure of the system so they can navigate through the interface.
- Feedback: Provide the user with feedback and error correction capabilities.
- Workload: Keep user mental workload within acceptable limits.

- Individualization: Accommodate individual differences through automatic or user tailoring.

The Evolution of Aviation Automation

It is important to remember that aviation, as we know it today, did not evolve in a vacuum. Most advances and improvements within the past 50 years were initiated to improve efficiency, increase safety, and decrease pilot workload. One of the most significant led to reducing flight crewmembers from three to two persons on transport aircraft in the 1980s.

World War II was the beginning of modern aviation. Jet engines, radar, on-board navigation, and initial automation were products of that era. Getting the aircraft off the ground and supporting sustained flight had consumed the earlier years. The high performance required for combat aircraft from the war period carried over into civil aviation following the war.

In 1992 there were 192,000 civil aircraft operating in the U.S. Of these, 7,300, about 4%, were commercial air carrier aircraft (AOPA, 1994). The majority of the air carrier aircraft are turbojets, some carrying nearly 500 people. The growth in commercial aviation has been phenomenal since the 1950s. Data for 1997 show 599 million passengers were carried in commercial service.

Older transports had limited automation compared to newer aircraft. Flight was in a much less congested environment, using slower aircraft, and operating from far fewer major airports. General aviation aircraft include everything from very old planes with no automation, to experimental aircraft, to modern turbojets as sophisticated as any air carrier aircraft. As the numbers and types of all aircraft have increased, so have the problems associated with mixing performance. The air traffic control system must be able to accommodate everything operating, from the smallest and slowest, to the largest and fastest, without causing a hazardous operating environment. The operational environment has been required to accommodate closer spacing in both lateral and in-trail separation, without decreasing safety. In recent years, the operation of private aircraft has decreased, somewhat, with the increased cost of aviation operations.

As aircraft have grown faster and more complex, the industry has tried to use automation to compensate for human limitations. This automation must also be recognized as a crewmember. Complex automation is sometimes perceived as having a mind of its own, especially when it does something unexpected (Hollnagel, 1993). Unexpected actions from automated systems erode human trust in the system. Human operators must be able to form a predictable mental model of how the system is expected to operate. Surprises disrupt the integrity of such internal models, and are symptomatic of design flaws. Different airlines have adopted different approaches to how they will use and implement automation in their cockpits (Byrnes & Black, 1993).

The Role of the Human in Automation

Automation can either enhance or diminish situational awareness, and there is need for the designers, operators, and management to understand the risks associated with its use. For automation to truly enhance the task of a pilot, the design must be predictable, consistent, contextually correct, and provide adequate feedback for the pilot to maintain situational awareness at all times (Curran, 1992). Such an approach requires knowledge of what has worked before, what has not, and why. Economic and market issues will ultimately be the deciding factor on many automation issues, and should be considered by the designers. Just because it is "doable" doesn't automatically justify its inclusion on the flight deck.

As the pilot and the aircraft are operated at near their design limits, automation will be applied more often as a way to mitigate human failings. As was stated earlier, one of the driving concepts is that the pilot is in command, and the automation is simply a tool to enhance performance. As aircraft and their operational environment become more complex, the pilot's role will continue to shift to that of aircraft manager, and away from aircraft operator. Managing the integration and use of a number of complex systems will become a full time job. It will require extensive automatic monitoring and sensing beyond what the pilot is capable of handling. Tasks best done by the human (Fitts, 1951), and those best done by machines, need to be identified in light of today's new technology. Humans and machines must be looked at as complementary, not as competing (Jordan, 1963).

Crew resource management (CRM) will gain in importance as cross-cockpit communications becomes more critical. Displays will have to be designed to minimize visual clutter, while preserving the primary flight display in case manual reversion is necessary. There are tasks that pilots may not perform, but they must always remain cognizant of the actions of the automation. Functioning as a crew is not a cure-all for preventing accidents however. A phenomenon has been identified where a crew can become so linked they start thinking and acting as one, and may they fail to recognize each other's errors.

Issues for Future Automation

Although technology is often separated into control, information, and management automation, the lines separating them are becoming blurred because of increased functional integration. Systems that have recently been introduced as automated systems include traffic collision avoidance system (TCAS), enhanced traffic collision avoidance system (EGPWS), 3-D[7] terrain mapping, cockpit display of traffic information (CDTI), wind shear, and global positioning system (GPS). Systems slated for near-term future automation includes automatic dependent surveillance (ADS-B), several data link implementations, aircraft to air traffic control communication, electronic flight bags, and increased multifunction display integration.

A brief look at some enhancements proposed for current and future transport aircraft will give us an idea of the types of automation that are being considered. These enhancements include:

- Control Automation
- Low-visibility taxiing guidance
- High-precision in-trail operations
- Automated collision avoidance systems
- Automated wind shear avoidance maneuvers

[7] 3-D refers to spatial positioning (X, Y, and Z), 4-D refers to X, Y, and Z, plus time.

- Information Processing
- Electronic library system
- Electronic flight bag
- Satellite navigation
- Digit data link
- Satellite communications world-wide
- Automatic dependent surveillance
- Integrated multifunction cockpit displays
- Enhanced head-up displays
- Synthetic vision systems
- Management Automation
- Easier flight management systems (FMS) interfaces
- Direct FMC-ATC communications
- Improved error tolerance
- Improved electronic checklists
- Improved mental models for designers

Typically, automation of these applications will increase the cognitive workload of the flight crew. They also have the potential to further isolate the pilot from the operation of the aircraft. Integrating several display functions onto a single display can lead to visual clutter and decrease the pilot's ability to separate the symbology and information of the individual functions.

Free flight is envisioned as virtually eliminating the need for air traffic control inputs for enroute flying. The flight crew will not only be responsible for operating the aircraft, but they will assume responsibility for aircraft separation, with little support from an air traffic control system. Communications will become automatic between the aircraft and ground facilities. On-board systems will advise the crew of impending conflict, and, if necessary, provide guidance to avoid collision. Terrain display, charts and maps, weather, and all other environmental data needed to maintain safe flight will be available to the flight crew in the cockpit via on-board sensors, or data link, or both.

The rapid pace of automation is outstripping our ability to comprehend all the implications for crew performance (Wiener, 1985). It is impossible, even undesirable, to halt the automation movement, but the designers must proceed with caution, recognizing the behavioral implications for the flight crew.

Principles mentioned earlier need to be reiterated. The human operator, or pilot, must be in command. Relinquishing command to another person or to automation, by overly restrictive operating policies and procedures, and by systems designers and manufacturers, can compromise command. The human operator must remain involved in operating and controlling the system at all times. The human operator must remain informed of systems status and operations, especially automated systems. The behavior of automated systems must fit the pilot's mental model, and must be predictable. Automatic systems should monitor human performance for error, and be tolerant of input errors. To do this automation must be designed to recognize the context of an operation.

Systems should be automated only if there is a valid reason to do so. Typically this is determined by considering the time within which a response is required, if a task is extremely complex, if human error has a high probability of leading to disastrous results, and if a task is boring, repetitive, or distracting (ATA Human Factors Task Force Report, 1995). If automation is selected it must be easy to train, to learn, and to operate. A primary role of automation is to increase situational awareness for the flight crew, hence improving operational safety. Automation must never be allowed to fail, or to perform, without advising the flight crew of the action.

The following reference demonstrates that behavioral scientists have recognized the danger in over-automating the modern cockpit for a number of years. Wiener and Curry stated in 1980, "it's no longer a question of whether a system can be automated, but, rather, should it be." Some modern interpretations of automation place the human operator in the situation of doing tasks that they are the least suited to perform. A comparison of strengths associated with the human operator, and those for automation follow:

Human Operator:

Ability to sense inputs from various inputs.
Ability to perceive new patterns of light and sound.
Ability to improvise and use flexible procedures.
Ability to reason inductively.
Ability to exercise judgment.
Adaptability.
Ability to remember large amounts of information of various types and recalls it at appropriate times.

Automation

Ability to perform repetitive, routine tasks.
Ability to monitor for extended periods of time.
Ability to respond quickly to control signals, and to apply precise control.
Ability to perform computational tasks quickly and accurately
Ability to accept, process, and respond to inputs quickly.
Ability to do a number of tasks simultaneously.
Ability to handle highly complex operations.

Automation in the cockpit must operate in much the same manner, as the human operator would perform under similar circumstances. The aviation environment and infrastructure has evolved over an extended period of time to meet certain needs. Anything that operates in that environment must recognize that structure and be compatible with it. The national airspace, airport operations, the aircraft design, size of aircraft and airport facilities, all are based on accepted standards that provide a predictable operational environment. Equipment design must recognize human limitations and abilities in its design, as do operational procedures. The size of the landing gear pattern on aircraft is built to operate within existing airport runways and taxiways. Likewise, the size of the aircraft themselves must be compatible with runway and ramp loading, boarding gates, service vehicles, and the ability to load passengers. If change is warranted, it will take place, but it must offer substantial, and sustainable, economic benefits to be able survive, and to become widely accepted.

Automation should be applied in a manner that will reduce pilot workload, and improve situational awareness. Many aircraft accidents are associated with a loss of situational awareness. This loss of awareness from automation is attributed to complexity, coupling, autonomy, and inadequate feedback (Woods, 1996). Even the most capable pilots can lose state awareness when automation forces them out of the operational loop on complex aircraft. In the aviation domain, where humans are responsible for the outcome of aircraft operation, it is essential that the human remains the primary focus, and the automation remains a tool to assist with carrying out the mission. The following principles (Billing, 1996) are the basis for a human-centered design:

- Air Traffic controllers bear the responsibility for traffic separation.
- Pilots must remain in command of their flights.
- Controllers must remain in control of air traffic.
- The pilot and controller must be actively involved.
- Both human operators must be adequately informed.
- The pilot bears the responsibility for safety of flight.
- The operators must be able to monitor the automation.
- The automated system must be predictable.
- The automated system must also monitor the human operator.
- Every intelligent system element must know the intent of all other intelligent elements.

There as been one notable exception to evolve in recent years with the advent of free flight, the pilot also shares responsibility for separation.

CREW PROCEDURES

Everything that has been discussed for equipment design and implementation also applies to flight crew procedures. Procedures must recognize the strengths and limitations of the human operator, and serve to augment, or complement, that performance. Any new piece of equipment will normally have associated procedural changes that must be evaluated. It can also affect crew-training requirements.

FLIGHT SIMULATORS

FAA Advanced Simulator Program

The advanced simulator program administered by the Federal Aviation Administration for air carriers and commercial training centers is based on requirements set forth in Advisory Circulars (AC) AC 120-40B, Airplane Simulator Qualification, and AC 120-45, Airplane Flight Training Device Qualification. The AC's give specific criteria required to obtain and maintain approval on commercial simulators to be used for flight crew training. Key elements of the approval process include aerodynamic database fidelity, aircraft system fidelity, and realistic motion and visual systems performance, including system throughput.

The fidelity of the simulators is established by the comparison of simulator test data to actual aircraft flight test data and systems design requirements. In addition to the original approval, all commercial simulators must be rechecked a minimum of twice annually over the operational life of the equipment to maintain approval. There are generally 100 to 150 operational tests that are included in an approval test guide to check performance. The specific number can vary, depending on the aircraft type. More complex systems can add more tests. These tests are all repeated in the course of a year, and performed randomly in an order specified by the evaluator. Failure to meet any of the test requirements can mean loss of training credit approval. Each simulator is built to match, by performance and configuration, a specific aircraft, identified by aircraft tail number. The Department of Defense (DoD) is now in the process of developing their own approval process. The DoD system will inevitably be more complex because of the sophisticated on-board systems, and the tactical mission requirements involved.

Typically, any regulatory effort is looked upon as burdensome.   The simulator approval process, however, was jointly developed by the FAA and industry as a means of ensuring improved training for flight personnel, while saving industry enormous amounts of time and money. The gains in fidelity, quality, reliability, time, and money savings have firmly established the value of the program with the operators. The higher fidelity provided by applying the requirements for the simulator approval are essential if simulators are to be used for definitive studies. If a pre-existing approval status is missing, each system and the fidelity of the simulator being used must be determined before the results can be applied.   There is an ongoing struggle, mostly based on economic factors to reduce approval requirements.

Fidelity

The key to the value of the advanced simulators is system fidelity. This fidelity does not come cheaply. New simulators for large aircraft can cost $15 million or more.   The new cockpits with the requisite motion and visual performance extremely close the real aircraft in performance, sound, visual presentation and feel.

Fidelity has several definitions. The one most familiar to most people is simply ”faithfulness” (Webster's New World Dictionary), but the Fidelity Working Group developed the one I prefer, and will use in this document, for the DoD Simulator Interoperability Standards Organization (1998). This definition reads as follows:

> **Fidelity.** The degree to which a model or simulation reproduces the state and behavior of the real world, or the perception of a real world object, feature, condition, or chosen standard in a measurable or perceivable manner; a measure of the realism of a model or simulation. Fidelity should generally described with respect to the measures, standards, or perceptions used in assessing or stating it, See accuracy, precision, resolution, repeatability, model/simulation validation (SISO, 1998).

This definition conveys the message that when we speak of fidelity in relation to safety critical evaluation processes, we must be prepared to validate the stated fidelity in quantifiable and verifiable terms. To use a simulation to "prove" a concept, or to validate the operation of a new avionics system, we must be able to document and validate the supporting simulator in some manner, including the human-aircraft interfaces. The proper way is through the use of objective testing judged against real-world performance data, coupled with a subjective assessment by expert operators, or in this case, experienced professional pilots.

Non-Approved Simulators

One of the primary reasons for establishing the advanced simulator approval program was to improve fidelity, improve maintenance programs, and ensure currency with existing aircraft configurations and performance in simulator equipment. Non-approved simulators do not meet the same stringent oversight requirements, so are limited in training credit allowed by the authorities.

