AN EVALUATION OF INTERVAL MANAGEMENT (IM) USING TASK ANALYSIS AND WORK DOMAIN ANALYSIS

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Kurt A. Swieringa

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AN EVALUATION OF INTERVAL MANAGEMENT (IM) USING TASK ANALYSIS AND WORK DOMAIN ANALYSIS

Approved by:

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

Dr. John-Paul Clarke
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Jennifer Murdoch
Research Psychologist
NASA Langley Research Center

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Aircraft
ADS	Abstraction-Decomposition Space
ADS-B	Automatic Dependent Surveillance-Broadcast
AH	Abstraction Hierarchy
AMSTAR	Airborne Merging and Spacing for Terminal Arrivals
ASTAR	Airborne Spacing for Terminal Area Routes algorithm
ATAAS	Advanced Terminal Area Approach Spacing
ATC	Air Traffic Control
ATOL	Air Traffic Operations Laboratory
ATOS	Airspace and Traffic Operations Simulation
CDA	Continuous Descent Arrival
CDTI	Cockpit Display of Traffic Information
CPDLC	Controller Pilot Data Link Communication
CTA	Control Task Analysis
CWA	Cognitive Work Analysis
DOF	Degrees Of Freedom
DTS	Development Test Simulator
EICAS	Engine Indicating and Crew Alerting System
EID	Ecological Interface Design
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAS	Final Approach Speed

FDMS	Flight Deck Merging and Spacing
FIM	Flightdeck Interval Management
FMS	Flight Management System
GIM	Ground Interval Management
HITL	Human-In-The-Loop
HTA	Hierarchical Task Analysis
ICAO	International Civil Aviation Organization
IFD	Integration Flight Deck
ILS	Instrument Landing System
IM	Interval Management
IMSPiDR	Interval Management with Spacing to Parallel Dependent Runways
LCD	Liquid Crystal Display
M	Mean
MCDU	Multi-Function Cockpit Display Unit
MCP	Mode Control Panel
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NOAA	National Oceanic and Atmospheric Administration
OPD	Optimized Profile Descent
PC	Personal Computer
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
RTA	Required Time of Arrival

RUC-13	Rapid Update Cycle weather model with 13km resolution
SD	Standard Deviation
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Routes
TAPSS	Terminal Area Precision Scheduling and Spacing
TCAS	Traffic Collision Avoidance System
TMA	Traffic Management Advisor
TMA-TM	Traffic Management Advisor with Terminal Metering
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
TTG	Time-To-Go
UPS	United Parcel Service
WDA	Work Domain Analysis

SUMMARY

Work Domain Analysis (WDA) and task analysis are methods that can be used to develop complex systems that support human operators. Task analysis can be used to describe the nominal tasks of many complex safety critical systems which are also highly proceduralized. However, complex systems may require human operators to have a greater understanding of the system’s dynamics than can be obtained from procedures derived from a task analysis. This is particularly true when off-nominal events occur, for which there is no procedure. By concentrating on the constraints in the work domain instead of tasks, work domain analysis can complement task analysis by supporting operators during off-nominal events that do not have any predescribed procedures.

The goal of this study was to use WDA and two forms of task analysis to derive interface and procedure modifications for a new aviation concept called interval management. Interval management is a new concept whose goal is to increase runway throughput by enabling aircraft to achieve a precise interval behind a lead aircraft. This study used data from a human-in-the-loop study conducted at NASA Langley Research Center to develop a Hierarchical Task Analysis (HTA), Control Task Analysis (CTA), and WDA. The HTA was used to describe a nominal set or procedures, the CTA was used to describe strategies pilots could use to make decisions regarding the IM operation, and the WDA was used to determine representations and procedures that could convey complete and accurate knowledge of interval management to the flightcrew.

CHAPTER 1

INTRODUCTION

Task analysis and Work Domain Analysis (WDA) are methods that have been used in the design of complex systems [1], [2]. Each of these methods is built on different, yet complementary, philosophies. Task analysis assumes that there is a predictable series of tasks, or actions, which must be completed to control a system. By understanding these tasks, interfaces and procedures can be designed to support their completion. Furthermore, task analysis can be used to identify tasks that are error prone and to build appropriate redundancies into the system. Often times, task analysis is thought of as a normative approach to designing a system, since task analysis often involves developing a particular scenario and pre-determining tasks needed to achieve the desired outcome. However, effective human performance in off-nominal conditions often requires deeper knowledge of the system than task analysis can provide. WDA is one method that has shown the ability to help designers provide this knowledge to the operator. WDA is built on the philosophy that a work domain has a number of operating constraints and a set of dynamics that describe how it will respond to a given input. The constraints and dynamics can be imposed by the laws of nature, rules and regulations, or logic programmed into automation. Outside the nominal operating conditions, the human operator may be required to use their knowledge of the operation’s dynamics to restore the normal operating conditions. Since the WDA concentrates on providing the operator with a deep understanding of the work domain, it has been suggested that the knowledge conveyed by the WDA can be used to support the operator when unanticipated circumstances are encountered for which there is no prescribed procedure.

Thus, previous research has suggested that task analysis and WDA are complementary methods that can be used together to design effective support for off-nominal conditions while also providing interfaces and procedures that support effective task completion [3]. Since WDA does not examine specific tasks, it does not assume any particular activities by the human operator. Instead, interfaces designed using WDA seek to convey an external mental model of the constraints and dynamics present in the system. In contrast, task analysis focuses on the nominal actions the operator is expected to perform, as well as the information and controls needed to complete those actions. Thus, a task analysis can help design procedures and interfaces for nominal events, and a WDA can result in interfaces that provide information that support effective responses when unanticipated events occur. For the purpose of this thesis, nominal events will be considered all of the normal and abnormal events that were anticipated during the design process. Off-nominal events will be considered unforeseen events or chains of events that the designers did not consider. Using task analysis and WDA together has the potential to result in displays and procedures that support the operator during both nominal operating conditions and convey a better understanding of the system which can be used to detect off-nominal events and plan an appropriate course of action if an unanticipated event occurs.

Interval Management (IM) is a concept that is currently being developed by the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA), as well as other organizations, to help aircraft achieve precise spacing intervals at the runway threshold. IM can be defined as delegating the responsibility of achieving and/or maintain a spacing interval behind one or more lead aircraft from Air Traffic Control (ATC) to the flightdeck [4]. Within the IM concept, Air Traffic Control (ATC) remains responsible for separation between aircraft, but the flightdeck is given the responsibility of maintaining a spacing interval. The IM system that is being developed at the NASA Langley Research Center contains two separate pieces: Flightdeck Interval Management (FIM) and Ground Interval Management (GIM). Previous studies have shown the ability of IM to increase the precision of arrivals, enabling fuel efficient descents during periods of high throughput. However, until recently, most of these studies have either concentrated on FIM or GIM instead of an integrated system. The ground portion and flightdeck portion are currently being integrated together and tested in preparation for a near-term flight demonstration [5].

The joint use of task analysis and WDA has the potential to help guide the development of flightdeck displays and procedures to increase the usability of the IM operation and help convey a deep understanding of IM to the flightcrew. The objective of this thesis is to use data from a recent Human-In-the-Loop (HITL) experiment along with two forms of task analysis and a WDA to evaluate the procedures and interfaces that are being proposed for IM. The HITL experiment is used to develop a Hierarchical Task Analysis (HTA), Control Task Analysis (CTA), and WDA. The HTA was used to describe a nominal set or procedures, the CTA was used to describe strategies pilots could use to make decisions regarding the IM operation, and the WDA was used to determine representations and procedures that could convey complete and accurate knowledge of interval management to the flightcrew. The HTA, CTA, and WDA are then used to describe interfaces and procedures that have the potential to increase pilots' understanding and the usability of IM. A secondary goal of this thesis is to demonstrate the joint use of HTA, CTA and WDA in aviation.

The remainder of this thesis is divided into five chapters. Chapter two will review HTA, CTA, and WDA, how they have been used in the aviation domain, and the previous research that has examined their joint use. Furthermore, chapter two will review previous HITL experiments that have studied IM. Chapter three describes a HITL experiment that analyzed an implementation of IM that supports arrivals to dependent parallel runways. The information obtained from this experiment is used to help build the HTA, CTA, and WDA models that are described in chapter four. These models concentrate on describing the constraints and dynamics of the IM system, as well as the nominal course of action pilots are expected to follow. Chapter five uses the results from the HITL study and information from the models to describe procedural and interface improvements that have the potential to provide pilots with an accurate mental model of IM. Chapter six, the final chapter, will provide an overview of the key points and conclusions of this thesis.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1. Task Analysis

2.1.1. What is a Task Analysis

Task analysis is the study of observable tasks or mental processes that need to be completed to achieve a system goal. A task is an action that is completed to operate a system. When designing a new system, or when analyzing existing systems, it is useful to examine the information and controls that are required for an operator to carry out a particular task and confirm that the operator has access to them. Additionally, it is important to ensure the tasks effectively move the system toward its intended objective. Several methods of completing task analysis have been proposed including: flow charts, network graphs, link analysis, Hierarchical Task Analysis (HTA), and timeline analysis, among others [6].

Of the task analysis methods, HTA was chosen for this study because of its ability to map tasks to higher level goals, its scalability, and its history of use. Research has shown that HTA can be used to provide guidance when designing training programs, workspace layout, equipment design, allocation of functions, and procedure design [7], [8]. Additionally, HTA can be used as an input for a large variety of human factors methods including human error identification, human risk analysis, and mental workload assessment, among others [8]. Furthermore, a significant portion of the work on combining task analysis and Work Domain Analysis (WDA) has focused on the combination of HTA and WDA [9–11].