The fidelity levels achieved and quality maintained varies widely between operators on non-approved equipment. Software programs are often changed considerably from the original loads. Similar problems can occur with cockpit hardware. Not all non-approved simulators suffer from these problems, of course, but it is difficult for an operator to maintain software and hardware configuration control without a formal process in place.

Many of the non-approved devices are in use by educational establishments and smaller training centers that find it difficult to justify the cost of maintaining certification status. NASA and some educational institutions, such as Embry-Riddle, have obtained FAA Level C or D approval on newer devices to receive added credits from their use, and to ensure fidelity. The general aviation (G/A) community has also been slower to move into the approved simulator arena. In many cases for G/A training, an actual aircraft can be much cheaper than an advanced simulator. But as costs come down on simulator equipment, the market is expanding. Some operators, such as Flight Safety, have sizable simulator operations for G/A training.

Advantages and Disadvantages of Approved Simulators

The most obvious benefit from using the approval process is the documented fidelity, as compared to the actual aircraft, that leads to the additional training credit allowed. System performance is assured within defined limits leading to more consistent results that help considerably with validating equipment performance. There are normally built-in diagnostics that allow one to easily check performance and integrity to ensure continued fidelity.

The approval process has built-in provisions for tracking changes and modifications, and maintaining configuration control. As practiced, this is not as onerous as you might expect. In most cases changes can be evaluated on-line before being permanently installed for use. Most hardware changes are driven by update programs to the aircraft and do not effect flight performance, so have limited impact on the approval process beyond initial evaluation after installation. Research specific hardware can be installed for use and then removed to return to training status.

The credibility of using approved simulators for top-end man-in-the-loop evaluations cannot be ignored. The time saved in system development, procedural development, training requirements assessment and risk assessment on safety issues is difficult to achieve in any other way.

Disadvantages of the approval process include cost and time requirements. The manpower needed to maintain daily checks and repairs can be considerable. Likewise with spare parts, and in-house technical talent. To justify the overhead of maintaining an approved simulator program, an operator must get maximum utilization from the equipment. There are situations with smaller operators where the burden of the approval process is not needed, nor desired. In most of these cases they buy simulator time from larger operators.

SUMMARY OF THE STANDARDS FOR ADVANCED LEVEL C AND LEVEL D SIMULATOR QUALIFICATION

General

- Cockpit, a full-scale replica of the airplane simulated.
- Circuit breakers
- Complete effects of aerodynamic changes

- All relevant instrument indications involved in the simulation of the applicable airplane automatically responded to control movement by a crewmember or external disturbances to the simulated airplane; that is, turbulence or wind shear.
- Communications and navigation equipment
- Simulator systems must simulate the applicable system operation, both on the ground and in flight.
- Instructor controls to enable the operator to control all required system variables and insert abnormal or emergency conditions into the airplane systems.
- Control forces and control travel which correspond to that of the replicated airplane.
- Significant cockpit sounds which result from pilot actions corresponding to those of the airplane.
- Sound of precipitation, windshield wiper, and other significant airplane noises perceptible to the pilot during normal operations
- Level (D) requires realistic amplitude and frequency of cockpit noises and sounds, including precipitation, static and engine and airframe sounds.
- Ground handling and aerodynamic programming to include:
- Ground effect
- Ground reaction
- Ground handling characteristics
- Wind shear models
- Representative crosswinds
- Representative stopping and directional control forces for at least the following runway conditions based on airplane related data.
  (1) Dry
  (2) Wet
  (3) Icy
  (4) Patchy Wet
  (5) Patchy Icy
  (6) Wet on Rubber Residue in Touchdown Zone
- Representative brake and tire failure dynamics
- A means for quickly and effectively testing similar programming and hardware.
- Simulator computer capacity, accuracy, resolution, and dynamic response sufficient for the qualification level sought.
- Control feel dynamics which replicate the airplane simulated.
- Relative responses of the motion system, visual system, and cockpit instruments shall be coupled closely to provide integrated sensory cues. For Levels C and D, response must be within 150 milliseconds.
- Aerodynamic modeling throughout all phases of flight.
- Aerodynamic and ground reaction modeling for the effects of reverse thrust on directional control.
- Self-testing for simulator hardware and programming to determine compliance with simulator performance tests
- Diagnostic analysis printouts of simulator malfunctions
- Timely permanent update of simulator hardware and programming subsequent to airplane modification.
- Daily preflight documentation.

Motion System

- Motion (force) cues perceived by the pilot shall be representative of the airplane motion.
- A motion system that produces cues at least equivalent to those of a six-degrees-of-freedom synergistic platform motion system.
- Special effects programming to include:
  (1) Runway rumble, oleo deflections, effects of groundspeed and uneven runway characteristics.
  (2) Buffets on the ground due to spoiler/speed brake extension and thrust reversal.
  (3) Bumps after liftoff of nose and main gear.
  (4) Buffet during extension and retraction of landing gear.
  (5) Buffet in the air due to flap and spoiler/speed brake extension.
  (6) Stall buffet to, but not necessarily beyond, the FAA certificated stall speed, Vs.
  (7) Representative touchdown cues for main and nose gear.
  (8) Nose wheel scuffing.
  (9) Thrust effect with brakes set.
  (10) Characteristic buffet motions that result from operation of the airplane

Visual Systems

- Continuous minimum collimated visual field-of-view of 75 degrees horizontal and 30 degrees vertical per pilot seat.
- A means for recording the visual response time
- Verification of visual ground segment and visual scene content at a decision height on landing approach.
  (1) Airport and runway used.
  (2) Glideslope transmitter location for the specified runway.
  (3) Position of the glideslope receiver antenna relative to the airplane main landing wheels.
  (4) Approach and runway light intensity setting.
  (5) Airplane pitch angle.
- Visual cues to assess sink rate and depth perception during takeoff and landing.
- Test procedures to quickly confirm visual system color, RVR, focus, intensity, level, horizon, and attitude as compared to the simulator attitude indicator.
- Dusk scene to enable identification of a visible horizon and typical terrain characteristics such as fields, roads, bodies of water.
- A minimum of ten levels of occulting.
- Level (D): Daylight, dusk, and night visual scenes with sufficient scene content to recognize the airport.
- Light point size of not greater than 6 arc-minutes.

Approval Validation Testing

Simulator performance and system operation must be objectively evaluated by comparing the results of tests conducted in the simulator to airplane data for the specific aircraft being simulated. Recordings of the simulator performance are normally made, and then compared to the airplane source data.

Tolerances are established for all major performance measures, depending on the system or specific maneuver being evaluated. While including all of the tolerance values is beyond the scope of the main body of this paper, examples include airspeed, +/- 3 knots, pitch, +/- 1.5 degrees, bank, +/- 2 degrees and +/- 2 ponds on control forces. These tolerances are applied against performance plots of actual aircraft performance for that variable under identical conditions. The commercial simulators must maintain these tolerances throughout the operating life of the equipment or lose certification. Appendix A contains tolerance values for the tests used in AC120-40B.

Configuration Control.

In accordance with FAR Part 121, Appendix H, operators must notify the POI and NSPM at least 21 days prior to making software program or hardware changes that might impact flight or ground dynamics of a simulator. A complete list of these planned changes, including dynamics related to the motion and visual systems and any necessary updates to the MATG, must be provided in writing. Operators must maintain a configuration control system to ensure the continued integrity of the simulator as qualified. The configuration control system may be examined by the FAA on request. Modifications which impact flight or ground dynamics, systems functions, and significant ATG revisions may require an FAA evaluation of the simulator. The FAR requires that simulators must maintain their approved performance, functions, and other characteristics.

DISTRIBUTED INTERACTIVE SIMULATION (DIS)

Current DIS Applications

A step up from using a single simulator to evaluate a procedure or new avionics equipment is to create a network of real-time simulators operating as individuals within their own separate domains, but dynamically connected to transfer data real-time between cockpits, and, possibly, with a central control center via modem and phone lines. Data collection can be done at the individual sites and/or at the control center. The possibilities for interactive operations are practically unlimited. This process has proven extremely useful for parallel runway operations and data link prototyping (Ozmore and Morrow, 1997, Ozmore and Morrow, 1996). Other near term uses includes cockpit display of traffic information and converging approaches. The FAA currently is implementing a program known as the Operational Evolution Program (OEP) that will perform large-scale interactive simulations involving simulated aircraft dynamically linked to Air Traffic Control facilities operating in the projected 2010 National Airspace System.

OTHER APPROACHES TO SIMULATION

There are a number of approaches to simulation including virtual and constructive simulations of varying degrees of fidelity, realism and complexity. In any constructive simulation you will be dealing with a physical representation of systems components or cockpit layout, possibly using actual aircraft hardware and software. These all have a valid role to play in program development. In fact, many part-task, limited simulation programs targeting specific systems, such as GPS, TCAS and CDTI, are an essential step towards final design and full integration that needs to take place in a full-mission simulator or aircraft.

Virtual Simulation

The latest simulation technique is referred to as virtual simulation. A virtual cockpit is a representation of a single device with operational logic and graphical representations of cockpit components and controls. It allows a designer to dynamically interact with functional components and to evaluate, and refine, concepts within a short period of time. These models can then be integrated with other virtual models and functionally integrated prior to actually constructing a hardware-based system.

Virtual simulation has its place in the overall process of program design, but it also has very definite limitations. Through virtual simulation a designer can model, animate, operate and integrate a new system, such as a display, into a virtual cockpit on a computer. The skills required, and the process itself, are extremely complex, but the value of the model is only as good as the designer's input. It is essential that any flight operational evaluation ultimately be based on a pilot-centered design with a qualified pilot at the controls, and operating in a realistic environment. Even if you have a pilot "flying" the virtual model on a computer, it is still not a realistic environment. Virtual simulation is at its most valuable when used in the conceptual design stages, evaluating proposed changes, and for quick looks at "what if" scenarios with clearly defined variables.

It is possible today to link constructive simulators, such as approved pilot training devices, with virtual simulators where the constructive cockpit reflects the current technology or procedure, and the virtual simulator can be set up to reflect proposed design changes. Another use, and one used more often in technical evaluations and risk analysis, is to take actual flight test data from piloted approved simulators or aircraft, install it on a virtual aircraft model and run fast-time simulations for risk assessment or feasibility studies. These virtual aircraft models are very complex, in fact, can be similar to the sophistication of advanced simulator programs, representing specific aircraft models and performance. This enables one to get some of the data needed in spite of the limited availability of simulator and test pilot resources.

The value of virtual modeling for engineering design work and systems integration is without question. The results speak for themselves, but we need to remember that it is essential that we strive to keep the human in the process. Any tool is at its most valuable when used properly.

REFERENCE MATERIAL

The growing interest in aviation human-factors has led to a growing emphasis within professional organizations. SAE G-10, Human Factors Engineering Committee has, and continues, to publish a wide range of materials specifically related to aviation topics. RTCA, AIAA, and IEEE have expressed a growing recognition that there is a need for more relevant human-factors material that can be utilized in the design and implementation of new systems. The Bibliography contains a listing of reference materials used in this document that contain valuable insight into the subjects of behavioral psychology and aviation human-factors.

Copies of the documents printed by government, engineering, and professional organizations are available from the following sources, or, if unpublished, from the authors:

FAA AC documents are available from:

US Department of Transportation
Utilization and Storage Section
M-443.2
Washington, DC 20590

SAE publications are available from:

SAE
400 Commonwealth Drive
Warrendale, PA 15096-0001

RTCA/EUROCAE documents:

RTCA Inc.
1140 Connecticut Ave, Suite 1020
Washington, DC 20036

MIL Standards:

DODSSP
Building 4D, Customer Service
700 Robbins Avenue
Philadelphia, PA. 19111-5094

CHAPTER III

MAJOR ISSUES WITH CONDUCTING OPERATIONAL EVALUATION PROGRAMS

The fundamentals and infrastructure that must be in place in order to conduct high-end real-time pilot-in-the-loop human-factors and equipment operational evaluation programs is extensive. We will look at the process of developing a test plan, the planning and coordination process, and examples of some specific programs that have been successfully completed using the process discussed here.

RESEARCH METHODOLOGY

All of the programs discussed here have been completed on Level C or D FAA approved commercial flight training simulators. Preliminary analysis was often accomplished either on computer workstations, or lower level devices, during early phases of the programs to conserve valuable simulator time. Data collection was accomplished using a personal computer (PC) interfaced to the parent simulator computer through RS-232 communications ports already in existence on the simulators. Data was collected in the PCs and, in some cases, transmitted via standard phone lines to a central facility for collection, storage, and processing. Where the data was not transmitted it was collected on disks, and sent to a central location for processing. SISO Compliant Protocol was not used because existing devises were not equipped and the associate cost and overhead were not warranted.

Test subjects were qualified professional pilots, and, where used, active air traffic controllers. Test scenarios were constructed so as to provide a realistic operational environment for the test subjects. Scenarios were initiated and controlled from on-board simulator instructor's facilities. Special pages were constructed to facilitate activation of the scenarios, and to monitor the progress of the testing and data collection.

INSTRUMENTATION

In the majority of the operational evaluations discussed here, most of the data was collected in a passive manner from the simulator database. Virtually any variable generated within the simulator software system is available for collection. Although there is no count of the number of variables available, it is easily in the thousands. If variables are needed, but not generated in the simulator, it is generally not difficult to calculate values for them from the simulator software and database. Sometimes it is necessary to generate faults and errors not already present. These can generally be generated without great difficulty.

Studying human behavior in a realistic test environment is not always easy. Performance can be measured by evaluating the corresponding input responses, and aircraft performance and tracking, much as it is done for accident investigations from on-board aircraft data recorders. It is desirable to not introduce anything that will inhibit or modify normal behavior in operational evaluations. However, in some cases it may be necessary to utilize head-tracking devices, physiological monitoring devices, or new equipment not normally fitted on the flight deck. Invariably, such devices will modify test results to some degree, so their use should be clearly stated and described to help qualify the results.

BUILT-IN LANDING PERFORMANCE MONITORING SYSTEMS

Many simulators have built-in performance measurement systems that may, or may not, be suitable for use for operational evaluation programs. Most systems have Crash/Hard Landing and Unsuccessful Landing Warnings that are incorporated into an automatic evaluation feature for the purpose of determining the quality of each approach and landing performed by students. After validating existing simulator logic, each run may be evaluated using these performance measurement systems and recorded with a data flag set to indicate the run did not satisfy all the criteria evaluated by the Crash/Hard Landing or Unsuccessful Landing Warning systems, as appropriate. If other limits need to be defined to evaluate performance, these can be added to software without major changes, and without effecting equipment flight performance.

As an example, on the FAA simulator the following conditions will activate the "Crash/Hard Landing flag:

- Bank Angle greater than +/- 6 degrees.
- Pitch Angle greater than 8 degrees.
- Nose gear touches first.
- Rate of descent greater than 13.38 FPS[8].

Landing Warning - The following conditions describe landing performance normally used for performance standards for autoland systems, but work equally well when used to monitor landing performance for manually flown approaches and landings (FAA, AC 20-57A). They can be set to activate a "warning" flag in the data. It is suggested that they remain activated for a period of at least 20 seconds to allow visual detection by the test monitor:

- Touchdown more than 2500' down the runway.
- Touchdown less than 200' down the runway.
- Center of mass more than 56 feet from centerline with touchdown.
- Airspeed below VREF-5 with go-around.
- If lateral tracking deviates more than 56 feet from centerline during final 50 feet of approach and landing.
- If the rate of descent, at touchdown, is greater than 10.38[9] FPS.

PROJECT PLANNING, DEVELOPMENT, AND COORDINATION

An approach successfully applied to the conduct of past simulation evaluations has been one of an open atmosphere associated with evaluation planning, development, and simulation execution. This requires full coordination by all interested government and industry segments. It also requires a sincere effort on the part of initiating parties to seek active participation in the planning and implementation from operators, pilots and pilots' organizations, aircraft and aircraft system manufacturers, technical societies, relevant government agencies, and private organizations.

Reporting Results of the Simulator Evaluation

A report of simulation results should be completed and coordinated with the principals that participated in the planning and implementation of the evaluation. The coordinated report

[8] This value is generally based on the maximum certified touchdown rate for the particular aircraft. This was a B727-200.

[9] This value will work for a B727-200, but may need to be adjusted for other aircraft types.

should be made available for distribution as soon after the evaluation is completed as possible. Most organizations have a formalized process for printing and distributing documents. If not, the project manager may be required to handle the work. The resources for this effort should be identified during the simulation planning process. In the past, many studies were completed without formally documenting results, lending to the necessity of repeating the studies again when new issues arise.

Remaining Focused

The technical nature of most operational evaluations makes it imperative that the developer of operational evaluation programs remains focused on the problem at hand, while maintaining an awareness of the effects that the outcome will have on the entire NAS system. The implication is that, because of the complexity, adjustments may need to be made to accommodate other elements in the system. Efforts should be directed at solving the current problem, and peripheral problems should be handled separately and not allowed to interfere with the results of the evaluation underway. It is imperative that a systems approach to solving aviation-related problems is taken.

Maintaining Credibility

One of the most critical considerations is that any evaluation program must have input from all the stakeholders. These will normally include the aviation industry, equipment manufacturers, organizations representing some known constituency, such as ALPA, ATA, SAE, ICAO, other private organizations, and relevant government offices. This ensures a thorough evaluation of the issue, with critical input from those most concerned with the outcome, the stakeholders. Another benefit to be derived is that a consensus solution can be developed involving all affected parties before any potentially ill-fated implementation is attempted. An open approach will minimize mistakes and ensure a thorough review with adequate input from all parties.

Another direct benefit from this open approach is the credibility developed with the stakeholders during the process. If participants are convinced that an honest, thorough, and practical evaluation is being conducted, with their concerns being earnestly considered and evaluated, continued support and cooperation is assured. It is essential to gain and maintain trust, but we must also use appropriate equipment, procedures and test subjects to support acceptance of the validity of results.

Funding and Resources

Unless you are extremely fortunate, there will always be constraints on available funding and other resources needed to conduct simulator evaluations. However, certain approaches have proven to be effective in acquiring the required resources. Utilizing existing resources before starting procurement activities is the most obvious, cost effective, and efficient approach to completing a program. Designing infrastructures to support repeating issues with upgradable components is one. Often, you can design a program around existing resources, or design an evaluation in such a way that resources can be reused on future projects. Obviously all the equipment appropriate to do every program is not available within the organization. However, many times other stakeholders will provide access to equipment on a cooperative basis, and ALPA, APA, and other professional organizations have demonstrated a willingness to provide pilots as test subjects, minimizing internal funding requirements. All avenues need to be explored for resources when developing a formal operational evaluation program. Each evaluation program must be examined individually based on safety implications, cost, resources available, complexity, and time requirements to determine the most appropriate approach.

Level of Simulation

The preferred approach recommended in conducting an operational evaluation is the use of real-time pilot-in-the-loop operational simulators possessing a high level of fidelity, and having the designation of approved Level C or Level D simulator devices. Other methods of simulation such as numerical analysis, graphic plotting, mathematical or system modeling, and part-task simulation are valid techniques for use in certain situations, and these should certainly be used when appropriate. However, the acceptance provided through flight crew inputs, the opportunity to develop operational procedural enhancement, and identify training needs generally dictates that the highest level of simulation, appropriate to the particular task under evaluation, is the preferable approach.

EVALUATION PLAN

Any research program will involve the following elements: (1) identifying the problem, (2) considering alternatives, (3) selecting the most appropriate approach, (4) preparing a test plan, (5) conducting the evaluation, (6) analyzing the results, (7) operational implementation, and (8) in-service evaluation and feedback.

Over 60% of the time and effort used on a given program will be expended completing the planning, coordination, and analysis. Less than 40% will be used doing the actual physical testing. It is essential that everyone involved be brought into the process as soon as practical, and that a system of coordination and feedback be established early to support the tasks of quality control, funding, scheduling, and implementation. Some of the steps can be combined, but they must take place to ensure success.

Identifying the Problem

Identifying the real problem is essential if you are going to design, develop, and implement an effective program. It helps if someone in industry has a well-defined requirement. Always remember that anything changed in the system can have extensive human-factors implications, and changes must assure continued adequate situational awareness for crews. The design should be human-centered to the extent possible.

Identifying the problem means focusing on something that has a practical solution. This will provide a useful product in a more-timely manner. In order to be manageable, some complex problems must be broken into parts and incrementally addressed, as was discussed in systems engineering principles. Good examples of this are GPS, TCAS and multiple parallel approach programs. It is often difficult to solve complex problems in a wholesale manner, but using an incremental approach often provides early results for interim solutions which can be applied by others working related elements of similar, but larger, problems. Working carefully, selected pieces can also provide the flexibility needed to cope with rapidly changing technologies and priorities.

Some problems are difficult to solve due to state-of-the-art of a technology, cost, safety considerations, manpower requirements, or other causes. A cost/benefit analysis is one method that can often be used as a guiding factor. If the cost/benefits study will not stand up, it could reflect the lack of a proper problem definition or need.

In many cases, developing an accurate definition of the problem to be solved will help a great deal with the identification of specific areas needing work, as well as identification of the approach that should be taken to solve the problem. Any definition of the problem must include a clear and concise definition of success. This will establish the scope of the program and often defines the resources needed.

Developing Alternate Solutions

The objective is to arrive at the best overall approach for the evaluation. Total cost, resource availability, time constraints, industry support, and funding may dictate a single approach. You should at least identify and consider alternatives, and be prepared to recommend the optimum solution even though you might have to settle for something less than ideal. There are limits on how far you can back off and still do an acceptable job, and this must be acknowledged. If there are a number of alternatives offered and a consensus can't be reached, an unclear understanding of the original problem may be the cause. In this case the problem may need to be redefined. Inexperienced participants have a tendency to expand the scope of the task and include too much in the evaluation. This can lead to results that are of little real value in answering specific questions. Stay focused.

At the same time alternatives are being considered, contingency plans should be developed in case your first approach fails to materialize. This is especially important on time critical programs. Establishing contingency plans will help assess resource requirements, may determine the priority in certain approaches, and should enable you to respond to rapidly changing program requirements.

Considering Alternatives

This is a good time to start including the stakeholders in the process if it has not already been accomplished. A detailed examination of the alternatives will establish resource requirements, determine schedule requirements, and should identify the proper approach. Selection of the most appropriate method of evaluation normally falls out of this process automatically. Complex programs usually require strong industry input and support, and generally dictate using experienced subject pilots in real-time pilot-in-the-loop testing. This also involves rather extensive data collection for objective analysis. The method selected should provide a highly credible approach that will provide a clear and conclusive solution with active input and participation by all players. The use of full flight simulators provides credibility, especially with industry involvement. Always communicate with other stakeholders in terms that they can understand.

Typical Elements of a Simulator Evaluation Plan

An evaluation plan should contain the following information:

- Introduction
- Purpose
- Success Criteria
- Initial Conditions
- Weather Conditions
- Test Implementation Procedures
- Simulator Operating Instructions
- Scenario Initialization and Activation

Participant Briefing
Instructor Master Control and Scenario Page, or details on other methodology
Status Monitor - if applicable, for crash conditions, hard landing, etc.
Data Collection
Test Scenarios
Appendices

A - Data Collection, Fidelity & Validation
B - Approach charts for simulated runway
C - Approach Light configurations
D - Specified Flight Procedures
E - Visual Light Readings
F - Simulator Test Schedule
G - Pilot Data
H - Pilot Comment Sheet
I - Description of Navigation Model (if appropriate)
J - Observer Log

Preparing the Evaluation Plan

The test plan should include the following:

- Statement of Problem.
- Validation of simulator or systems for task at hand.
- Clear, concise definition of success.
- Adequate background material to make it's need clear.
- Accurate description of simulator or the equipment used.
- Detailed procedures for test implementation.
- Detailed pilot operating procedures.
- Detailed scenario description.
- Explicit information on data collection and parameters.
- Technical description of equipment systems of particular interest for the evaluation, such as visual system, automatic pilot, HUD, TCAS, etc.
- Number of pilot subjects to be evaluated.
- Description of any simulator systems modifications needed to conduct the test.

The test should be implemented in such a way as to allow a totally random sequencing of scenarios. On most simulators, the test can be automated via the instructor's facilities for test set-up, data collection, fault activation, and position resets. Each scenario should start from an explicitly defined set of initial parameters and positions to avoid induced variability and errors.

The number of test pilots needed and the number of scenarios each should fly will vary with the test, but some general guidelines that I have developed and have served well in the past follow below. My evaluations are considered either a "Proof of Concept", or a "Program Evaluation". A proof of concept normally requires at least 8 or 10 qualified test pilots, and is used as a quick look, or feasibility study, for a change to an existing procedure or policy, with extremely low safety and operational risk. A program evaluation, on the other hand, is an exhaustive detailed scientific study of a new procedure or technology that could carry higher risks. This requires a minimum of 18 pilots, with more preferred. The number of pilots needed in either case is considered enough to give a valid basis for statistical analysis of the results[10].

The number of runs on each scenario also varies, but a minimum of two runs on each scenario, plus some baseline runs, are required. The baseline scenarios can be used to benchmark an individual pilot's normal performance under a given set of circumstances. The approximate time required for each scenario run varies, but the following guidelines generally apply:

Approach to landing	6 minutes each
Take-Off to 800 feet	8 minutes each
Loft type scenario	12 minutes average

Test Subjects

A pilot can be expected to demonstrate top performance for approximately two hours, but after that, in a high stress test environment, performance can be affected. A minimum four-hour break is recommended if a pilot is to return for a second session. In most cases, test periods should be limited to two hours per day.

Test subjects should normally be rated and current on the aircraft type being used with at least 100 hours in the last six months, and preferably be current line pilots. These requirements vary sometimes, depending on the purpose of the evaluation and the population of test subjects available. On some evaluations, a two-man crew may be required if crew coordination is critical. Otherwise one qualified pilot with a second qualified pilot as second officer is acceptable.

Pilots should be given a briefing, with the amount of briefing time determined by the task at hand. There should be at least one test observer, in addition to a simulator operator, in the cockpit during all data runs. If the evaluation is highly complex, an additional test coordinator may be warranted. The simulator operator should initialize the equipment set-up, activate data collection, and coordinate crew activities. A separate test coordinator may be used to assist with the tasks and help complete crew questionnaires. The test observer should be a well-qualified observer that can take detailed notes and make subjective comment on crew performance.

Test Documentation

The following information/data should be collected on each run and used when evaluating the results:

- Pilot questionnaire - Pre-flight on pilot's background and qualifications.
- Operator's Log - Filled out during test to comment on anomalies, equipment failures, etc.
- Observer's Log - Professional subjective evaluation and comments on crew/pilot performance.
- Post Flight Questionnaire - Filled out by pilot, usually answering specific questions pertinent to the test and general comments.
- Objective Data - Collected real-time for each scenario showing relevant performance parameters to allow an objective evaluation of performance.
- Video and Voice - Collected real-time for each scenario in the cockpit to assist with evaluation. Be aware that some test subjects are not comfortable with this, and all

[10] The number of pilots, or test subjects, is always controversial. In pure statistical terms, you probably never have enough, since the more subjects you have, the more accurate the results will be. But, practicalities dictate that you must design around much fewer. The fact that they are all similarly skilled, experienced and trained helps in this regard by creating a fairly homogeneous group.

subjects should be told if they are being recorded. If the recording can't be done, the questionnaires and observers logs become even more critical.