2.1.2. Hierarchical Task Analysis (HTA)

HTA was developed in the 1960s as a means of producing training requirements [12]. Since then, HTA has expanded its original role and demonstrated usefulness in aiding the design of interfaces, procedures, and teams [2]. HTA is built on the philosophy that there are a number of tasks human operators complete to move a system toward its intended goal. These tasks can be analyzed by decomposing the high level tasks needed to achieve the system goal into subtasks. Thus, HTA is a variant of task analysis that organizes the task structure according to their contribution to system goals [7]. Each of the tasks may require an event to trigger them, information to support task completion, and access to controls that enable the operator to complete the task.

An HTA contains a hierarchy of tasks that stem from a system goal. From this goal, tasks are allocated and given subtasks. These subtasks can be decomposed into further subtasks until it is determined that further decomposition will not provide additional benefit. Figure 2.1 shows a simple task analysis with the system goal of operating a toaster. This goal is broken into subtasks, such as “insert bread,” which are required to accomplish the system goal. A plan describes the order of task completion, and the conditions that trigger the need to complete a given tasks. If necessary, these tasks can be decomposed into subtasks, such as “plug in toaster” and “ensure power to toaster is switched on.” A lower level plan describes how the subtasks should be completed. Thus, HTA represents subtasks needed to achieve a system goal, with a plan indicating when each of the subtasks should be completed. The process of expanding subtasks continues until the developer determines that further expansion will not provide adequate benefit. Shepherd describes the iterative process of completing an HTA as [2]:

1. Identify the main goal to be analyzed
2. Explore the operating constraints
3. Judge whether a goal will be met sufficiently
4. If the goal is met sufficiently, stop analysis; otherwise, continue expanding tasks
5. Examine the operation in terms of human-task interaction and form hypotheses
6. Estimate the cost-benefit of exploring the hypotheses
7. Redescribe the goal

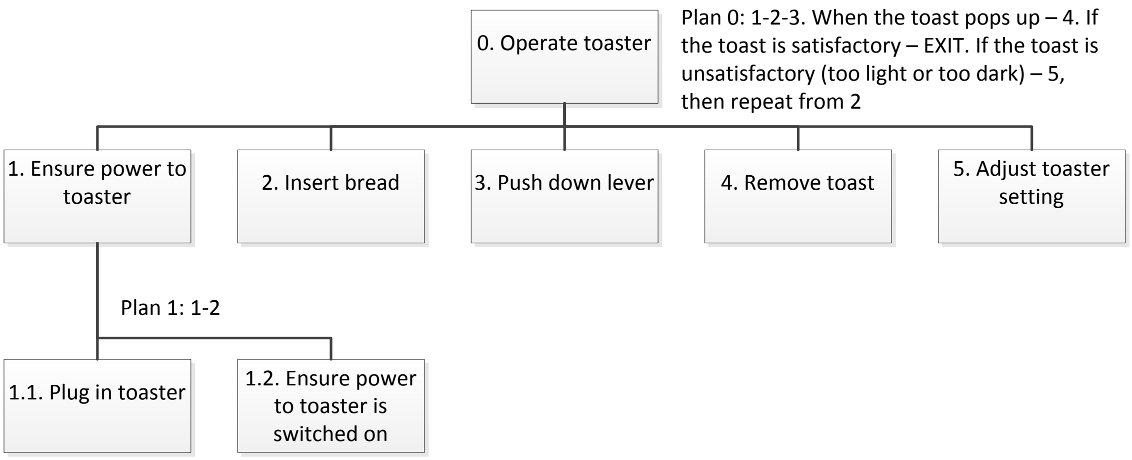


Figure 2.1: Example of a hierarchical task analysis, adopted from [2]

Once the HTA is completed, it can be used to define interface requirements and procedures [2]. Each task requires some method of activation and feedback to notify the operator that the task is completed successfully. Thus, system requirements can be defined by requiring either a display element or a procedural step to notify the operator that a task must be completed. Furthermore, the tasks can be analyzed to ensure that urgent tasks have salient activators and common tasks are streamlined. The designer can also look for task patterns that are similar to those used by other systems the operator is familiar with, and attempt to match them.

HTA excels at describing the tasks the operator must complete to achieve the system goal, as well as the information requirements needed to complete the tasks. However, HTA is limited to task sequences that are predicted within the design process, which can result in designs that are unable to support the operator during unanticipated events. This presents a particular challenge in aviation, where many accidents occur because of a complex sequence of events and actions that were not anticipated by designers. Furthermore, research has demonstrated that humans use three basic modes of behavior: skill based behavior, rule based behavior, and knowledge based behavior [13]. Skill based behavior can be thought of as automatic operations that are well practiced, rule based behavior as following a set of either internal or external rules (i.e. rules stored in memory or in a procedures/interface), and knowledge based behavior as problem solving. Task based interfaces often support skill based behavior and rule based behavior, but have problems supporting knowledge based behavior, which can result in the inability to develop an appropriate course of action when anticipated events occur or can result in an incomplete or incorrect understanding of a complex automated system. Additionally, the course of behavior mapped out by task analysis may not be optimal, effective, or efficient for every situation. Instead, it analyzes the tasks operators should perform from a limited set of predefined scenarios.

2.1.3. The Use of Task Analysis in Aviation

Task analysis has a significant history of use in the aviation industry, and has been used to examine many different aviation systems. For example, Keller, Leiden, and Small completed a cognitive task analysis of commercial jet pilots during instrument approaches with the purpose of aiding the design of synthetic vision displays [14]. Additionally, task analysis has been used to examine procedures for aircraft maintenance [15], [16]. Sperling used a task analysis along with a WDA to help identify complementary sets of information to provide to the commander and co-pilot of military helicopters [9]. Perhaps the most applicable task analysis to this thesis is one completed by RTCA to help identify minimum flightdeck requirements for IM [4].

2.2. Work Domain Analysis

2.2.1. Cognitive Work Analysis (CWA)

Cognitive Work Analysis (CWA) was proposed by Vicente and Rasmussen as a five step method that can be used to design systems that support the operator during both anticipated and unanticipated events [1], [17]. CWA can be broken into five major steps: work domain analysis (WDA); Control Task Analysis (CTA); strategies analysis; social, organization, and cooperation analysis; and a worker competency analysis. These steps are shown in Table 2.1; note that the steps of CWA proposed by Vicente and Rasmussen were slightly different from each other, with the largest difference being that Rasmussen proposed that CTA should have two parts: activity analysis and decision analysis. The first step of CWA, WDA, describes the entire work domain of the system. The second step of CWA, CTA, describes the tasks the operator can do to control the system and the decision making process the operator uses when completing the control task. The third step of CWA is a strategies analysis, which describes how to complete control tasks. This step is the most similar to task analysis. The fourth step of CWA is social, organization, and cooperation analysis, which examines how functions can be split between operators and goals. The final step of CWA is a worker competency analysis, which identifies the interface requirements and training an operator will need to function in the work domain.

Table 2.1: The parts of Cognitive Work Analysis (CWA)

Vicente (1999), [1]	**Rasmussen (1994),** [17]	**Description**
- Work Domain Analysis (WDA)	- Work Domain Analysis (WDA)	Describes the work domain in terms of the systems purpose, constraints, and relationships
- Control Task Analysis (CTA)	- Activity analysis in domain terms - Decision analysis in information terms	Describes control tasks that can be used to operate the system
- Strategies Analysis	- Information processing strategies	Describes the different strategies that can be used to complete a control task
- Social Organization and Cooperation Analysis	- Allocation of decision roles - Management structure	Examines how functions and goals can be split among cognitive agents
- Worker Competencies and Cooperation Analysis	- Mental resources, competency, and preferences of the individual actor	Describes what workers need to complete their responsibilities

A search of the literature found only a few instances where use of the entire CWA process has been documented. Ahlstrom conducted a CWA to assess practices of controlling air traffic during adverse weather conditions [18], and Sanderson, Naikar, Lintern, and Goss conducted a CWA for a military system called Airborne Early Warning and Control [19], [20]. There are several potential reasons why the entire CWA process is not used more frequently. Completing a CWA can be time consuming and requires extensive knowledge of the system and constraints imposed on the system. There has not been extensive research on the cost benefit of completing a CWA in comparison to other methods of system design. Furthermore, a search of the literature did not find a clear, consistent standard methodology for the latter steps of the CWA process, and the benefit of using these latter steps to investigate IM was unclear. Thus, only the WDA and CTA portions of CWA are used in this thesis.

A WDA describes the entire work domain of the system, and the constraints that govern the system. One common method of representing the work domain is the Abstraction-Decomposition Space (ADS), otherwise known as the Abstraction Hierarchy (AH) [1], [22]. The ADS has five different levels of abstraction along its vertical dimension: the first level describes the purpose of the system (abstract purpose), the second level describes the basic laws of nature that govern the system (abstract function), the third level describes the functions the system must achieve (generalized function), the fourth level describes the major components that are used to achieve the generalized functions (physical function), and the final layer describes the physical components, such as specific interfaces and buttons (physical form). The vertical axis of the ADS can be thought of as using the high levels of abstraction to describe *why* a system is being developed, the middle levels of abstraction to describe *what* the system will do, and the lower levels of abstraction to describe *how* the system will meet its goals. Functions within the levels of abstraction are connected by means-end relationships. The horizontal dimension of the ADS decomposes the system into smaller and smaller subcomponents. The result is a table where each block contains a complete description of the system constraints in different levels of generality. Naikar, Hopcroft, and Moylan described a procedure for using the ADS, which includes the following steps [23]:

1. Establish the purpose of WDA
2. Identify the project constraints

3. Determine the boundaries of WDA
4. Identify the nature of constraints
5. Identify the potential sources of information
6. Construct ADS
7. Validate ADS

Additionally, Naikar, Hopcroft, and Moylan further detail that the sixth step, construction of the ADS, should be completed by identifying the work-domain properties, defining the levels of abstraction and decomposition, developing a sketch of ADS, evaluating which cells of the ADS to populate, populating the selected cells, and then revisiting the original data to make sure that the ADS is representative [23].