All of these materials are critical to an accurate evaluation and should be retained for further reference if needed. Data and information has been revisited from previously conducted evaluations that were as much as 10 years old.

Equipment Configuration Control

Many programs will eventually involve more than one phase. This requires thorough documentation of modifications to equipment, briefing materials, and approved questionnaires and forms. This documentation should be retained for future use. One of the difficulties with using outside resources is the loss of the infrastructure developed for a particular program, and since different sites may be used, redevelopment of the infrastructure may be required. This adds considerably to the time and cost of conducting evaluations.

Simulator Costs

Pilots, simulator time, and equipment are expensive resources and extremely difficult to obtain. These should be used efficiently. If a program requires 80 hours of simulator time for data recording, at least that much simulator time is required for program development, scenario debug, and equipment preparation. If extensive modification is needed, this can easily double. Hourly simulator costs for a Level C or D device varies from around $300 to more than $1200, depending on the aircraft type and availability. A good average across all aircraft types would be around $600 per hour. In addition, you have flight crew costs, travel, equipment modification, equipment operators, and other costs. As a general rule, outside testing costs substantially more for the same class of equipment than if you have the capability of doing the work in-house, and in-house prototyping is more convenient and less costly. Equipment availability varies with the operation, but operators usually expect a minimum of 16 hours per day utilization from their simulators, including weekends and holidays. You can expect to work during off-hours to accommodate the operator's needs. There will be little room for flexibility. Training schedules can be established up to a year in advance, and are usually difficult to change.

Simulator Availability

An FAA simulator inventory (FAA, 1998), representing virtually every approved commercial airplane cockpit currently in service showed that there were 265 Level C flight simulators, and 109 Level D flight simulators available, most in the United States. The physical simulation of any airplane encompasses the entire flight deck area forward of the bulkhead, which is aft of the pilot, copilot, and the flight engineer station, if used. The simulated area is a facsimile of the actual aircraft flight compartment down to matching an aircraft tail number, and maintained to satisfy the performance standards of FAA Advisory Circular 120-40. Deviations from these configuration standards may be required during evaluations should installation of non-certified equipment, or non-certified software, be required to satisfy the objectives of a particular evaluation. Generally, software changes that cause aerodynamic performance changes from the original database are avoided. This ensures true fidelity for the aircraft system being tested.

Simulator Visual Systems

By definition, a simulator that qualifies as Level C or D will have either a daylight or dusk/night visual system installed. The visual system provides the real-time out-the-window computer generated image scenes consisting of lights, edges, and surfaces representing the visual environment. The visual system responds to flight simulator data defining viewing conditions, and displays to the flight deck occupants the updated images through collimated near infinity optics. The visual system transforms numerical data representing the three-dimensional visual environment into two-dimensional perspective images and then processes these images into signals to drive the displays. The visual system produces successive images at a rate sufficient to give the impression of smooth analog motion as the observer, or moving scene object, changes position and/or altitude. Daylight or night/dusk ambient illumination, landing light illumination, weather effects, and various special effects may also be simulated. Included in the list of weather effects are the following weather characteristics:

- Reduced Visibility - Gradual obscuration of scene details with fog.
- Partial Obscuration - Random smoothly varying visibility in cloud bottom transition layer that produces glimpses of the ground simulating patchy fog during final approach.
- Ground Fog - Altitude, visibility and RVR control settings determine the rate of visibility reduction during descent into a ground fog layer. Can normally be made patchy.
- Lightning effects.
- A full range of light intensity adjustments.

Automatic Flight Control System

The simulator will be equipped with the automatic flight control system appropriate to the aircraft being replicated. The simulator system will be fully operational through all ranges of flight, including unusual or abnormal conditions, and function as on the aircraft. The system can include an FMS or autopilot, or both.

Airport Models

Simulator facilities meeting the qualification requirements will have the capability of cockpit selection and replicating the environments of several U.S. airports. This includes the physical layout of runways, taxiways, obstructions and other key features. It also includes appropriate radio aids to navigation and lighting systems. Similar airport database capabilities will be available on all simulators, with the airports present being determined primarily by an operator's training needs. Most operators will have six to twelve models available. Visual databases used for evaluation programs must be reviewed prior to testing to ensure currency with the airport configuration. Airports are constantly undergoing changes.

Scenario Development

A system of scenario replication should be provided in the simulator to organize the various evaluation conditions into manageable units. These scenarios, depending on the particular type of evaluation being conducted, may include such things as approach and runway lighting settings, weather-related conditions such as RVR values, fog and cloud ceiling conditions, wind conditions, and anomalies of the selected system(s) to be evaluated. The scenarios can be identified by three-digit numbers, or other differentiation, to provide a means of controlling the implementation of simulated conditions and a means of correlating the recorded data with the particular simulator run for data analysis.

Test Numbering Convention

It is essential that a consistent numbering convention be established that will identify the scenario, test subject, and run number. One system that I have used successfully is a unique 6-digit dd/d/ddd identification number that is assigned to each test run. This number is stored as a data variable with each data sample. It allows precise tracking of scenarios and pilots for future use in analysis. Implementing such a numbered input is not difficult from the instructor's facilities.

CHAPTER IV

MAJOR RESEARCH AREAS

EVALUATION PROGRAMS

Looking at several actual operational evaluation programs that have been completed using the methods and processes that we have discussed will demonstrate the process. The ones chosen for discussion represent the introduction of new cockpit displays, use of a head-up display system for new operational applications, development of a wake vortex model, evaluating all-weather operations, simultaneous parallel closely-spaced runway operations, evaluation of airport lighting, foam arresting bed modeling, and a simulation to validate theoretical values for entertainment laser devices. These programs have been chosen in part to show the range available for simulator evaluation applications, and, in part, to demonstrate the complexity of some of the evaluations.

Other Considerations

It would be nice to think that all decisions will be based on the results of carefully constructed scientific evaluations. But, as with any research, the final decisions will have to take into account political influences, availability of resources, program funding, economic considerations, and expediency. The results do generally support the application of higher safety standards, better training, better human-factors designs, and more efficient operations, but often not to the levels originally envisioned. It requires a conscious effort for the researcher to not become disillusioned, or distracted, by the interference of these factors, but to work from within to get results that will offer the greatest benefit under the circumstances. Obviously there are situations where compromise is not possible, such as accident investigations, but most of the time the participants are aware of this, and will support the endeavor.

The Evolutionary Process

Not always, but in most cases, advances in aviation, as with most fields, evolve from existing science or technology over time. A massive infrastructure already exists with huge investments in equipment, parts, training, and personnel that must operate in a well define national airspace system already in existence. Revolution is expensive, and produces a lot of casualties. Evolution is much less wasteful, and allows the system to adjust to the changes and compensate for any mistakes that might occur. In our present operational environment, the marketers preach revolution, but, in reality, usually have to settle for, and are actually offering, evolution.

Aviation is no exception. Sometimes it seems that we are being overwhelmed with change, but when you look at what has happened, it has taken many years. Computers are one case. In reality, computers have now been in wide spread usage for 40 years. Desktop computers have been relatively common for 15 years. The same applies to aircraft systems. The Boeing 727 and early 737 aircraft have been in service for 30 years, the 747 for close to 30 years (Jane's, 1994), and when you look at the engines, cockpit displays, and other onboard systems, they have changed, but remain very much recognizable.

Situational Awareness

Situational awareness is a continuous perception and understanding of one's self and the aircraft in relation to the dynamic environment in which they operate. You can break it down further as visual awareness, positional awareness, attitudinal awareness, or traffic awareness, and there are others. All the training provided to pilots, and installation of aircraft sensor and display systems, is to try to improve the pilot's situational awareness.

Flight Deck Automation

One book on cockpit automation published in 1980 accurately warned us of the dangers of cockpit automation and workload (Wiener, 1980). We still hear the same concerns, but we are just now facing the true consequences of the technology. The concerns were valid in 1980, and are even more so today. The evolution of microprocessors has brought us to the point where it is possible to install the devices in virtually any sized device, including on-board aircraft systems. It is a well-known phenomenon that the availability of something creates pressure for its use. But, particularly in aviation where public safety is at stake, there has to be a reason to use something. It also must buy its way onto the aircraft with rapid financial or safety benefits. Otherwise it may show up as a product on the next generation of aircraft. Any new system must also fit the mental models that participants, including pilots and air traffic controllers, have of their piece of the aviation environment. It is counter productive to develop a system that may appear to reduce pilot workload, and then find out the pilot does not understand the innovation well enough to take control when necessary.

Most of the new systems going into aircraft today involve automation to some extent. Head-up display, flight management, and flight director systems provide integrated representations of information that previously required mental integration by the pilot. On the surface, we have reduced the pilot workload, but due to the nature of electronic displays the pilot is forced to work in a much more tighter control loop. The result can be more stressful, and can actually increase workload, even though it may improve pilot performance under normal conditions. Most of the new systems rely on a higher degree of command guidance, so care must be taken to ensure that the pilot maintains situational awareness in the event that manual reversion is necessary. Any system involving automation will have similar tradeoffs.

New Cockpit Displays

We have seen the introduction of several new display systems into the cockpit. Most of these are retrofitted onto older aircraft, and show up as an integrated function on newly manufactured aircraft. These include traffic collision avoidance (TCAS), global positioning systems (GPS), wind shear detection and guidance, and head-up display (HUD) systems. For our discussion here, we will look at one of the most recent: the cockpit display of traffic information, or CDTI, currently being installed by the cargo carriers.

Cargo carriers have been exempt from TCAS requirements, even though they have it on many of their aircraft as a result of purchasing already fitted aircraft. In an effort to capitalize on the advances in technology, and to be in a position to gain full benefit from many of the new data linking technologies, they have opted to design a new generation of equipment. Certification efforts are currently underway for a limited application of the equipment, with further functionality to follow.

Inevitably, questions arise about why these same enhancements were not simply added to the existing TCAS. There are several reasons, some political, some economic, and some regulatory. The political and economic reasons are closely related. The commercial aviation industry was forced to install TCAS by the FAA as a safety enhancement several years ago, which the industry has since embraced as a substantial safety improvement. Any effort to force more expenditure is met with fierce resistance. Earlier we discussed evolution versus revolution, this is an example of such a situation. To scrap the existing TCAS equipment and install a new system would be cost prohibitive. Not only would you be losing the previous investment, but also you would have to pay for new equipment with related training and support infrastructure costs. On the other hand, if you are a cargo carrier with no previous investment, you might as well go for the newest technology.

Another consideration is the considerable certification investment that the operators have made in TCAS. There is currently an update being released for the TCAS that will enhance some functionality, but once a system is certified, there is a great reluctance to do anything that will require a new, large-scale certification effort. Again, it is money. As new aircraft are designed and put into service, no doubt they will be fitted with the new equipment.

Simulation of the Cargo Carriers CDTI Implementation

The cockpit display of traffic information, CDTI, system is undergoing evaluation for certification by the Cargo Airlines Association, CAA, as an alternative to the TCAS equipment currently available. The CDTI utilizes advanced data link capabilities between equipped aircraft and between aircraft, and ground stations. The Link and Display Unit, LDPU will fuse traffic data from three different Automatic Dependent Surveillance-Broadcast, ADS-B, sources: Mode S Transponder, Universal Access Transceiver (UAT) and VHF Data Link Mode 4 (VDLM4). Data available through the ground based Traffic Information System (TIS) provided by the FAA's air traffic service will augment the system as it becomes available. There is a built-in GPS receiver in the LDPU for position information. In order for aircraft to see each other using the system, both must be equipped with appropriate hardware and displays. The CDTI will be able to use any of the three data link protocols, along with TIS, to detect and display air traffic. The CDTI can have a range greater than 150 NM.

The initial phase of the CDTI implementation will use the system only as an aide to visual acquisition. The crews are not authorized to use the CDTI for guidance or conflict resolution, and can maneuver only after visual acquisition has been achieved. All normal VFR procedures apply, and the pilots will maintain normal head-up and head-down scan.

The CDTI represents the first application of the type for display of traffic information. It has expanded capabilities compared to current systems, and incorporates several technological advances. It is the feeling of most who have flown the system that it provides better overall situational awareness than anything currently in use.

The simulator evaluations provided a collaborative environment for the cargo carriers, FAA operations, FAA certification officials, NASA and others to evaluate the training and briefing materials that will be distributed to the flight crews, and a method of validating proper operational integration of the new technology into the cockpit.

The objectives of the Phase I CDTI testing were:

- Evaluate pilots bulletins being released to Federal Express, UPS and Airborne flight crews that will be flying the CDTI during flight tests, scheduled for the summer of 1999.
- Evaluate the training materials that will be distributed to the Federal Express, UPS and Airborne flight crews for use during the flight evaluation work.

- Evaluate the overall effectiveness of training/briefings given to flight crews.
- Make a preliminary assessment of the human factors issues associated with implementation and use of the CDTI.
- Evaluate the effectiveness of the CDTI as an aide to visual acquisition.
- Provide a collaborative environment for the FAA, CAA, manufacturer, and Certification officials to identify and resolve potential problems and issues associated with deployment of the CDTI, and introduction of the new technology.
- Provide a solid basis for approaching flight trials in 1999, and for the more rigorous applications of Phase II.

The CDTI is the result of integrating several new technologies into the aircraft cockpit to provide improved situational awareness and operational safety. The system depends on the new FAA Traffic Information System, TIS, technology, and on data linking to other suitably equipped aircraft and ground stations to provide an accurate depiction of other air traffic in the area. While the CDTI can have an operational range of over 150 NM, scenarios in the simulator were limited to terminal area operations since that phase of flight operations is recognized as the most dangerous (Flight Safety Foundation, 1998). The accuracy of the information provided is as accurate as the GPS information being used to supply identification, position and track data, and the update rate is once per second versus over 3 seconds used by most existing conventional systems.