Table 2.2: The Abstraction-Decomposition Space (ADS) proposed by Rasmussen [17]

Decomposition Abstraction	Total System	Subsystem	Function Unit	Subassembly	Component
Functional Purpose	General				Specific
Abstract Function					
Generalized Function					
Physical Function					
Physical Form	Specific				

Control Task Analysis (CTA), the second part of CWA, is used to describe tasks that control the system. The decision ladder, which was developed by Rasmussen in 1976, is commonly used to represent the decision making process that operators use when conducting control tasks [24], [25]. The decision ladder is composed of an idealized rational decision making process, which includes data processing blocks (represented by rectangles in Figure 2.2) and states of knowledge the operator gains from data processing (represented by circles in Figure 2.2). The idealized decision making process is bent in half, creating the decision ladder. The left side of the decision ladder describes how the operator can gather knowledge of the system and the right side describes how the operator can determine a plan of action. Expert operators may be able to use knowledge of the system to skip certain steps in the decision ladder. These jumps can be categorized as shunts or leaps, and are represented by dashed lines in Figure 2.2. Shunts connect data processing blocks to states of knowledge, and are intended to describe instances where data processing allows the operator to skip steps on the decision ladder. For instance, information from displays may tell an operator what the target state of the system should be. Leaps connect two states of knowledge together, and are intended to show pieces of information that are connected. For instance, a user may observe information from a display, and automatically associate it with a procedure.

The decision ladder can also be used to describe skill, rule, and knowledge based behaviors. Skill based behavior can be thought of as well trained automatic processes that require little thought. The bottom portion of the decision ladder represents skill based behavior as observing data and executing a predetermined plan. Rule based behavior can be thought of as a series of IF, THEN statements. The rule based portion of the decision ladder includes steps where the operator describes the system state, and determines tasks that can be used to achieve a given goal. Knowledge based behavior is used when there are no skills or rules that apply to a given situation, and can be thought of as learning and experimenting to develop an appropriate course of action. The entire decision ladder describes knowledge based behavior, with the top portion focused on an iterative process of determining a system goal, predicting the consequences of attempting to achieve that goal, and determining a new goal when the existing goal is not adequate.

CTA is commonly used along with the WDA [1]; however, it can also be a useful way of describing control tasks presented in an HTA. In the HTA example presented in Figure 2.1, many of the tasks were descriptive. However, control tasks can be added. The decision ladder can be used to determine if the user has adequate information and controls to perform the control task. In this way, the HTA can be viewed as a complete description of nominal behavior that the operators can complete, and use to identify different control tasks. In contrast, the WDA is used to describe the breadth of decisions the operator can make. The decision ladder can be linked to both the HTA and WDA. If there is an appropriate procedure described in the HTA, the operator can leap to the procedure and execute it. If there is not an appropriate procedure in the HTA, the operator must evaluate options and formulate a course of action. This involves using information from the WDA.

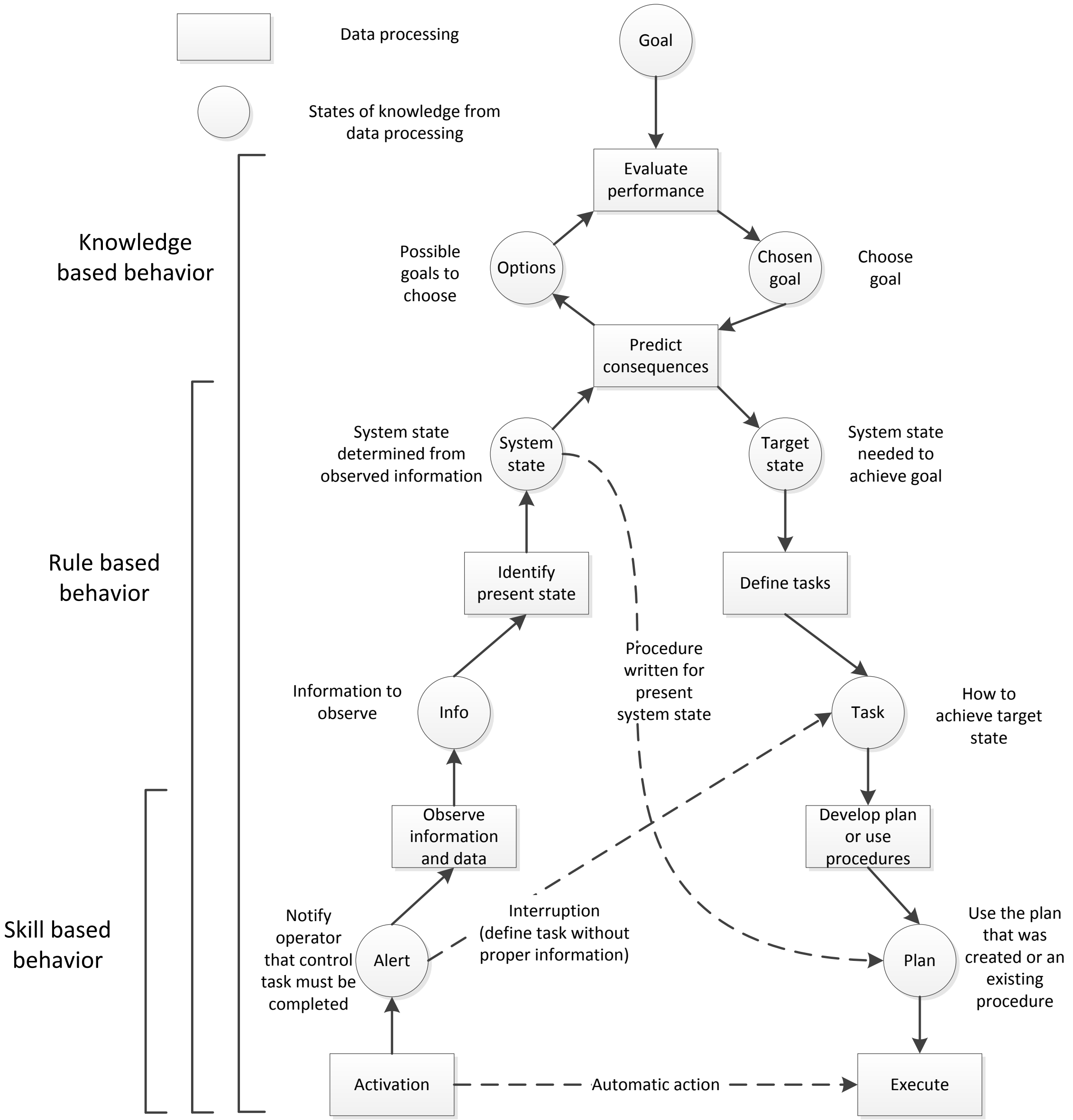


Figure 2.2: The decision ladder, developed by Rasmussen, provides a framework that can be used to describe how humans operators complete control tasks (adapted from [24], [25])

When developing interfaces using a WDA, designers often use Ecological Interface Design (EID) principles [26]. The philosophy behind EID is to use interface elements to transfer an accurate mental model of a system to the operator. This is accomplished by displaying the operating constraints and dynamics of a system in an integrated and natural way, using appropriate representations. By creating interfaces that serve as an external mental model of the system EID seeks to support skill, rule, and knowledge based behavior [13], as well as skill and rule based behavior that can often be supported using a task based approach. When designing EID interfaces it is common to use the ADS to describe the system and then transfer the constraints from the ADS into display elements.

EID displays seek to integrate a large amount of complex information into intuitive representations of the system, allowing the operator to gain an accurate mental model of the system. Zhang and Norman described distributed representations [27], and later applied it to flightdeck displays [28]. The idea of distributed representations states that each system has both internal and external representations. Internal representations refer to those that the operator must memorize. External representations refer to representations that can be inferred from displays or the environment. The internal and external representations can be combined to form a mental model of how a particular system works.

While WDA has demonstrated its ability to inform the designs of complex systems, the aviation domain creates unique challenges that WDA does not consider. The aviation industry is heavily proceduralized, and many non-normal circumstances have been anticipated and addressed. Furthermore, the WDA does not contain information regarding time critical tasks or the operator’s taskload. Lastly, there are limited resources for monitoring information aboard a flightdeck. WDA and EID often entail presenting the operator with a large amount of information, albeit in an integrated and easy to understand manner. Nevertheless, commercial aviation is complex, and there is potential that providing too much information, without regard to taskload, may decrease the benefits of an EID interface.

2.2.2. The Use of Work Domain Analysis in Aviation

Accidents that occur in aviation are often the result of a string of events which were not anticipated in design. WDA has the potential to assist in the design of avionics and ATC automation that support pilots and air traffic controllers during these unforeseen events. A number of researchers have used WDA to help design novel flight concepts, interfaces, and teams.

WDA has been used to examine concepts and displays in support of free flight concepts and collision avoidance. Van Dam, Mulder, and Paassen used WDA to develop an interface for a tactical airborne separation tool that would grant pilots greater freedom to choose their own trajectories [29]. They used the WDA to determine workspace constraints, which were translated into display elements that showed pilots the trajectories they could fly while maintaining proper separation from other aircraft. Ho and Burns used a WDA to design interfaces for collision detection and avoidance automation [30]. They created a WDA that encompassed the aircraft, environment, and collision avoidance system, and found a number of pieces of information that may help pilots choose the correct action when presented with a conflict. Borst used EID to design interfaces for a terrain awareness warning system [31]. The goal of this research was to help pilots deduce why a particular warning was given. Their findings indicated that providing pilots with an EID display helped increase their understanding of terrain warnings. Furthermore, placing information about the operational envelope on the displays caused the pilots to ‘push the envelope’ more; however, the displays helped prevent the pilot from pushing the envelope over the limit. Lastly, Amelink, Paassen, Mulder, and Flach used a WDA to gain more insight into what factors are involved with aircraft energy management [32].

In addition to free flight concepts and collision avoidance, WDA has been used to help pilots monitor their aircraft's engine performance, manage their aircraft's energy, and help ATC monitor weather. Ahlstrom used all of the steps of CWA to examine weather displays for air traffic controllers, helping them discover beneficial information that was missing from ATC weather displays [18]. Dinadis and Vicente used a WDA to create a prototype interface for the fuel and engines of a Lockheed Hercules C-130 [33]. They used an ADS to model each part of the fuel and engine interface, and found that the then-current interface portrayed the higher and lower levels of abstraction; however, the middle levels of abstraction in the ADS were only partially portrayed. Furthermore, they found that the EID operating philosophy was significantly different from the aviation operating philosophy of the time. The aviation operating philosophy placed a low emphasis on deep knowledge of the system, and instead emphasized following procedural steps to achieve mission success. Dinadis and Vicente cited several reasons why the aviation industry used this philosophy. Most notably, knowledge based behavior may take more time than pilots have available during a crisis, and managing aircraft systems is secondary to flying the aircraft (i.e. the pilots can just turn the automation off). However, they conclude by describing reasons why WDA and EID are pertinent to aviation. Most notably, procedures are unable to capture all possible events, especially as air traffic increases.

Research has also shown that WDA can be useful when designing teams and training requirements. Naikar and Sanderson used WDA to develop an effective training program for the F/A-18 [34]. They used WDA to decompose the system into functions, which were then used to develop a comprehensive training program. Sperling used both HTA and WDA to determine complementary information to show team members, and found that the performance of teams increased when they were each provided with complementary information that was relevant to their tasks instead of all team members being presented with all available information [9].

2.3. The Joint Use of Task Analysis and Work Domain Analysis

Miller and Vicente (1998) were among the first researchers to suggest that task analysis and WDA could be used together to develop interfaces that support specific tasks the operators were required to complete, while providing the operator with the information needed to make critical decisions during unanticipated circumstances [35]. They determined that the information provided by task analysis and WDA was complementary. Specifically, they found that task analyses were good at describing proceduralized information and time pertinent information, whereas WDA contained deep knowledge of a system that could be used to help operators gain an accurate mental model of the system. By adding task based information to EID displays, they were able to add strategy guides, expectation indicators, sequencing information, information prioritization, and dynamic organization, among other information to their interface design.

Sperling examined the joint use of HTA and WDA with the goal of designing interfaces that support complementary mental models among team members [9]. He conducted two HITL experiments with similar work domains and task domains: a helicopter navigation task, and an automobile navigation task. A WDA and HTA were used to show that the helicopter simulation and automobile simulation had similar work domains and task domains, and to determine complementary sets of information to display to the participants. The experiment results demonstrated that providing a team of operators with complementary information can increase team performance and help clarify team roles.

Researchers have described different approaches regarding how to combine task analysis and WDA into a unified model. Miller and Vicente took the approach of generating requirements from a task analysis and WDA, combining those requirements, and using them to generate a display [36]. Sperling mapped information sources onto supporting tasks (i.e. tasks that used those information sources) [9]. Hajdukiewicz and Vicente developed and demonstrated a model where each task was described by a relevant segment of the ADS [10]. The ADS was narrowed from the entire ADS that described the whole work domain, to a small portion of the ADS that included the current state of the ADS when the task began and the desired state of the ADS after the task was completed.

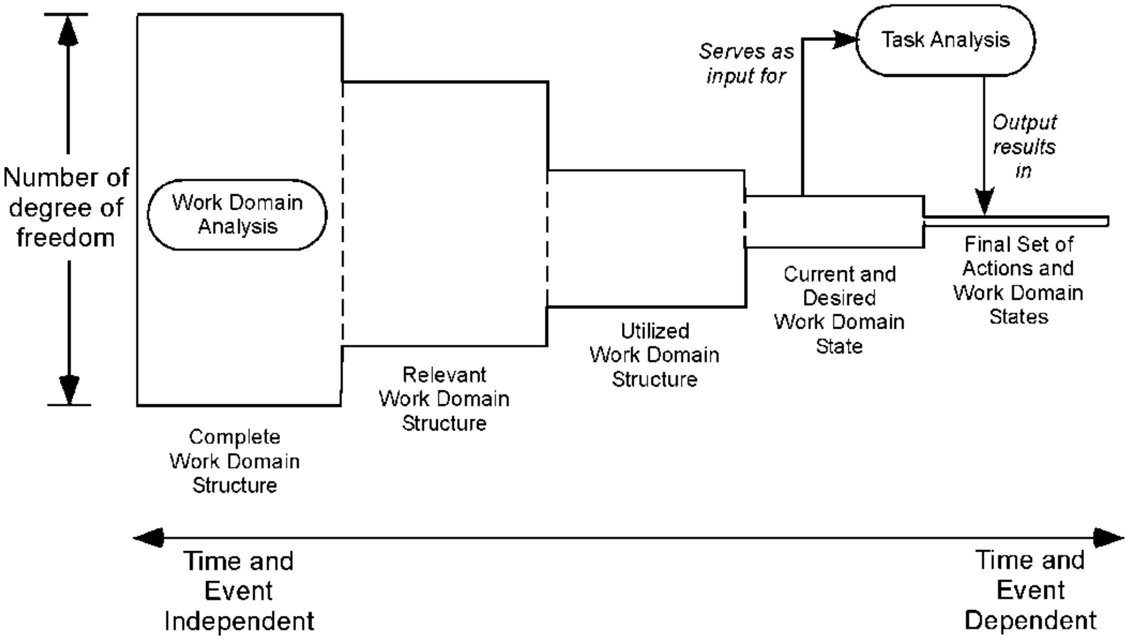


Figure 2.3: A joint task analysis and work domain analysis model developed by Hajdukiewicz and Vicente [10]

In two separate experiments, Jamieson (2002) and Burns (2008) examined the real-world benefit of using a joint task analysis and WDA method to design interfaces. Jamieson (2002) conducted a HITL study examining the use of a legacy interface, a traditional EID display, and an EID display with task information [37]. In a separate experiment, Burns et al. investigated interfaces for nuclear process control [38]. In both cases, the EID interfaces resulted in increased performance during unanticipated events. Furthermore, the addition of task information to EID interfaces resulted in increased performance during anticipated non-normal events.

WDA was only meant to be the first step in a multi-step processes that includes CTA, strategies analysis, social organizational and cooperation analysis, and worker competencies analysis [1]. However, most of the work that has been completed on the joint use of task analysis and WDA has not discussed the impact of the other steps in CWA. One exception is the work done by Salmon [11]. Salmon compared the theory, methodology, and contribution to system design of HTA and CWA. The comparison suggested that CWA and HTA were complementary: HTA may be more useful when designing improvements to an existing system or when analyzing a highly proceduralized system, and CWA may be more useful when analyzing very complex systems or when designing a system that is the first of its kind. However, many complex systems are also highly proceduralized. Thus, there is the potential for complex proceduralized systems to benefit from both task analysis and WDA.

Overall, the literature has shown that the joint use of task analysis and WDA can provide a number of benefits. Task analysis is good at identifying priority information, supporting the design of procedures, and describing a nominal set of actions the operator should complete. WDA is good at providing deep knowledge of the constraints and dynamics of a system. These advantages have the potential to make the joint use of WDA and task analysis useful to aviation. The commercial aviation industry is heavily proceduralized during nominal conditions and contains many time critical tasks, such as preventing separation violations, or reacting to a TCAS advisory. Task analysis can help provide insight into these issues. However, the procedures can be either incomplete or incorrect when off-nominal circumstances are encountered, requiring operators to intervene and problem solve. This requires a thorough understanding of the constraints and dynamics of the automation. WDA has the ability to help develop interfaces that can convey deep knowledge of the system. Thus, developing displays and procedures using a task analysis and a WDA has the potential to result in interfaces, procedures, and training programs that help pilots complete tasks, while providing them with knowledge needed to respond to unanticipated events.

2.4. Interval Management

The joint use of HTA and WDA can be applied to Interval Management (IM), which is an aviation operational concept that is currently being developed by various organizations around the world. The goal of IM is to enable aircraft to achieve precise spacing intervals behind a lead aircraft at a particular geographical location. This section will provide background information on IM and a review of major Human-In-The-Loop (HITL) experiments that have been conducted.

2.4.1. Background

By 2030, the number of passengers, cargo aircraft, and commercial aircraft are expected to increase by over 50% (from 2009 numbers) [39]. If current day operations are maintained, the increased traffic will result in greater noise pollution, air pollution, delays, and the need for new infrastructures. The desire to minimize the impact of these effects has motivated the development of various systems, which have been collectively named the NextGen air system [40]. Optimized Profile Descents (OPDs), also known as Continuous Descent Arrivals (CDAs), are near idle thrust descents that have the potential to decrease aircraft noise, fuel usage, and air pollution. However, OPDs can cause a higher level of uncertainty in the aircraft arrival time at the runway because they limit the extent to which aircraft can slow down or be vectored by ATC. Larger spacing buffers are needed to ensure that aircraft on OPD arrivals will not produce a separation violation, limiting the use of OPDs to periods of low traffic. One proposed method of minimizing this uncertainty, and consequently maximizing runway throughput, is to delegate spacing and separation responsibilities from Air Traffic Control (ATC) to the flightcrew. In 2001 the Federal Aviation Administration (FAA) and Eurocontrol defined four levels of delegation of responsibility [41].

- **Airborne Traffic Situational Awareness**: Airborne traffic situational awareness tools improve the flight crew’s situation awareness. ATC remains responsible for the spacing and separation of all aircraft.
- **Airborne Spacing**: The flightcrew is responsible for maintaining spacing from an aircraft delegated by ATC. ATC is still responsible for maintaining separation from all aircraft.
- **Airborne Separation**: Responsibility for separation from a lead aircraft that is properly equipped can be delegated to the flightcrew by ATC. The flightcrew will have the responsibility to maintain all separation requirements from the delegated aircraft, whereas ATC will remain responsible for separation from all non-delegated aircraft.
- **Airborne Self-separation**: Airborne self-separation delegates the responsibility of maintaining separation from all surrounding aircraft to the flightcrew. ATC is no longer responsible for separation.