Head-Up Display Systems

The use of a head-up display (HUD) system can make a mediocre pilot good, and a good pilot great. This observation was made by a senior Delta Airlines Captain, since retired, during the low visibility programs we will discuss below. The Captain's comment was made in reference to the fact that the performance loop is so tightly coupled that the pilot virtually becomes a part of the aircraft control system. Comparative performance measures consistently show a HUD equipped approach has similar performance to that of an autoland approach. The workload can be intense for the pilot, and the pilot not flying must use specific procedures to ensure backup monitoring of aircraft systems, since the pilot flying the HUD cannot see the head down (HDD) displays.

HUD systems have been in common usage in the military in high performance aircraft for over two decades. There is a considerable difference with the strategic missions in the civilian world, however, requiring the systems to undergo considerable redesign before they could be adapted to commercial aircraft. Consequently, there have been problems getting some civilian pilots to accept their use because of the command nature of the guidance. Younger pilots with military flight backgrounds, however, accept their usage largely without hesitation. With their growing usage, the resistance to their use has all but disappeared in recognition of the safety benefits.

Categories of Low Visibility Conditions

HUD systems in the commercial aviation world are most valuable in low visibility landing situations. The FAA maintains a “see to land” operational concept. What this means is that a pilot must achieve visual contact with the runway before landing, regardless of the operating minimums. The descriptions of current visual operational categories taken from AC 120-29 and AC 120-28C are shown below:

Category I: An instrument approach procedure which provides for approaches to a decision height (DH) of not less than 200 feet and visibility of not less than ½ mile or RVR 2400 (RVR 1800withoperative touchdown zone and runway centerline lights).

Category II: An instrument approach procedure that provides approaches to minima less than DH 200 feet/RVR 2400 to as low as DH 100 feet/RVR 1200.

Category IIIA: A precision instrument approach and landing with no decision height (DH), or a DH below 100 feet (30 meters, and controlling runway visual range not less than 700 feet (200 meters).

Category IIIB: A precision instrument approach and landing with no DH, or with a DH below 50 feet (15 meters), and controlling runway visual range less than 700 feet (200 meters), but not less than 150 feet (50 meters).

Advantages of HUD in Low Visibility Approaches

All restricted visibility categories currently require visual acquisition of the runway at the operating minimums for that runway at that airport. There is a Category IIIC that will allow landing with no visual reference, but the procedure is not approved operationally at this time. Failure to achieve visual contact with the runway requires that the pilot execute a go-around, or missed approach, and re-establish the approach. Most people are familiar with accident reports where a pilot tried to force a landing only to have an accident. There are a number of operational and human-factors issues that can lead to the forced approach syndrome. One is that the pilot has been gone several days, is nearing home, and will not be deterred. Another is the amount of time that is lost if a pilot has to perform a missed approach, and then get a new landing slot. This often involves entering a holding pattern until air traffic control can work the aircraft into the pattern again. And finally, company pressure on flight crews for on time performance. Although companies will not publicly advocate dangerous operations, they have been known to impose pressure on flight crews to take any measure possible to maintain on-time service and save fuel.

HUD enables the pilot to remain heads-up during the approach. This means that he does not have to transition from head-down to head-up during the final approach. The critical flight information is displayed full time on a see-through combiner glass that allows monitoring of the out-the-window visual scene while watching aircraft performance data displayed in essentially the same format as heads down. The first officer monitors heads down information and calls out critical information to the pilot. The pilot sees the runway immediately when it becomes visible.

Problems with Using HUD

The use of HUD is not without it's problems. The pilot's eyebox is a relatively small area where a pilot must keep his eyes in order to see the HUD symbology. This can be uncomfortable when pilots first start using the system, or for extended periods, but since current applications generally require only short periods in the position, pilots adjust rapidly. Other human-factors problems are related to the nature of the human visual system. It is possible to focus on the outside world and look completely through the HUD symbology without seeing any of it. By the same token, it is possible to focus on the symbology without seeing the outside world.

HUD Training

Training in the proper use of the HUD, and procedures to strengthen crew skills mitigate most of these problems. Use of a well-designed conformal HUD is very intuitive, but it still takes practice to master its usage. The pilot must develop scanning skills similar to those used head-down, including scanning the content of the symbology, but also including a scan of the outside world. HUD usage, as with most piloting skills, deteriorates with fatigue, and in stressful situations a pilot develops "tunnel" vision that excludes much of the information available from peripheral vision. It has been my experience that it requires four to eight hours for pilots to become reasonably comfortable with, and competent, with operating the HUD for limited applications. Longer for full proficiency.

Operational Procedures

One of the most demanding problems is for the pilot flying the HUD to have to transition between the head-down displays and the HUD. Moving in either direction requires an adaptation period. The most effective procedure to use in a HUD approach is for the pilot to fly the HUD, while the first officer (FO), or pilot not flying (PNF) in a dual HUD installation, to monitor the head-down instruments. The PNF will call out critical altitudes, and monitor engine performance and other instruments. Under most low visibility approaches, autopilot will be coupled, or engaged. The pilot monitors the autopilot performance with the HUD, and can take over control of the aircraft without interruption, if necessary.

Issues

With any new technology there are a large number of issues that must be evaluated prior to operational implementation. These issues are normally compiled and analyzed by professional organizations that enjoy a diverse membership from industry, government, professional organizations, and the military. On HUD systems the most comprehensive description of remaining issues has been compiled by SAE (SAE, ARD-50016, 1997). These issues will be resolved as applications develop, and are often used by the academic community to develop their research programs.

Development of a Wake Vortex Model

Wake vortices are the disturbances generated by an aircraft wing when it is producing lift. The vortices manifest themselves as rotating air turbulence coming from the wing tip of the generating aircraft. The traditional method of avoiding the problem is to fly slightly higher on the glide path than the lead aircraft, and to land slightly further down the runway. The separation standards imposed to avoid encountering the vortices requires building in a time or distance buffer to allow the vortex to exit the flight path.

As we force aircraft closer and closer together, wake vortices will become the limiting factor on closely spaced parallel and higher frequency landing operations. The approach previously used to mitigate the effects of vortices by increasing the in-trail and lateral spacing between aircraft negates the potential capacity gains from increased traffic density. The push is on to increase capacity at airports without increasing the investment in infrastructure.

Separation is applied to aircraft operating directly behind a heavy or B757 jet aircraft at the same altitude or less than 1000 feet below the leading aircraft. Current separation standards imposed by the FAA are (FAA, N7110.157, 1996, FAA, N7110.65J):

Heavy jet behind a heavy jet	4 miles

Large/heavy behind a B757	4 miles
Small aircraft behind a B757	5 miles
Small or large aircraft behind a heavy jet	5 miles

The designation for large, heavy, and small aircraft is based on take-off gross weight maximums. ATC assigns the classifications for wake vortex separation as follows[11] (AIM, 1998):

Heavy - Aircraft capable of takeoff weights in excess of 255,000 pounds
Large - Aircraft capable of more than 41,000-pound take-offs
Small - Aircraft capable of 41,000 or less take-off weights

Also, separation is measured at the time a preceding aircraft is over the threshold. A small aircraft behind a heavy aircraft is 6 miles, a small behind a B757 is 5 miles, and a small behind a large aircraft is 4 miles. Similar requirements are imposed on departing aircraft.

Title 14 of the Federal Aeronautics Regulations (FAR), paragraph 91.3(a) states: "The pilot-in-command of an aircraft is directly responsible for, and is the final authority, as to the operation of the aircraft". The pilot can refuse or accept separation imposed on them based on their appraisal of the situation.

Concerns about the risks associated with wake vortices have increased as the size of commercial aircraft has increased. The strength of a vortex is proportional to the mass of the generating aircraft, in most cases. Studies have been conducted for years on ways to prevent or weaken vortices. But, so far, they still exist, and as aircraft get larger, they get stronger.

While working on a vortex separation program for La Guardia Airport with Dr. Bill Eberle, of Lockheed Missiles and Space Company, it became apparent that, even though we cannot stop the development of vortices, we could train the pilots on how to recognize and respond to them, much as we have done with severe wind shear encounters today. Test pilots that we ran through the program unanimously recommended that a realistic vortex program would be a valuable addition to simulator pilot training programs. Once the pilots experienced the effects, they seldom experienced further upset.

While the physics of what a vortex is, and how it behaves, is fairly well understood, there has never been a realistic model constructed for installation on commercial training simulators. One problem has been the capacity of the simulator host computers, but with the advances of recent years that problem has lessened. With the assistance of Dr. Eberle and others, I have developed a realistic vortex model for use on FAA approved commercial flight simulators. The primary purpose of the model is to improve safety through pilot training, but it will also be used on operational evaluation programs as we force aircraft closer together. The model is now being reviewed by the domestic and international aviation community, and is available as needed for their use.

All Weather Operations

Competitive and economic forces have increased the pressure for commercial air carriers to make on time arrivals and departures, regardless of the weather conditions. The problem is more critical in some markets than others because of prevailing climate patterns. Europe has a worse situation than domestic U.S. carriers, but operators in our northwest and Alaska regions experience frequent weather related delays. Technology has offered some relieve in the form of head-up displays, flight management systems, and improved autopilot systems. But, the pilot still must see to land the aircraft.

[11] Remember, the weight is what they aircraft is capable of, not what it weights at the time.

Current FAA operating rules allow pilots to operate down to Category IIIB minimums of 150 feet (50 meters) runway visual range, and less than a 50-foot decision height with properly equipped aircraft and qualified flight crews. Airlines are constantly opening new routes and installing new equipment that requires re-assessment of operating minima. Each request for a particular low visibility operational approval must be evaluated and approved by the FAA. As a result, operators can apply for, and receive, additional credit for equipment if it can be demonstrated that it increases safety and compensates for the absence of runway equipment or landing aids.

Simultaneous Approaches to Closely Spaced Parallel Runways

As the volume of air traffic has increased, and the cost to construct airport infrastructure, such as runways and land acquisition, have soared, pressure has increased to get more productivity from existing facilities. One of the most frequent targets is the FAA's minimum runway spacing for simultaneous parallel instrument approaches. The current standard is no closer than 4300 feet. For urban airports with limited land available for expansion, this places a maximum limit on flight operations. New technology, both on the ground and in the aircraft, has enabled us to take a look at these standards, and under some circumstances, reduce the separation.

One of the limiting factors is the reaction time of pilots when required to execute missed approach or break out maneuvers. In all parallel runway operations there is a no-transgression zone (NTZ) established between the runways. If, for any reason, either aircraft in the parallel operation blunders into the NTZ, the other aircraft is immediately ordered to turn away from the intruder and break off the approach. At 150 knots aircraft can move approximately 150 feet per second. Given that typical reaction time is around 6 seconds (Human Factors Design Handbook, 1992), a blundering aircraft can easily travel the distance between closely spaced runways and pose a threat to any parallel traffic. In the above scenario, an aircraft could have traveled about 3000 feet in those 6 seconds. In FAA simulator evaluations using professional pilots, we have found the reaction time can be as low as 4 seconds, but we have to anticipate the worst case for safety, including the size of the aircraft. Current standards at parallel runways with high update radar and especially trained air traffic controllers, the FAA has approved operations down to 3500 feet. While others claim greater reductions are possible, each application must be evaluated on it's own merits and circumstances. There are some efforts underway that would use cockpit display systems to enhance reaction times.

Evaluations of Airport Lighting

Airport lighting systems are expensive to install and maintain, but they work great. Often, when considering changes to the current standards, we must decide how much is public safety worth. How do you put a value on situations that do not happen because the current infrastructure prevents it? Often the rationale used to justify trying to reduce standards is that we have not had any accidents or casualties, so it may not be needed, when in fact, not having accidents is why the infrastructure was installed to start with. Not all programs are looking to save cost. Some are looking at improving efficiency, or runway capacity.

Changes to airport infrastructure are extremely expensive. They also frequently require putting a portion of the airport out of service while work is accomplished. The changes also would replace existing systems with new systems that will require training and new parts, and may not fit well with other existing airport infrastructure. Airports, as with airlines, try to maintain a large degree of commonality between systems and components to reduce cost and complexity. Changing anything in an existing airport can require an extended period of time to accomplish.

Simulation has been used extensively to evaluate a number of these proposed changes. It is much quicker and much less costly to do in a simulator than to start pouring concrete. Parallel runway programs have been evaluated for Raleigh-Durham, Memphis, Minneapolis, and Atlanta. In all of the cases, installation of precision runway monitor radar has been required to gain the desired closer spaced operations at an equivalent level of safety to current standards.

A second method of achieving capacity gains on closely spaced runways is through the use of offset localizer, or LDA, approaches. Procedures have been evaluated for St. Louis and San Francisco utilizing relocated ground guidance equipment and revised pilot operating procedures. All of these methods rely on the pilot being able to achieve VFR, or visual flight rules, clearance, at the missed approach point in order to continue the approach.

Still another use of simulation in a related area is for modeling new airports, and changing the configuration of taxiways and runways. In one case an extensive study was completed to prove the concept of redesigned high-speed exits to reduce runway occupancy time. In another, the new Denver International Airport was modeled on an advanced simulator, complete with surface movement and guidance lighting, long before the actual airport was open for business.

Foam Arresting Bed Modeling

There is an ever-present danger that during an aborted takeoff, or due to certain aircraft failures, an aircraft can overrun the end of the runway. Current barriers are often destructive to the aircraft and passengers, or there is not enough room to allow for an obstacle free area at the end of the runway. In an effort to reduce the risk of damage to the aircraft and passengers, the FAA has evaluated a number of arresting bed configurations and materials

In more recent studies, the emphasis has been on building deceleration beds of structural foam made of aerated concrete or phenolic materials. Since baseline data did not exist for the aircraft, it was necessary to first collect the aircraft data, validate the simulation model, updating it as necessary, and then performing additional tests. In our actual tests the simulator had an 11 feet, out of 568 feet, difference with the baseline data from our test aircraft. We were able to continue and complete the testing, saving considerable cost and at lower risks, than when using live aircraft testing.