The airborne spacing concept includes delegating the responsibility of maintaining a spacing interval to the flight crew, with ATC remaining responsible for separation between all aircraft [41]. Many different implementations of airborne spacing have been studied; however, the focus of this study is on an implementation of IM that has been developed at NASA Langley Research Center. This particular implementation uses the a trajectory based approach where an arrival time is projected along a 4-D trajectory for both the spacing aircraft and its lead aircraft, as opposed to a state-based approach which uses the lead aircraft's state to control the spacing interval. The major advantage of a trajectory based approach is that it allows an aircraft to achieve a spacing interval behind a lead aircraft that is on a different trajectory. This allows an aircraft to begin the spacing operation earlier than it could without knowledge of the lead aircraft's trajectory. The IM operation that this thesis investigates includes two parts: a ground scheduling tool that creates an arrival schedule for aircraft, and flightdeck automation which provides the speeds that the flightcrew can fly to achieve a desired spacing interval at a designated *achieve-by* point.

Particular attention has been given to the airborne spacing concept during arrivals to busy terminal areas, with a focus on achieving the maximum precision possible during normal and anticipated non-normal conditions. HITL experiments have demonstrated the benefits of both the ground scheduling tool and the flightdeck tool during arrivals to busy terminal areas. A HITL experiment conducted by MITRE revealed that current day operations result in a mean spacing interval at the runway threshold of 24.8 seconds, with a standard deviation of 17.0 seconds. In contrast, the largest mean spacing error at the runway threshold for multiple airborne spacing scenarios was 2.2 seconds with a standard deviation of 1.3 seconds [42], [43]. Baxley et al. reported that precise runway delivery can reduce ATC's spacing buffer by 10 to 15 seconds, resulting in a 5% to 10% increase in runway throughput [44]. While these gains may seem small, Credeur's (1997) analysis of terminal operations showed that a 5% increase in runway throughput can result in a 29% decrease in delays for an airport running at 85% capacity [45].

A number of HITL experiments have examined the flightdeck and ground portions of IM. Some of the major investigators have been Eurocontrol, MITRE, NASA

Langley, and NASA Ames. Additionally, an industry standards group, RTCA, has recommended a set of minimum standards for Flightdeck Interval Management (FIM) [4]. Many of the HITL studies conducted by each of these organizations will be discussed in the next section. In addition to the HITL studies, various batch studies have been conducted, and different spacing algorithms considered. These are considered outside of the scope of this thesis, and will not be discussed.

2.4.2. Airborne Spacing Experiments

Eurocontrol completed a set of experiments assessing an airborne spacing concept under their CoSpace project. Their first experiment examined the acceptability and effectiveness of three spacing instructions: *remain*, *merge*, and *heading then merge* [46]. Overall, the pilot participants rated their workload as acceptable; however, they requested either a speed advisory when manually entering speeds or an auto-throttle mode to manage the speed. Additionally, the flight crew requested an indicator to describe how well they were maintaining the spacing interval. In a subsequent experiment, Eurocontrol examined the effect of 1NM, 0.5NM, and 0.25NM spacing intervals on flightcrew acceptability, speed of action, spacing accuracy, and safety [47], [48]. The results of this experiment indicated that the number of speed actions increased from 1 to 1.7 speed actions per minute as the spacing interval was decreased with the 0.25NM spacing interval causing higher workload for the Pilot Flying (PF). Even with the addition of the trend indicator, pilot comments indicated that they preferred an auto-throttle mode to manage the speed. As the final experiment of the CoSpace project, Eurocontrol examined airborne spacing with Continuous Decent Arrivals (CDAs), as well as speed and lateral modes managed by the autopilot [49]. Pilot participants gave high acceptability ratings throughout the experiment.

In addition to conducting airborne spacing studies of the flightdeck, Eurocontrol examined the usability and acceptability of their airborne spacing concept from ATC’s perspective. Eurocontrol investigated the usability of airborne spacing during periods of high traffic [50]. They found that air traffic controllers experienced a reduction in workload and increased predictability of spacing on final approach, as well as less vectoring late in the arrival. In another study, Eurocontrol investigated the usability of airborne spacing procedures under medium-high traffic [51]. Controller feedback indicated that the airborne spacing procedures were usable. Furthermore, controller responses indicated they preferred using time based spacing intervals as opposed to distance based spacing intervals. Lastly, controllers were reluctant to cancel the airborne spacing operation. Eurocontrol investigated a number of non-normal conditions, including a go-around, an emergency aircraft that had to be integrated into the flow, a radio failure, and spacing instructions that were not correctly executed [52]. They concluded each of the conditions tested were the same difficulty as today’s operations. Lastly, Eurocontrol conducted an experiment investigating the joint use of an aircraft sequencing tool and the airborne spacing instructions [53]. They conducted separate evaluations for the en-route airspace and the terminal area. They found that heading and speed instructions reduced in terminal area, and that the scheduler helped controllers ensure the capacity of terminal airspace was not exceeded.

MITRE conducted four HITL experiments examining an airborne spacing concept called Flight Deck Merging and Spacing (FDMS). These experiments were designed to examine the FDMS concept that was being developed by the FAA, and that the United Parcel Service (UPS) desired to implement. The first of these experiments, FDMS 1, evaluated the air traffic efficiency, communications, safety, workload, and situational awareness from ATC's perspective [54]. The results of the experiment demonstrated that the FDMS operations resulted in about half of the interventions that were present in the baseline scenario while providing favorable ratings of workload and situational awareness. MITRE's second HITL study, FDMS 2, examined the flight crew's acceptance of FDMS procedures during nominal and off-nominal operations [42]. In general, the pilot participants found the FDMS procedures and a majority of the display elements acceptable, with the exception of the Cockpit Display of Traffic Information (CDTI) displayed on an Electronic Flight Bag (EFB). Pilots stated that the location of the EFB made it difficult to work the CDTI into their scan patterns. MITRE's third HITL study, FDMS 3, evaluated flight crew's acceptance of FDMS procedures coupled with CDAs under both nominal and off-nominal conditions [55]. The experiment results demonstrated large improvements in aircraft delivery precision, and pilot participants found the overall concept acceptable. However, there were areas for improvement, such as the number and frequency of speed changes. MITRE's fourth HITL study, FDMS 4, examined FDMS with CDAs from ATC's perspective [56]. The results demonstrated that controllers found the FDMS procedures acceptable, and that controller interventions to a single arrival stream of aircraft were lessened.

NASA has a long history of researching airborne spacing. NASA Langley was one of the primary investigators of interval management in the late 1970's and early 1980's [57], [58]. Within these studies, pilots were required to use a CDTI to monitor the progress of the spacing operation and determine specific actions needed to conform to a given spacing interval [57], [59]. The results found that cluttered displays and a long refresh rate of four seconds contributed to increased dwell time on the CDTI. Since these early experiments, there have been technological advances including precise position information and the ability for aircraft to transfer information to each other. These advances, in conjunction with the push for the NextGen air system, spawned new research of airborne spacing.

Around 2002, NASA Langley renewed its interest in airborne spacing. In 2002, Oseguera-Lohr completed a HITL study examining NASA's Advanced Terminal Area Approach Spacing (ATAAS) concept [60]. The experiment examined a baseline of today's operations and three spacing modes: manual control, speed intervene, and an autopilot managed mode. The results of the experiment demonstrated that the ATAAS procedures and workload were acceptable. The head down time and number of speed changes increased from the baseline scenario, but still received favorable ratings. In 2005, a HITL study was conducted to examine a new airborne spacing concept, Airborne Merging and Spacing for Terminal Arrivals (AMSTAR) [61]. AMSTAR was built on the previous spacing algorithm called Airborne Precision Spacing (APS), and contained an onboard algorithm that used 4-D trajectories to calculate a commanded speed that could be flown to achieve the desired spacing interval. Overall, pilots provided acceptable ratings of AMSTAR; however, pilot's found some deficiencies. It was suggested that these deficiencies were the results of poor training and the use of medium fidelity simulators.

After this experiment, the airborne spacing concept was renamed from AMSTAR to IM. Murdoch describes a HITL study in 2009 that examined the flightdeck implementation of IM coupled with CDAs during nominal and off nominal conditions [62]. The objectives of the experiment were to determine pilot acceptability of the IM concept and procedures, and to characterize system performance. They found that the IM procedures were acceptable, and only resulted in a small increase in workload. The pilot participants indicated that the procedures were adequate for the events in the experiment, but a significant number of pilots indicated that the procedures were incomplete. Another HITL experiment conducted at NASA Langley examined IM during dependent parallel arrivals into a busy terminal area [63]. Overall the participants found the IM concept, workload, procedures, interface, and commanded speeds acceptable. Nevertheless, there were changes to the procedures and interface that were recommended, including more salient alerting of commanded speed changes and the ability of a single crewmember to set up the IM operation. In preparation for the HITL experiment investigating IM to dependent parallel runways, Volk conducted a suability analysis of the IM displays. During the study, he showed pilots' video recordings of aircraft displays with various IM displays added, and gathered pilots' responses [64]. He found that pilots provided highest ratings to displays that contained graphical spacing trend indicators, though it was unclear how pilots used the information from the trend indicators.

Other organizations have also conducted research on airborne spacing concepts. Pritchett and Yankosky examined airborne spacing using three different displays that were presented on the Cockpit Display of Traffic Information (CDTI), and three different procedures [65]. The three displays included a baseline display without speed information, a display showing the speed of the lead aircraft, and a display showing the speed target and the current speed of the lead aircraft. The three sets of procedures were represented as a baseline STAR without speed information, a STAR that told the flightcrew what speeds to expect at a particular point in the arrival, and a STAR with both speeds and the merging path. They determined that there was interaction between the CDTI displays and procedures, and that the information contained in the procedures was useful as long as the lead aircraft followed their procedure. They conclude by suggesting that a robust system may need greater emphasis on displays as opposed to procedures or further controller oversight. In DO-328, RTCA conducted the only known task analysis of IM and used it to recommend minimum display requirements needed to complete the operation [4]. This thesis will build on the task analysis RTCA conducted, with the goal of describing procedures and interfaces that will best support the operator, as opposed to focusing on minimum requirements.

In addition to flightdeck automation, the IM concept requires ATC to have the ability to schedule aircraft. NASA Ames has been investigating ATC automation that has the ability to create precise runway schedules, and is expected to serve as the ground portion of IM. The ground scheduling system is built on the Traffic Management Advisor (TMA), which was developed at NASA AMES research center in the 1990s, and is currently in use at some Air Traffic Control Centers [66], [67]. TMA is a strategic tool that can provide air traffic controllers with the ability to optimize the traffic flow at high demand airports by using trajectory prediction, constraint-based runway scheduling, and traffic flow visualization. The ground portion of IM is based on Traffic Management Advisor with Terminal Metering (TMA-TM). Figure 2.4 shows a number of display

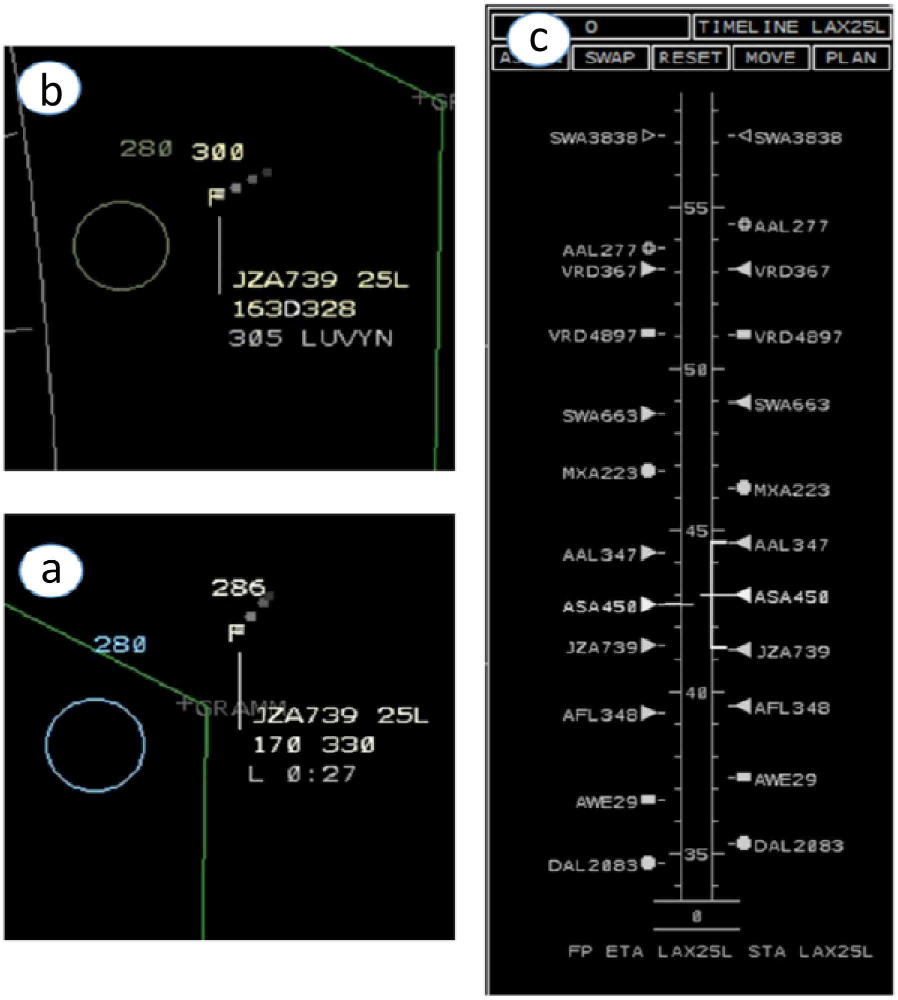


Figure 2.4: Moving clockwise from bottom left to right [68], a) Flight data block how early or late the aircraft is, b) Flight data block showing an advised speed, and c) TMA timeline with ETAs on the left and STAs on the right

elements that TMA-TM can use [68]. Figure 2.4 (a) shows the slot marker (circle) which is designed to show the location TMA expects the aircraft to be, and the time error of the aircraft in the bottom row of the data block. Figure 2.4 (b) shows the same slot marker (circle), with a data block containing an advised speed that controllers can convey to the aircraft keep them on schedule. Figure 2.4 (c) shows a time line that contains the TMA schedule. The left side shows the Estimated Times of Arrival (ETA), and the right side shows the Scheduled Times of Arrival (STA). The bracket shows the required separation between leading and trailing aircraft, which can also be used to identify gaps in the schedule. Overall, it is envisioned that there will be three pieces to a new airborne spacing system: TMA-TM will compute an aircraft schedule and Estimated Time Of Arrivals (ETAs); Controller Managed Spacing will use the time schedule generated by TMA, and provides speed advisories to air traffic controllers, which they can relay to aircraft that are not equipped for airborne spacing; and FIM equipped aircraft, which will use onboard speed guidance to achieve a precise interval at a designated point.

A number of experiments examined TMA used with ground based spacing. This discussion will concentrate on the most recent work with The Terminal Area Precision Scheduling and Spacing (TAPSS) system built on TMA. A HITL study compared the TAPSS system with today's operations at traffic levels similar to today's air traffic, and increases of 5%, 10%, and 20% from today's traffic levels [69]. The experiment demonstrated that the TAPSS system was capable of achieving a 10% increase in runway throughput from today's operations when the airport was busy. TAPSS has also demonstrated benefits such as a decrease in level segments, flight distance savings, flight time savings, and a greater ability for aircraft to maintain fuel efficient CDAs [70]. Another HITL experiment was conducted to examine how air traffic controllers used three different displays when wind errors and other disturbances are present [71]. The three display conditions included a timeline, slot marker, and advisory tool. The study determined that controllers thought the timeline was very useful, and preferred the displays that contained the slot markers (circles). Currently, HITL experiments are examining these ATC operations integrated with IM in the flightdeck.

The experiments described in this section reveal extensive research into IM. This research has shown that IM is capable of substantially increasing the arrival precision of aircraft, and that air traffic controllers and pilots generally find the IM operation acceptable. Nevertheless, many of the HITL experiments suggest improvements that could be made to the IM operation. Currently, work is being conducted on integrating the flightdeck and ground components of IM. As this integration occurs, and as IM moves closer to implementation, it is important to examine procedures and interfaces that have the potential to support pilots and air traffic controllers when conducting IM operations.

2.5. Summary

Task analysis and WDA are two methods that have been successfully used to design procedures and user interfaces. Task analysis examines the actions an operator is required to complete, ensuring that operators are provided with appropriate information and controls needed to complete a given task. However, task analysis does not provide the operator with guidance on how to complete tasks that the designers of the system did not anticipate. Furthermore, displays designed using a task analysis may not convey a complete mental model of the work domain. This can be problematic when an operator is required to devise an appropriate course of action when unanticipated events occur. WDA is a complementary approach that analyzes the domain in terms of different levels of abstraction and decompositions, creating a map of the domain’s functions and constraints. EID can be used to develop representations of these functions and constraints which support skill, rule, and knowledge based behavior during off-nominal circumstances.

Research has shown that task analysis and WDA are complementary methods that can be used together to help design systems that support operators during both anticipated and unanticipated situations. Task analysis is a method that can help designers increase the usability of a system by ensuring tasks are supported with appropriate displays, procedures, and training. WDA provides deep knowledge about the domain and its constraints.

IM is a new concept that is being developed with the goal of increasing the arrival precision, enabling the use of OPDs during periods of high traffic and increasing runway throughput. Multiple experiments examined the ground based portion of IM and the flightdeck portion. These experiments have concentrated on anticipated (nominal) events, and have demonstrated the ability of IM to increase the precision of arrivals. Moreover, these experiments have discovered improvements that can be made to the IM system. RTCA has written a document that recommends a set of minimum performance requirements, display requirements, and procedure requirements. This thesis will build on this previous work and seek to define an optimal set of displays and procedures that will support pilots and air traffic controllers during both nominal and off-nominal operations.

CHAPTER 3

IM HUMAN-IN-THE-LOOP EXPERIMENT

3.1. Introduction

A Human-In-The-Loop (HITL) experiment, called the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) experiment, was conducted at NASA Langley to investigate Interval Management (IM) to dependent parallel runways using the Airborne Spacing for Terminal Area Routes (ASTAR) spacing algorithm [63], [72]. The IMSPiDR experiment examined the flightdeck implementation of IM during arrivals to dependent parallel runways using two control methods and three sources of error. Since this experiment was only designed to evaluate the flightdeck portion of IM, a runway scheduler was not used. Instead the scenarios were scripted, and the arrival flow was carefully conditioned to avoid any conflicts. The results from this experiment will be fed into the joint Work Domain Analysis (WDA) and Hierarchical Task Analysis (HTA) analysis in the next chapter.

The purpose of the IMSPiDR experiment was to evaluate IM with dependent parallel runways when significant disturbances were present. The goal was to determine the acceptability of the IM operation and evaluate the spacing algorithm's performance when aircraft were controlled by human pilots. The acceptability of the IM operation can be broken into four categories: acceptability of the IM concept, the spacing algorithm's behavior, the IM procedures, and the IM interfaces. Data on the interfaces and procedures, as well as the pilots understanding of IM, are of particular interest to this thesis.