Validating Emission Standards for Laser Devices

One of the more controversial, and important, evaluations done with live simulation involves the use of laser devices. The first hurdle is the connotations we have about the dangers of laser exposure based on their use as weapons. Another factor is the criticality of visual acuity to commercial airline pilots, and avoidance of anything that can threaten their vision.

There have been several hundred laser exposures of aircraft in flight in recent years. Most of these have occurred around entertainment sites, such as Las Vegas, but others have occurred randomly against police and other emergency aircraft. Concern continues to grow about the dangers of lasers for impairing pilot vision.

Some illuminations in Las Vegas and California have resulted in flash blindness and severe after-imaging for the victims, leading to incapacitation. Fortunately, there has always been a crewmember unaffected that could take control and avert disaster. The FAA, in response to these concerns, has updated guidance material and validated maximum exposure levels called out in regulatory materials (FAA, 7400.2E, 1999). Concerns have now spread to the international arena where ICAO has developed standards for member states relying on results from evaluations.

As part of the FAA's validation effort I developed a test program that used live pilots in an advanced simulator test program (Dillard, 1999). The pilots were illuminated with the proposed light levels from a laser device synchronized with pilot job-function specific maneuvers. We were looking for flash blindness, after imaging, and distraction. We were also looking for recovery times, and training and procedures that could help mitigate the effects of the illumination. Illumination levels were far below any values known to cause biological damage, but could help safe lives in the future by establishing levels that avert side effects.

Needless to say, this is a very emotional issue with pilots. Any threat to their vision is a threat to their livelihood. Interestingly, the military has had as much interest in the results of this evaluation as the civilian authorities. The laser device was a 532 nanometer wavelength yellow-green device, which provides a light of the wavelength to which our eyes are the most sensitive. Performance variables were recorded as part of each scenario, and each test subject had a number of baseline scenarios that were used to baseline individual performance.

Other critical human factors issues associated with this evaluation were the effects of aging, fatigue, and medications on test subject's eyes. One interesting phenomenon noted thus far is the extreme reaction that military veterans with combat flight experience under heavy fire, such as in Viet Nam, have to the light illuminations.

Operational Evolution Plan

The modernization of the National Aerospace System is based on an evolving concept of operations made up of a series of operational changes. The emphasis on NAS modernization is built on increasing collaborative roles between pilots and controllers, use of new tools to support decision-making in air traffic control, and increased reliance on aircraft avionics to provide information to pilots. While the controller will remain responsible for separation assurance, the pilot will be expected to operate in the NAS with higher situational awareness and more responsibility to improve performance of the NAS.

There are concepts within the Operational Evolution Plan that require measurement of performance, workload changes, and definition of changes in roles and responsibilities. Before pilots and controllers can commit to these operational changes and fly procedures that gain capacity, efficiency, and reduce delay, the procedures must be safe. The pilot community places high confidence in simulations that allow "flying" the proposed procedural changes before they happen. Likewise, controllers view human-in-the-loop simulations as an opportunity to try new decision support tools, airspace changes, and procedures before committing to operational changes. The integration of simulations around consistent operational scenarios derived from the Operational Evolution Plan allows pilots and controllers to experience the future, help define final procedures, and will reduce time to implementation.

Simulation capabilities at the FAA, NASA, and industry will be integrated so that operational scenarios can be developed and then flown with controllers and pilots through the combined use of ATC and aircraft simulators. Airlines will be encouraged to participate through the use of their pilots and training simulators.

N-AS 2010 is the simulation of the NAS representing this combination of operational improvements. Pilots and controllers will step into the year 2010 and be able to fly through the

N-AS and control air traffic at 2010 traffic loads. Simulators will be configured with the tools of 2010, new decision support tools and avionics, and used with capabilities defined in the Operational Evolution Plan. Low-fidelity simulation capabilities will be used to define the operational scenarios. The NASA Tower Simulator will be used to define and demonstrate surface movement management system operational performance. Integration between the William J. Hughes Federal Aviation Technical Center and the Flight Standards flight simulator at Oklahoma City (OKC) will be used for human-in-the-loop simulations using scenarios for both controllers and pilots that allows them to work together during the simulations. The OKC simulator team can work with NASA and the airlines to allow their simulators to be configured and linked to the FAA Technical Center's ATC simulation capabilities and expand participation by pilots.

Common scenarios shall be run for improvements within each domain (surface, terminal, en route, oceanic) that represent the changes described within the Operational Evolution Plan. Scenarios can be modified based on results to refine operations. The year 2010 has been selected as the target scenario date to take advantage of the timing for en route and terminal automation changes, several years experience on the part of the controllers in using decision support tools from Free flight, phase1, and expected avionics equipage for satellite navigation, ADS-B, data link, and safety improvements. Controller and pilot teams will be identified early in the scenario development process and will be trained on proposed new operating procedures. The N-AS 2010 Team will remain together for subsequent experiments. The N-AS 2010 Team shall include research psychologists, concept developers, controllers and pilots.

DATA COLLECTION

The ability to collect data has increased immeasurably in the past few years. Once limited to on-site collection in the simulator main frame, data can now be collected in off-line computers. Furthermore, the number of variables, and sample rates, are substantially higher. Also, data can be collected and sent to remote sites for assembly, or dynamic integration. The FAA Boeing-727 and other facilities frequently sends simulator-generated air traffic data to the FAA Technical Center, and other sites, to drive air traffic control targets on controller's displays in air traffic studies.

Using a network for a data collection system allows you to collect an almost unlimited number of variables at high sample rates, using commercially available communication lines or satellite relays, on most Level C and D simulators in service at this time. This amount of data can be collected for several hours, depending on the storage capacity of the recording computer. More sophisticated data collection hardware can allow you to collect hundreds of variables at a time for extended periods.

Normally, data will be recorded at predetermined intervals, and will begin when the aircraft meets a set of pre-defined conditions. The conditions can be triggered by geographical position, altitude, speed, system failure, or any number of other conditions. Collection will cease when the aircraft no longer meets the conditions.

The data collected from each test run will normally be recorded in tabular form. The data can then be retained in tabular form, or can be processed for real-time plots for analysis. It is helpful if the operator can provide a quick look at early results to spot any problems. On most systems, virtually any variable available in the simulator database can be accessed for recording. It may be necessary to perform some scaling on the values, but generally selecting recorded variables doesn’t present a major problem.

METHODOLOGY ASSUMPTIONS

To ensure the validity and accuracy of evaluation results that will be needed to meet requirements to approve a procedure, or the operation of a new system, it is essential that Approved Level C and Level D simulator be used. In the applications we have discussed, anything less would not have had the credibility to produce usable results. If non-approved simulators are used, the simulator and all related sub-systems will have to undergo validation certification to produce the same level of performance. Calibration and accuracy of simulator visual systems, motion, and computer capacity would all require similar certification. If you are going to that much expense and effort, the use of an approved simulator is a better solution.

When you accept the results of a simulation to make decisions on the acceptability of a new piece of aircraft equipment, or to grant approval for a new procedure or policy, the decision is based on the assumption that suitable equipment was used, operated by experienced and qualified pilots, performing scenarios that adequately test the capabilities of the equipment, procedure, or pilots. You are also accepting that the data was honestly and accurately processed, and analyzed.

When you do accept that an advanced simulator is suitable for a proposed evaluation, there are validation checks that still must be made. All elements of the scenarios, such as weather setup, faults and failures, data parameters sampled, and crew briefing materials must be thoroughly reviewed and checked, under actual test conditions for accuracy and relevance. While you cannot conduct programs without some level of trust and acceptance, critical elements must all checked, and rechecked, to ensure that there are no errors, or oversights in their design, and implementation.

LIMITATIONS

As with any complex undertaking, there are restrictions and limitations on the use of advanced flight simulators. The first is that the simulator operator will have to accomplish all modifications and changes. Simulator operators are not going to let outsiders make changes to their equipment without active oversight and control. There are cases where they will work with you, but generally they will require a finished design that specifies details the work and preparation that needs to be done. In a research environment this is not always easy, so a means must be established to deal with changes and modifications during the installation phase. Another problem is equipment availability. While simulators are relatively common, they are extremely heavily scheduled which may require flexibility on the part of the evaluation sponsor.

The training software on advanced simulators is sacred. Nothing can be done that will affect the training computer load, and possible endanger the approval status of the simulator. You may also be required to work at night, or in periods of light training schedules because of the heavy demand placed on most training simulators. The training at commercial airlines affects peoples livelihood, and nothing should be done that will interfere with that. Cost to obtain access to the advanced simulators can also be a limiting factor.

The installation of hardware, as with software, will only be permitted as long as it can be removed to return the simulator to the approved configuration. These are very stringent approval policies, and operators cannot afford to risk doing otherwise. The good news is, generally, that most new cockpit equipment is designed around existing cockpits, and takes into consideration the limited panel space and size restrictions for installation. All new aircraft equipment will be required to fit into the existing installation rails, as with existing equipment

They are cases where a non-standard installation is required, as with the new electronic flight bag, where temporary mountings, or fixtures, may have to be fabricated to accept the equipment for testing. In these cases, you should be able to work out an installation, in spite of difficulties, but the nature of the installation must be taken into account when analyzing results.

Advanced simulators will require the involvement of highly skilled technical experts that may, or may not, understand the processes required for evaluation programs. Engineers and technical specialists are conditioned to work in an orderly, controlled environment. They may also fail to appreciate the importance that an evaluator might place on data precision and accuracy. Many programs breakdown when the evaluator fails to relay exact details on what is required from the simulator. In most situations you will find some technical support staff members that have absolutely no interest in the evaluation, and others that are intrigued and challenged by the effort. Because of this variability, you must be prepared to validate all facets of the program implementation. Most problems are caused by a failure to understand exactly what is required.

CHAPTER V

CONCLUSIONS

The sophistication and fidelity of modern flight simulators has enabled their application as evaluation tools to a level not possible a few years ago. The validation process used to approve advanced training simulators has provided the precision and fidelity necessary to apply the use of the equipment to an ever-expanding range of programs. Lower level and non-approved devices can also be used in a similar manner, but the test director must provide for separate validation for the devices or systems being used. A definitive simulator evaluation program must include accurate visual representation, weather effects, navigation databases, and avionics displays. Every evaluation program must have a formal test plan completed prior to commencement of testing. Data analysis should include a thorough review of subjective comments from test participants and observers. It is essential that an affective validation process be developed that ensures appropriate fidelity and accuracy for the task at hand.

It is essential that operational evaluation programs for procedures and new systems for aircraft use appropriately qualified test subjects, and pilots should be part of the program design team. Engineers may not be able to accurately construct equipment without qualified pilot input. The situational awareness needed to operate a modern, complex aircraft is greater than ever. Many new systems coming to market from small, high technology, entrepreneurial companies are developed without an adequate understanding of human-factors issues in the cockpit. The use of virtual simulation is a valuable tool for the development and design of new systems or procedures, but in most cases final decisions should not be made until qualified flight crews are tested in a realistic environment.

There are major differences in the manner in which the major large aircraft manufacturers approach automation. In their latest design philosophy, Boeing recognized, and implemented, human-factors considerations in all phases of the design process. This was not done in theoretical sense, but by including pilots, psychologists, engineers and others in teams to consider every aspect of the process. Airbus, on the other hand, has implemented automation on recent models that may further isolate the pilot from the flying process.

We keep hearing that most accidents are caused by human error. Normally we assume it to be the pilot’s error that caused the problem, but the pilot is not the only responsible human in the process. The designers, engineers, company management, air traffic controllers, and regulatory authorities also share the responsibility. When a pilot doesn't understand the automation well enough to override it and take control, or when the automation operates in inconsistent or unpredictable ways, the designers are at fault. When a pilot forces a landing or a take-off in poor conditions because the company wants on-time performance, or fuel savings, then they share the blame. When the governing authorities certify poorly designed equipment or allow operations beyond the safe performance levels of man or machine, they share the blame.

There is a growing recognition that it is essential that human-factors considerations be included in all phases of aviation design and operation. Human performance is constrained by our inherited physical, visual, auditory, and mental limitations, and evolution is not going to correct these problems anytime soon. Human learning and memory skills also limit the amount of compensation that we can apply, but we can design and implement automation that recognizes these limits. There is resistance to constraining cockpit automation, however, because of the perceived improvement in some aspects of operating the aircraft. Recruiting the highest qualified candidates for piloting careers, and keeping them trained to proficiency may be more costly, and strict adherence to correct human-factors design principles may not be quiet as economical, especially if some maneuvers are limited or eliminated due to operational limitations, but to maintain and improve public safety in aviation, we must recognize that human-factors must be accommodated in the design and operation of aircraft.

The design, development and implementation of modern avionics systems is a long, drawn out, expensive process that must successfully involve the skills and involvement of many stakeholders. Development of modern avionics systems is outrunning our ability to certify and deploy the new technology. Government officials that certify and approve the new systems are bound by regulations and federal laws to ensure that any system approved for use meets stringent standards for reliability, operational safety, and accuracy. These standards cannot be drastically changed without significant effects on aviation safety, and significant cost to the users.

Applying modern technology in a careful and scientific manner can speed up the approval and certification process by incorporating human-factors evaluations in the early stages of development using subject pilots qualified for the intended use. Advanced flight simulators are currently used for complete training of airline pilots with little, or no, aircraft flight time required. Modern simulators offer advanced high fidelity performance for aircraft aerodynamics and avionics systems. The Federal Aviation Administration (FAA) B727-200 simulator in Oklahoma City conducts a number of human-factors, equipment, and procedural studies, on an ongoing basis, on critical safety issues that provide definitive results, in short time periods, to support installation of new avionics equipment, National Transportation Safety Board inquiries, procedures development, and airport infrastructure design decisions. Most of these result in decisions have been delivered much quicker, and at lower costs, than conventional methods, and have provided human-factors reviews of the equipment, or process, for the designers and approving officials.