This chapter will include a description of the IMSPiDR experiment, and an analysis of a subset of its results. The data that will be examined will include measures of workload and pilot acceptance, procedural and operational issues, pilot ratings of IM displays, and the time it took for pilots to accomplish time critical tasks. The data and conclusions from this chapter will be used to create a WDA and HTA model that will be presented in chapter 4, and will ultimately help determine modifications to the procedures and displays that will be discussed in chapter 5.

3.2. Experiment Method

3.2.1. Experiment Procedure and Scenario Design

Scenario Design

The objective of the IMSPiDR HITL experiment was to investigate IM and Required time of Arrivals (RTAs) to dependent parallel runways when significant spacing perturbations were present. Each scenario included a number of simulated aircraft and six human piloted aircraft flying arrivals into Dallas Ft. Worth, from a point just prior to the Top of Descent (TOD) to the runway threshold. Pilots were asked to follow speed commands generated by onboard avionics to achieve a spacing interval designated by Air Traffic Control (ATC).

This experiment's goal was to investigate IM to dependent parallel runways. When arriving to dependent parallel runways there are two separation requirements that must be considered; a wake vortex separation requirement from the aircraft arriving to the same runway as the spacing aircraft, and a diagonal separation requirement for an aircraft arriving to the parallel runway (see Figure 3.1). The spacing algorithm used in this experiment had the capability of spacing off of two lead aircraft. The aircraft that constrained the operation the most at any given time was used to control the spacing interval.

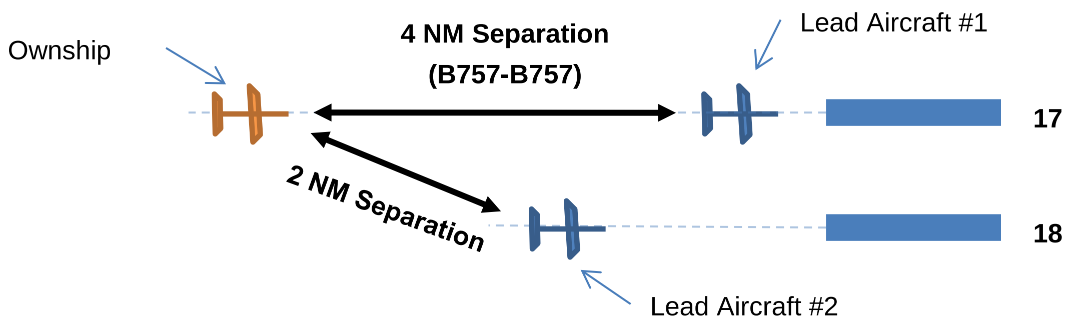


Figure 3.1: IM to dependent parallel runways

The scenarios were designed to simulate a near term NextGen environment, where a high runway throughput rate was required. All of the arrivals in this experiment were fuel efficient Optimized Profile Descents (OPDs). To add to the realism, Standard Terminal Arrival Routes (STARs) were modified for the OPD arrivals and provided to pilots. Controller-Pilot Data Link Communication (CPDLC) messages were used for all IM and RTA clearances; however, voice commands were used to provide pilots with frequency changes and other clearances. Additionally, radio chatter was simulated to provide pilots with a more immersive environment.

Experiment Procedure

Three groups of eight pilots participated in the experiment. Each group was present for a four day period. During this time, they trained, conducted eleven data collection runs, filled out an extensive post-experiment questionnaire, and participated in a group debrief after the experiment had concluded. The eight pilots from each group were assigned one of three different simulator types: two different high fidelity two-crew simulators, and four copies of the same type of single crew PC simulator. Throughout the experiment each pilot rotated between a series of different routes and the scenarios were ordered randomly to prevent order effects due to learning and fatigue.

Comprehensive classroom sessions as well as three training scenarios were provided to participants to help them learn the IM procedures and acclimate to the simulators. Two major classroom sessions were conducted prior to data analysis. The first session concentrated on the controls and displays present in each simulator, and was followed by two training runs that were intended to allow the participants to acclimate to the simulators. The second session concentrated on the IM displays and procedures, and was followed by two training runs that allowed the participants to acclimate to the IM/RTA operations. An additional IM training run was conducted at the beginning of the second day as a refresher course.

Both qualitative and quantitative data was collected during this experiment. The quantitative data included aircraft state data and data from the spacing algorithm, describing its performance. The qualitative data included three questionnaires, as well as a verbal debrief. A pre-experiment questionnaire was provided to the participants prior to the experiment to collect biographical data and any preconceptions of IM they had. After each run, a post-run questionnaire was provided to the participants to gather workload ratings, acceptability ratings, and any participants' comments pertaining to the particular run. After all of the data collection runs were complete, the participants were given an extensive post-experiment questionnaire. The post-experiment questionnaire was intended to collect information about the usefulness and usability of the IM displays and procedures. Lastly, a group debrief session was conducted to allow the participants to verbally relay their thoughts on the IM operation, procedures, and interface.

The dependent measures that were of interest in this experiment ranged from algorithm performance data to crew acceptability ratings; the ratings and comments related to the procedures and interfaces are of particular interest to this thesis. The Modified Cooper-Harper workload scale was used to collect both an average and peak workload from participants after each run, and pilots were asked to provide the segment of flight where their peak workload occurred. In addition to workload ratings, qualitative data on the acceptability of speed commands were gathered after each run. Quantitative data on the performance of the algorithm were also collected during each run. The quantitative data of interest includes the time error at the runway threshold (a measure of throughput), the number of speed changes (a measure of taskload), and the time it took pilots to respond to their IM clearances and react to new speed changes. Lastly, qualitative ratings on the displays and procedures were collected from the post-experiment questionnaire.

Participants

There were 24 pilots that participated in this study. All of the pilots were experienced commercial airline pilots that were employed by major U.S. air carriers. The pilot’s ages ranged from 37-61 years old, and they had an average of 20 years of experience and 11,000 hours of airline flight time. In general, pilots were matched with simulators that were similar to aircraft they had experience on to reduce the amount of training needed; and of the 12 pilots assigned to the two-crew flight simulators, 5 of the 6 pairs were selected from the same airline to enable them to use consistent airline procedures for intra-crew coordination.

3.2.2. Pilot Tasks

All of the human piloted aircraft in the nominal scenarios began their flight at a point just prior to the TOD and flew to the runway threshold. Shortly after the simulation began an IM/RTA CPDLC clearance was provided to the flightcrews, who were expected to review the clearance, determine that it was acceptable, and begin the IM operation. If the pilots were conducting an RTA scenario, they were expected to follow the speed commands provided by the RTA algorithm to the runway threshold. If the pilots were conducting an IM scenario, they were expected to follow speed commands generated by the RTA control method until they were within Automatic Dependent Surveillance-Broadcast (ADS-B) range of their lead aircraft. At this point the aircraft would switch from the RTA control method to the IM control method, and pilots would follow IM speed commands to achieve a precise spacing interval at the Final Approach Fix (FAF).

Pilot Procedures

The procedures that the pilots were asked to use can be broken into three parts: activating IM, conducting IM, and terminating IM. The procedures were designed to be simple and easy to follow. The procedures in this experiment assumed that the IM or RTA clearance would be provided by a CPDLC message, and that the flightcrew would cancel the spacing operation if there were any problems.

Activating the IM operation required receiving a clearance from Air Traffic Control (ATC), reviewing the clearance, activating ASTAR to calculate an initial commanded speed, and executing the operation if the flightcrew deemed the clearance and ASTAR commanded speed was acceptable. The activation was completed differently in the single crew simulators and two-crew simulators. In the single crew simulators, pilots used the Engine Indicating and Crew Alerting System (EICAS) display to load and review the CPDLC clearance; and the Multi-Function Cockpit Display Unit (MCDU) to activate ASTAR, view the initial commanded speed, and execute the IM operation if the speed was acceptable. Pilots in the two-crew simulators used the MCDU to load, review, and respond to the CPDLC clearance; and the other MCDU to activate ASTAR, view the initial commanded speed, and execute the IM operation if the speed was acceptable. This was similar to how CPDLC message are currently done in oceanic operations, and required extensive coordination between the Pilot Flying (PF) and Pilot Not Flying (PNF).

When the flightcrews were conducting the operation, they were required to carry out their normal flight duties while monitoring the Primary Flight Display (PFD) for speed changes and monitoring for any ASTAR memos, advisories, or cautions. IM speed changes were indicated in three ways: a change in the commanded end speed value, a green box that appeared around the commanded end speed for ten seconds (consistent with aircraft mode changes), and the speed bug would begin moving from the old commanded end speed toward the new commanded end speed. When a commanded speed change occurs, the flightcrews were required to update it. Pilots in the Integration Flight Deck (IFD) simulator were expected to update the Mode Control Panel (MCP) speed window to match the commanded speed all the time. The Flight Management System (FMS) in the single crew Personal Computer (PC) simulators and Development

Test Simulator (DTS) would automatically command the auto throttles to match a new commanded speed. However, the speed window would open when the aircraft had captured the Instrument Landing System (ILS), forcing the pilots to manually match the commanded speed using the MCP speed window. In addition to watching for changes to the commanded speed, pilots were required to monitor for ASTAR errors. These errors were displayed on the EICAS display. An additional task pilots had in the IM scenarios was to notify ATC when they transitioned from the RTA control method to the IM control method. In this experiment, this transition occurred when the spacing aircraft was within ADS-B range of its lead aircraft. The pilots in the ATOL could arm a report that would automatically be sent to ATC, and the pilots in the IFD and DTS were required to make a radio call to ATC.