Many new equipment manufacturers, or those not familiar with commercial aviation avionics certification requirements, do not understand the FAA's certification and approval processes. This can lead to extensive delays and redesign efforts before a system, or procedure, is finally approved. The designers are typically engineers with no flight background, and have no, or limited, access to professional pilots during the design process.

The software and hardware designers must become totally familiar with a product as it is developed, and are dismayed when the end users, the pilots, complain about poor design, or functionality, and FAA approving officials start placing extensive testing and evaluation requirements on the products for which the manufacturer, or customer, were not prepared. Pilots often do not fully understand, or are not informed, of design limitations imposed for various reasons, and may have expectations based on their own mental models of what to expect. Operators may purchase new technology without fully understanding the risks and costs of introducing and maintaining the new system in their fleet operations.

There are operational evaluation programs conducted on advanced simulators that provide guidance for implementation directly into the aircraft or training programs. Advances in computer technology now make it possible to model virtually any new system to near perfect accuracy. The human, however, remains an enigma. So far there is no truly high fidelity model of a human that can operate in a dynamic, challenging environment such as end-to-end flight missions. Yet manufacturers are trying to automate systems that do just that. The drive to economize, sometimes even at the expense of hurting safety, is a continual pressure that somehow must be resisted. The more we study the design and implementation of previous generations of equipment and procedures, the more we recognize that, even with their limited knowledge and experience in what was to come, they did a tremendous job of recognizing the limits of the human operator, their needs to conduct safe flight, and the design for ground and airborne infrastructure that provided an operational environment with reasonable margins of safety. Machines are built to serve humans, and to do so the human operator must be cognizant of the machines activities and intent, and be able to assume operational control safely, and without interruption, at any time.

CHAPTER VI

RECOMMENDATIONS

Human-factors considerations must become an integral element of any new equipment, or procedural, introduction. Human limitations should be a part of the studies for any scientific education to ensure their application in actual practice. Because of the discipline required in many scientific fields, the most practical way to ensure consideration of human-factors is to form teams that contain representatives from all disciplines involved, that permits the members to function efficiently in their respective specialties, but that also fosters open communication and cooperation, without hindering innovation and vision.

Evaluation of new products or procedures using simulation must be done on advanced equipment that truly represents the actual aircraft that will be affected, and that uses qualified pilots as test subjects. This requires objective evaluation of simulator performance against actual or predicted aircraft performance data, and rigorous simulator maintenance and configuration control programs. The use of general aviation pilots to evaluate equipment and procedures targeted at commercial aircraft will not yield valid, credible results. Any evaluation should not be conducted until there is a completed test plan, reviewed by all stakeholders, that contains a clear definition of success on the outcomes.

Often the greatest value will come from the observations and interactions that are part of such an evaluation, providing the fidelity of the simulators being used meet required standards and have the support of the participants. The increased understanding from all perspectives will provide the basis for future cooperation and progress. Any new procedure or product that could affect safety of flight, or automation, should undergo validation testing in advanced simulators as a matter of course. The efforts to use low end devices, or Monte Carlo modeling, is not a suitable substitute for realistic, pilot-in-the-loop evaluations, and any Monte Carlo processing should be based on data collected directly from piloted simulation or actual aircraft performing the same tasks.

AREAS REQUIRING FURTHER RESEARCH

While modern advanced flight simulators have made major strides in recent years, there are still areas of concern. Many of these have not been resolved because of the primary purpose being to conduct training. When used for research and operational evaluation programs though, the emphasis can change. Actually what is there must be maintained, but we also must address others that are not necessarily critical for training.

Unusual Attitudes

Modern training simulators typically have high fidelity modeling only for the normal flight envelope. Some accidents in recent years have shown the need for training for recovery outside the normal operating envelope when emergencies arise. The aircraft manufacturers are reluctant to provide actual flight test data to support high-fidelity modeling and the simulator manufacturers would rather not have to address it, but it must be done. The requirements for computer capabilities, aerodynamic models, motion cues and forces, and aircraft control laws all must be re-examined and updated to correctly address unusual attitudes in an accurate manner. We can certainly model the entire aircraft operating envelope, but to do it accurately we need flight test data or high quality engineering predictive data.

Motion Fidelity

Modern motion bases do a reasonable job of providing realistic motion cues, but many questions remain. The modern motion base is design to fit into a standard space that will accommodate simulators from all major manufacturers. The size of actuators, the amount of hydraulic fluid required and the allowed motion operating envelope drive the motion system design. Questions about the necessity for, and, if so, how much, motion is required, remains to be answered. There are camps that claim that no motion is needed, but with commercial simulators the requirement remains. From what I have seen, those that advocate no motion either have little experience with it, are having to pay for simulators where motion represents 10% to 15% of the cost, must provide building to house them or pay for maintaining the systems. My observation has been that motion is a critical part of the simulator environment, and the motion cues are critical for system failures, weather, upset recovery, crosswind or wake vortex recovery and operations, low visibility. I realize that it is not feasible to simulate full motion maneuvering for fighters and other high performance aircraft throughout their full flight regime, but that is not how commercial aircraft operate, and to somehow extrapolate the fact that their simulators can't do it to stating that motion is not needed doesn't make sense. However, we also should develop objective standards for motion that define how much platform movement is needed to accurately reflect normal commercial aircraft movement. Whether that information is applied to standard commercial simulators designs is another issue, but at least we would know what is needed for an accurate simulation.

Computer Based Training

There is an on-going debate about how much, if any, flight training can be conducted on PCs. Like everyone else, I have an eight-year old grandson that can fly the heck out of Microsoft Flight Simulator, but that doesn't make him a pilot. We need to develop objective standards that clearly define what training is appropriate for PC based instruction and what is not. I realize that most educational institutions and companies that are trying to develop a market in this area have a vested economic interest in promoting PC training. But, we need an objective assessment by a non-biased entity that establishes what level of fidelity is required, where we can use PC based training for job performance competency training, and then define it for specific professions. There has been a lot of work done in this area, but much of it is academic and not practical when you try to apply it to the actual workplace, especially a complex workplace.

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APPENDIX A

TABLE OF VALIDATION TEST TOLERANCES

1. PERFORMANCE

a. TAXI

(1) \1\ Minimum Radius Turn
\2\ ±3 Feet (0.9 m) or 20% of Airplane Turn Radius
\3\ Ground/Takeoff

(2) \1\ Rate of Turn vs. Nose Wheel Steering Angle
\2\ ±10% or ±2°/second Turn Rate
\3\ Ground/Takeoff

b. TAKEOFF

(1) \1\ Ground Acceleration Time and Distance
\2\ ±5% Time and Distance or ±5% Time and ±200 Feet (61 Meters) of Distance
\3\ Ground/Takeoff
\4\ Unfactored aircraft certification data may be used. Acceleration Time and Distance should be recorded for a minimum of 80% of total segment. (Brake release to Vr).

(2) \1\ Minimum Control Speed Ground (Vmcg) Aerodynamic Controls Only per Applicable Airworthiness Standard, OR, Low Speed, Engine Inoperative Ground Control Characteristics
\2\ Maximum Airplane Lateral Deviation ±25% or ±5 Feet (1.5 Meters)
\3\ Ground/Takeoff
\4\ Engine failure speed must be within ±1 knot of airplane engine failure speed.

(3) \1\ Minimum Unstick Speed or equivalent as provided by the airplane manufacturer
\2\ ±3 Knots Airspeed
±1.5° Pitch
\3\ Ground/Takeoff
\4\ Vmu is defined as that speed at which the last main landing gear leaves the ground. Main landing Gear Strut Compression or equivalent air/ground signal should be recorded. Record as a minimum from 10 knots before start of rotation.

(4) \1\ Normal Takeoff
\2\ ±3 Knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±20 Feet (6 Meters) Altitude

±5.0 lb (2.224 dN) or ±10% Column Force*

* Applies only to reversible control systems.

\3\ Ground/Takeoff and First Segment Climb
\4\ Record Takeoff profile from brake release to at least 200 feet (61 meters) Above Ground Level (AGL).

(5) \1\ Critical Engine Failure on Takeoff
\2\ ±3 Knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±20 Feet (6 Meters) Altitude
±2° Bank and Sideslip Angle
±5.0 lb (2.224 dN) or ±10% Column Force*
±5.0 lb (2.224 dN) or ±10% Rudder Pedal Force*
±3.0 lb (1.334 dN) or 10% Aileron Wheel Force*

* Applies only to reversible control systems.

\3\ Record Takeoff profile at maximum takeoff weight to at least 200 feet (61 meters) AGL. Engine failure speed must be within ±3 knots of airplane data.

(6) \1\ Crosswind Takeoff
\2\ ±3 Knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±20 Feet (6 Meters) Altitude
±2° Bank and Sideslip Angle
±5.0 lb (2.224 dN) or ±10% Column Force*
±5.0 lb (2.224 dN) or ±10% Rudder Pedal Force*
±3.0 lb (1.334 dN) or 10% Aileron Wheel Force*

* Applies only to reversible control systems.

\3\ Ground/Takeoff and First Segment Climb
\4\ Record Takeoff profile to at least 200 feet (61 meters) AGL with same relative wind profile as airplane test.

(7) \1\ Rejected Takeoff
\2\ Overall Distance ±?
Braking Effort ±?
(to be determined)
\3\ Ground
\4\ Auto brakes will be used where applicable. Maximum braking effort, Auto or Manual.

c. CLIMB

(1) \1\ Normal Climb
All Engines Operating
\2\ ±3 knots Airspeed
±5% or ±100 FPM (0.5 Meters/Second) Climb Rate
\3\ Climb With All Engines Operating
\4\ May be a Snapshot Test. Manufacturer's gross climb gradient may be used for flight test data.

(2) \1\ One Engine Inoperative
Second Segment Climb
\2\ ±3 knots Airspeed ±5% or ±100 FPM (0.5 Meters/Second) Climb Rate, but not less than the FAA Approved Flight Manual Rate of Climb
\3\ Second Segment Climb With One Engine Inoperative

(3) \1\ One Engine Inoperative Approach Climb for Airplanes With Icing Accountability per Approved AFM
\2\ ±3 knots Airspeed ±5% or ±100 FPM (0.5 Meters/Second) Climb Rate, but not less than the FAA Approved Flight Manual Rate of Climb
\3\ Approach Climb With One Engine Inoperative
\4\ May be a Snapshot Test. Manufacturer's gross climb gradient may be used for flight test data. Use near maximum landing weight.

d. STOPPING

(1) \1\ Deceleration Time and Distance, Wheel Brakes Using Manual Braking, Dry Runway (No Reverse Thrust)
\2\ ±5% of Time. For distance up to 4000 feet (1220 meters) ±200 feet (61 meters) or ±10% whichever is smaller. For distance greater than 4000 feet (1220 meters) ±5% of distance.
\3\ Landing
\4\ Time and Distance should be recorded for at least 80% of the total segment (TD to Full Stop). Brake system pressure should be available.

(2) \1\ Deceleration Time and Distance, Reverse Thrust, Dry Runway (No Wheel Braking)
\2\ ±5% Time and the Smaller of ±10% or 200 feet (61 meters) of Distance
\3\ Landing
\4\ Time and Distance should be recorded for at least 80% of the total demonstrated reverse thrust segment.

(3) \1\ Stopping Time and Distance, Wheel Brakes, Wet Runway (No Reverse Thrust)
\2\ Representative Stopping Time and Distance

\3\ Landing
\4\ FAA approved Airplane Flight Manual (AFM) data is acceptable.

(4) \1\ Stopping Time and Distance, Wheel Brakes, Icy Runway (No Reverse Thrust)
\2\ Representative Stopping Time and Distance
\3\ Landing
\4\ FAA approved Airplane Flight Manual (AFM) data is acceptable.

e. ENGINES

(1) \1\ Acceleration
\2\ Ti ±10%
Tt ±10%
\3\ Approach or Landing
\4 Ti = Total time from initial throttle movement until a 10% response of a critical engine parameter.
Tt = Total time from Ti to 90% go-around power. Critical engine parameter should be a measurement of power (N1, N2, EPR, Torque, etc.). Plot from flight idle to go-around power for a rapid (slam) throttle movement.

(2) \1\ Deceleration
\2\ Ti ±10%
Tt ±10%
\3\ Ground/Takeoff
\4\ Test from maximum takeoff power to 10% of maximum takeoff power (90% decay in power). Time history should be provided.

2. HANDLING QUALITIES

a. STATIC CONTROL CHECKS **

** Column, wheel, and pedal position vs. force shall be measured at the control. An alternate method acceptable to the NSPM in lieu of the test fixture at the controls is to instrument the simulator in an equivalent manner to the flight test airplane. The force and position data from this instrumentation can be directly recorded and matched to the airplane data. Such a permanent installation would eliminate the need for installation of external devices.

(1) \1\ Column Position vs. Force and Surface Position Calibration
\2\ ±2 lbs (0.89 daN) Breakout
±5 lbs (2.224 daN) or ±10% Force
±2° Elevator
\3\ Ground
\4\ Uninterrupted control sweep, stop-to-stop.

(2) \1\ Wheel Position vs. Force and Surface Position Calibration
\2\ ±2 lbs (0.89 daN) Breakout
±3 lbs (1.334 daN) or ±10% Force
±1° Aileron
±3° Spoiler
\3\ Ground
\4\ Uninterrupted control sweep, stop-to-stop.

(3) \1\ Pedal Position vs. Force and Surface Position Calibration
\2\ ±5 lbs (2.224 daN) Breakout
±5 lbs (2.224 daN) or ±10% Force
±2° Rudder
\3\ Ground
\4\ Uninterrupted control sweep, stop-to-stop.

(4) \1\ Nose Wheel Steering Force and Position
\2\ ±2 lbs (0.89 daN) Breakout
±3 lbs (1.334 daN) or ±10% Force
±2° Nose Wheel Angle
\3\ Ground
\4\ Uninterrupted control sweep, stop-to-stop.

(5) \1\ Rudder Pedal Steering Calibration
\2\ ±2° Nose Wheel Angle
\3\ Ground

(6) \1\ Pitch Trim Calibration Indicator vs. Computed
\2\ ±0.5° of Computer Trim Angle
±10% Trim Rate
\3\ Ground and Go-Around
\4\ Measure trim rate for go-around. Trim rate input and surface rate time history is appropriate.

(7) \1\ Alignment of Power Lever Angle vs. Selected Engine Parameter (EPR, N1, Torque, etc.)
\2\ ±5° of Power Lever Angle
\3\ Ground
\4\ Simultaneous recording for all engines. A 5° tolerance applies against airplane data and between engines. May be Snapshot Test.

(8) \1\ Brake Pedal Position vs. Force
\2\ ±5 lb (2.224 daN) or 10%
±10% or 150 psi (1033 kPa) brake hydraulic pressure
\3\Simulator computer output results may be used to show compliance. Relate hydraulic system pressure to pedal position in a ground static test.

b. DYNAMIC CONTROL CHECKS **

** Column, wheel, and pedal position vs. force or time shall be measured at the control. An alternate method acceptable to the NSPM in lieu of the test fixture at the controls is to instrument the simulator in an equivalent manner to the flight test airplane. The force and position data from this instrumentation can be directly recorded and matched to the airplane data. Such a permanent installation would eliminate the need for installation of external devices.

(1) \1\ Pitch Control
\2\ ±10% of time for first zero crossing, and ±10(n + 1)% of period thereafter.
±10% amplitude of first overshoot. ±20% of amplitude of 2nd and subsequent overshoots greater than 5% of initial displacement.
±1 overshoot.
\3\ Takeoff, Cruise, Landing
\4\ Data should be normal control displacement in both directions. Approximately 25% to 50% of full throw.
n is the sequential period of a full cycle of oscillation.

(2) \1\ Roll Control
\2\ Same as (1) above.
\3\ Takeoff, Cruise, Landing
\4\ Data should be normal control displacement. Approximately 25% to 50% of full throw.

(3) \1\ Yaw Control
\2\ Same as (1) above.
\3\ Takeoff, Cruise, Landing
\4\ Data should be normal control displacement. Approximately 25% to 50% of full throw.

c. LONGITUDINAL

(1) \1\ Power Change Dynamics
\2\ ±3 knots Airspeed
±100 feet (30 meters) Altitude
±20% or ±1.5° Pitch
\3\ Approach to Go-Around
\4\ Wing flaps should remain in the approach position. Time history of uncontrolled free response for time increment from 5 seconds before the initiation of the configuration change to 15 seconds after completion of the configuration change.

(2) \1\ Flap/Slat Change Dynamics
\2\ ±3 knots Airspeed
±100 feet (30 meters) Altitude

±20% or ±1.5° Pitch
\3\ Retraction, After Takeoff.
Extension, Approach to Landing
\4\ Time history of uncontrolled free response for time increment from 5 seconds before the initiation of the configuration change to 15 seconds after completion of the configuration change.

(3) \1\ Spoiler/Speedbrake Change Dynamics
\2\ ±3 knots Airspeed
±100 feet (30 meters) Altitude
±20% or ±1.5° Pitch
\3\ Cruise and Approach
\4\ Time history of uncontrolled free response for time increment from 5 seconds before the initiation of the configuration change to 15 seconds after the completion of the configuration change.

(4) \1\ Gear Change Dynamics
\2\ ±3 knots Airspeed
±100 feet (30 meters) Altitude
±20% or ±1.5° Pitch
\3\ Takeoff to Second Segment Climb, Approach to Landing
\4\ Time history of uncontrolled free response for time increment of 5 seconds before the initiation of the configuration change to 15 seconds after the completion of the configuration change.

(5) \1\ Gear and Flap/Slat Operating Times
\2\ ±1 second or 10% of Time
\3\ Takeoff, Approach
\4\ Normal and alternate flaps, extension and retraction. Normal gear, extension and retraction. Alternate gear, extension only.

(6) \1\ Longitudinal Trim
\2\ ±1° Pitch Control (Stabilizer and Elevator)
±1° Pitch Angle
±5% Net Thrust or Equivalent
\3\ Cruise, Approach, Landing
\4\ May be Snapshot Tests.

(7) \1\ Longitudinal Maneuvering Stability (Stick Force/g)
\2\ ±5 lbs (2.224 daN) or ±10% Column Force or Equivalent Surface
\3\ Cruise, Approach, Landing
\4\ May be series of Snapshot Tests. Force or surface deflection must be in correct direction. Approximately 20°, 30°, and 45° bank angle should be presented.

(8) \1\ Longitudinal Static Stability
\2\ ±5 lbs (2.224 daN) or ±10% Column Force or Equivalent Surface

\3\ Approach
\4\ Data for at least 2 speeds above and 2 speeds below trim speed. May be a series of Snapshot Test

(9) \1\ Stick Shaker, Airframe Buffet, Stall Speeds
\2\ ±3 knots Airspeed
±2° Bank for speeds higher than stick shaker or initial buffet
\3\ Second Segment Climb and Approach or Landing
\4\ Stall Warning Signal should be recorded and must occur in the proper relation to stall.

(10) \1\ Phugoid Dynamics
\2\ ±10% of Period
±10% of Time to 1/2 or Double Amplitude or ±.02 of Damping Ratio
\3\ Cruise
\4\ Test should include 3 full cycles (6 overshoots after input completed) or sufficient to determine time to 1/2 amplitude whichever is less.

(11) \1\ Short Period Dynamics
\2\ ±1.5° Pitch or ±2°/second Pitch Rate
±.10g Normal Acceleration
\3\ Cruise

d. LATERAL-DIRECTIONAL

(1) \1\ Minimum Control Speed, Air (Vmca), per Applicable Airworthiness Standard, OR, Low Speed Engine Inoperative Handling Characteristics in Air
\2\ ±3 knots Airspeed
\3\ Takeoff or Landing (Whichever is most critical in airplane)
\4\ Vmca may be defined by a performance or control limit which prevents demonstration of Vmca in the conventional manner.

(2) \1\ Roll Response (Rate)
\2\ ±10% or ±2°/second Roll Rate
\3\ Cruise and Approach or Landing
\4\ Test with normal wheel deflection (about 30%).

(3) \1\ Roll Response to Roll Controller Step Input
\2\ ±10% or ±2°/second Roll Rate
\3\ Approach or Landing
\4\ Roll rate response.

(4) \1\ Spiral Stability
\2\ Correct Trend, ±2° Bank or ±10% in 20 Seconds
\3\ Cruise

\4\ Airplane data averaged from multiple tests may be used. Test for both directions.

(5) \1\ Engine Inoperative Trim
\2\ ±1° Rudder Angle or ±1° Tab Angle or Equivalent Pedal
±2° Sideslip Angle
\3\ Second Segment and Approach or Landing
\4\ May be Snapshot Tests.

(6) \1\ Rudder Response
\2\ ±2°/second or ±10% Yaw Rate
\3\ Approach or Landing
\4\ Test with stability augmentation ON and OFF. Rudder step input of approximately 25% rudder pedal throw.

(7) \1\ Dutch Roll, Yaw Damper OFF
\2\ ±0.5 seconds or ±10% of Period.
±10% of Time to 1/2 or Double Amplitude or ±.02 of Damping Ratio.
±20% or ±1 second of Time Difference Between Peaks of Bank and Sideslip.
\3\ Cruise and Approach or Landing
\4\ Test for at least 6 cycles with stability augmentation OFF.

(8) \1\ Steady-State Sideslip
\2\ For a given rudder position ±2° Bank, ±1° Sideslip, ±10% or ±2° Aileron, ±10% or ±5° Spoiler or Equivalent Wheel Position
\3\ Approach or Landing
\4\ May be a series of Snapshot Tests.

e. LANDINGS

(1) \1\ Normal Landing
\2\ ±3 knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±10% Altitude or ±10 feet (3 meters)
\3\ Landing
\4\ Test from a minimum of 200 feet (61 meters) AGL to Nose Wheel Touchdown. Derotation may be shown as a separate segment from the time of main gear touchdown.

(2) \1\ Crosswind Landing
\2\ ±3 knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±10% Altitude or ±10 feet (3 meters)
±2° Bank Angle

±2° Sideslip Angle or Yaw Angle
\3\ Landing
\4\ Test from a minimum of 200 feet (61 meters) AGL to Nose Wheel Touchdown and rollout to 60 knots. Use near maximum landing weight with same Relative Wind Profile as aircraft test.

(3) \1\ One Engine Inoperative Landing
\2\ ±3 knots Airspeed
±1.5° Pitch
±1.5° Angle-of-Attack
±10% Altitude or ±10 feet (3 meters)
±2° Bank Angle
±2° Sideslip Angle or Yaw Angle
\3\ Landing
\4\ Test from a minimum of 200 feet (61 meters) AGL to Nose Wheel Touchdown.

(4) \1\ Directional Control (Rudder Effectiveness) With Reverse Thrust, Symmetric and Asymmetric
\2\ ±5 knots Airspeed
\3\ Landing
\4\ Airplane test data required, however, airplane manufacturer's engineering simulator data may be used for reference data as last resort. Airplanes with demonstrated minimum speed for rudder effectiveness ±5 knots. Others, test to verify simulator meets conditions demonstrated by airplane manufacturer.

f. GROUND EFFECT

(1) \1\ A Test to Demonstrate Longitudinal Ground Effect
\2\ ±1° Elevator or Stabilizer Angle
±5% Net Thrust or Equivalent
±1° Angle-of-Attack
±10% Height/Altitude or ±5 Feet (1.5 meters)
±3 knots Airspeed
±1° Pitch Attitude
\3\ Landing
\4\ See paragraph 4, this appendix. A rationale must be provided with justification of results.

3. MOTION SYSTEM

a. \1\ Frequency Response
\2\ As specified by operator for simulator acceptance.
\3\ Appropriate test to demonstrate Frequency Response required.

b. \1\ Leg Balance

\2\ As specified by operator for simulator acceptance.
\3\ Appropriate test to demonstrate Leg Balance required.

c. \1\ Turn Around Check
\2\ As specified by operator for simulator acceptance.
\3\ Appropriate test to demonstrate Smooth Turn Around required.

d. \1\ Characteristic Buffet Motions
\2\ See Appendix 1, paragraph 3.f.
\3\ Compliance statement required. Test required.

4. VISUAL SYSTEM - (Note: Refer to Appendix 3 for additional visual tests).

a. \1\ Visual Ground Segment (VGS)
\2\ ±20%
Threshold lights must be visible if they are in the visual segment. (See example in Comments.)
\3\ Landing. Static at 100 feet (30 meters) Wheel Height Above Touchdown Zone on Glideslope. Runway Visual Range = 1200 feet or 350 meters.
\4\ The ATG should indicate the source of data, that is, ILS G/S antenna location, pilot eye reference point, cockpit cutoff angle, etc. used to make visual ground segment scene content calculations.
Tolerance Example: If the calculated VGS for the airplane is 840 feet, the 20% tolerance of 168 feet may be applied at the near or far end of the simulator VGS or may be split between both as long as the total of 168 feet is not exceeded.

b. \1\ Visual System Color
\2\ Demonstration Model

c. \1\ Visual RVR Calibration
\2\ Demonstration Model

d. \1\ Visual Display Focus and Intensity
\2\ Demonstration Model

e. \1\ Visual Attitude vs. Simulator Attitude Indicator (Pitch and Roll of Horizon)
\2\ Demonstration Model

f. \1\ Demonstrate 10 Levels of Occulting Through Each Channel of System
\2\ Demonstration Model
\3\ May be requested for recurrent evaluation.

5. SIMULATOR SYSTEMS

a. VISUAL, MOTION, AND COCKPIT INSTRUMENT RESPONSE

\1\ Visual, Motion, and Instrument Systems response to an abrupt pilot controller input, compared to airplane response for similar input.
\2\ 150 milliseconds or less after airplane response.
\3\ Takeoff, Cruise Approach or Landing

B. LEVEL A/B DEVICES
\1\ 300 milliseconds or less after airplane response
\2\ Takeoff, Cruise, Approach or Landing
\3\ One test is required in each axis (pitch, roll, and yaw) for each of the 3 conditions compared to airplane data for a similar   input. (Total 9 tests.) Visual change may start before motion response, but motion acceleration must occur before completion of visual scan of first video field containing different information.

OR

\1\ Transport Delay - Level C/D
\2\ 150 milliseconds or less after control movement.
\3\ Pitch, Roll, Yaw
\4\ One test is required in each axis. (Total 3 tests.)
\5\ 300 milliseconds or less after control movement for Level A/B.
\6\ Pitch, Roll, Yaw
\7\ See Appendix 1, Item 2.v.

b. SOUND
\1\ Realistic amplitude and frequency of cockpit noises and sounds, including precipitation static, and engine and airframe sounds. The sounds shall be coordinated with the weather representations required in FAR Part 121, Appendix H, Phase III (Level D), Visual Requirement No. 3. Test results must show a comparison of the amplitude and frequency content of the sounds that originate from the airplane or airplane systems.

c. DIAGNOSTIC TESTING
(1) \1\ A means for quickly and effectively testing simulator programming and hardware. This could include an automated system which could be used for conducting at least a portion of the tests in the ATG.
(2) \1\ Self-testing of simulator hardware and programming to determine compliance with
Levels B, C, and D Simulator Requirements.
(3) \1\ Diagnostic analysis as prescribed in FAR Part 121, Appendix H, Phase III (Level D) Simulator Requirement No. 5.