The final portion of the procedures described how, and when, the IM operation could be terminated. There are four general reasons why the flightcrew could terminate the spacing operation: if they no longer thought the spacing operation was acceptable, if there was an ASTAR error that required termination, or if the time error moved outside the ‘excessive spacing’ bounds. In addition, ATC could terminate the operation to prevent a separation violation or provide any other needed commands. In the nominal scenarios, the flightcrew was notified of any ASTAR errors and breaching of the excessive error bounds by and EICAS message. In the exploratory scenario, the flightcrew could also use the conformance box on the Navigation Display (ND) to monitor the excessive error bounds.

3.2.3. Facilities

This experiment was conducted at NASA Langley Research Center using three separate types of simulator platforms: the Air Traffic Operations Laboratory (ATOL), the Development Test Simulator (DTS), and the Integration Flight Deck (IFD). Each of the simulators used the same 6 Degrees Of Freedom (DOF) aerodynamics model; however, the displays came from the flightdecks of different aircraft. The facilities were linked together, allowing the simulators to run together in real time.

Figure 3.2: Clockwise from the top left: (a) Air Traffic Operations Laboratory (ATOL), (b) Development Test Simulator (DTS), (c) Integration Flight Deck (IFD)

The ATOL is comprised of a number of medium fidelity PC simulators that run on the Airspace and Traffic Operations Simulation (ATOS) platform [73]. The ATOL is comprised of hundreds of PC simulators that can be used for batch simulation. Twenty of the ATOS simulators are set up to be operated by a human. These simulators include a mouse controlled interface, a 6-DOF kinematic and aerodynamic model, a modeled FMS, and an ADS-B model.

The DTS is a high fidelity simulator of a large transport aircraft (Figure 3.2, b). The DTS uses a high fidelity 6-DOF aerodynamics model, and is equipped with eight D-Sized LCD displays, sidestick controls, rudder pedals, two color MCDUs, and additional interface devices derived from a variety of commercial aircraft.

The IFD is a full scale simulator of a large transportation aircraft, and is the highest fidelity simulator used in the experiment (Figure 3.2, c). The IFD contains actual aircraft hardware, a high fidelity 6-DOF aerodynamics model, and a 200° horizontal by 40° vertical field-of-view out the window. The IFD has the ability to be placed on a motion platform; however, motion was not used in this experiment.

Flightdeck Automation

The Airborne Spacing for Terminal Area Routes (ASTAR) algorithm was designed to provide the flightcrew with speed advisories to enable them to precisely meet their assigned spacing interval [74–76]. ASTAR10, the latest version of ASTAR, added the capability to support dependent parallel runway operations. ASTAR uses knowledge of the spacing aircraft's and lead aircraft's 4D-trajectories to compute a Time-To-Go (TTG) to an *achieve by point* for each aircraft. ASTAR's speed control law uses the knowledge of the spacing aircraft's TTG and the lead aircraft's TTG to compute a commanded speed that the spacing aircraft can fly to achieve the designated spacing interval at the *achieve by point*. The main advantage of using a trajectory based approach is that it permits aircraft that are on separate routes to space off each other, enabling the spacing operation to begin earlier in the arrival.

Within this experiment, the ASTAR speed control algorithm contained a number of filters and constraints designed to reduce the number of speed changes while maintaining arrival precision. ASTAR has three mechanisms that that are intended to decrease the number of speed changes. The first mechanism is a gain schedule that made commanded speed changes more sensitive to a given time error as the aircraft approached the runway. The second mechanism is a notch filter that subtracted the filter value from the time error. For example, if the raw (unfiltered) time error was twenty seconds, and the filter value was fifteen seconds, the time error used to generate the commanded speeds would be five seconds. The third mechanism is a function that looked ten seconds ahead for a profile speed decrease, and inhibited speed increases during that ten second period.

ASTAR also has mechanisms that keep it from generating unacceptable commanded speeds, and features that help it align with regulations. To keep the commanded speeds within an acceptable range, ASTAR limits it commanded speed deviations to +/- 10% of the nominal profile speed. To keep the speeds consistent with regulations, ASTAR has the capability of complying with the 250 knot speed restriction below an altitude of 10,000ft. Additionally, if the *achieve by point* is the runway threshold, ASTAR will stop providing speed commands around the Final Approach Fix (FAF) to allow the flightcrew to concentrate on achieving a stabilized approach and landing the aircraft.

The Pilot Interface

Interfaces were added to the PFD, the ND, the MCDU, and the EICAS displays. Each of the displays varied slightly between different simulator types; however, the philosophy of the display design remained the same. Each display has similar indicators of the ASTAR commanded speeds, visualization of the lead aircraft, visualization of the spacing error between aircraft, as well as other IM displays.

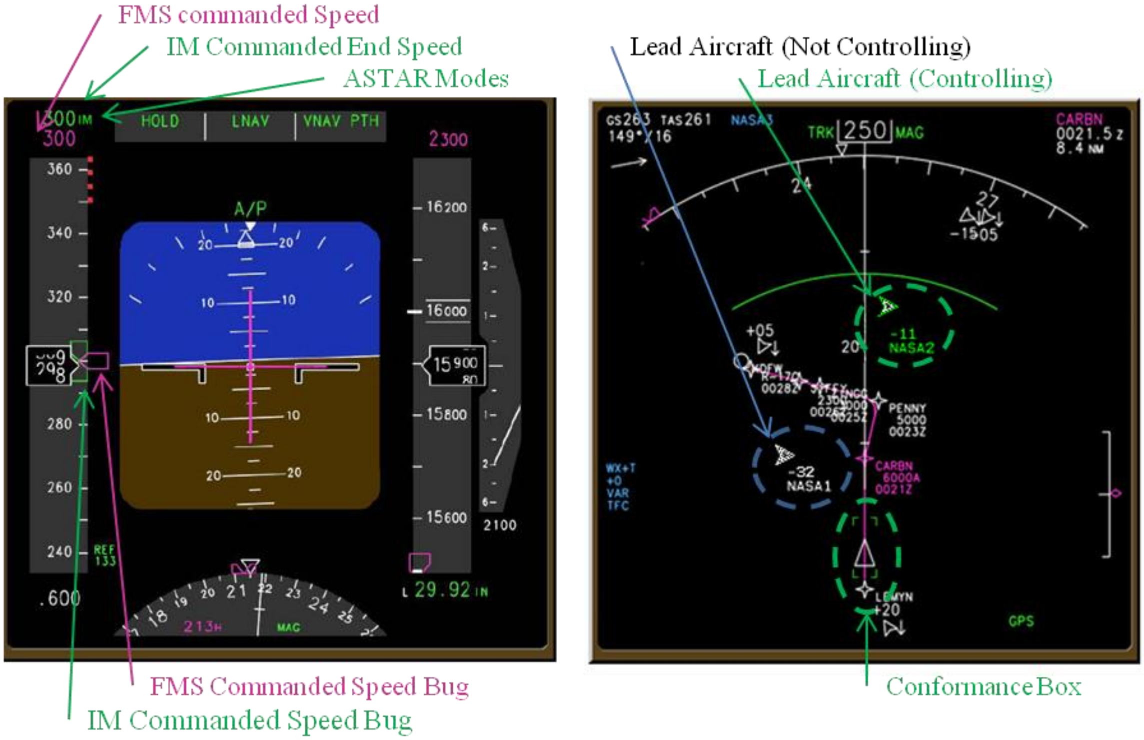


Figure 3.3. Display elements added to the PFD (left) and the ND (right) in support of the spacing operation.

The displays that were added to PFD to support the IM operation are shown in Figure 3.3. The commanded end speed was a green number shown above the speed tape that indicated the ASTAR commanded speed chunked in five knot increments. The commanded end speed was located just above the FMS commanded speed in the ASTOR simulators and DTS (the IFD did not have a number for the FMS commanded speed above the speed tape), allowing the flightcrew to easily determine if the IM commanded end speed and the FMS commanded speed matched. If it did not, the flightcrew was required to dial the IM commanded end speed into the MCP speed window. The instantaneous commanded speed bug was placed on the speed tape, and moved smoothly between a previous commanded end speed and a new commanded end speed, allowing the flightcrew to accelerate or decelerate their aircraft at the rate ASTAR predicted.

Additionally, the speed bugs implemented in the ASTOR simulators and DTS were +/- 5 knots wide, matching the five knot conformance limit that pilots were asked to achieve (The IFD's speed bug was different due to a different FMS speed bug style). When a speed change occurred, a green box would appear around the commanded end speed for ten seconds and the speed bug would begin moving toward the new commanded end speed. Lastly, ASTAR modes were displays next to the commanded end speed. The ASTAR modes included *RTA*, *IM*, *Rvt* (If there were any errors), and *fnl* (after the aircraft passed the final approach fix). When the ASTAR mode changed, a green box appeared around the ASTAR mode indicator for a period of ten seconds. This was consistent with the annunciation of the aircraft autopilot mode changes.

The indications added to the ND portrayed both lead aircraft, the differential altitude between the spacing aircraft and the lead aircraft, and the lead aircraft's callsign. The two lead aircraft were indicated by double chevrons (or double diamonds in the IFD and DTS). To indicate which lead aircraft was controlling the spacing operation at a given time, the outermost chevron of the aircraft that was controlling the commanded speed was turned green. Additionally, the data tags of the lead aircraft were modified to include their callsign and the difference in altitude between the spacing aircraft and the lead aircraft. Lastly, a trend indicator called the "conformance box" was added to the display during the exploratory run. The conformance box was a green box that appeared around the depiction of the spacing aircraft, and was designed to provide the flightcrew with a method of quickly determining how well the spacing operation was proceeding. When the time error was zero, the nose of the spacing aircraft would lie in the center of the conformance box. If the nose of the aircraft symbol moved outside the conformance box, it meant that the error had moved beyond the “excessive error” bounds, triggering an EICAS message, and indicating that the flightcrew should cancel the operation.

```
        ACT IM-S          1/3
IM-RTA WPT            ..IM-RTA
IM-S SPD            _TIME ERROR
0.80M

ACFT1                    ACFT2
<NASA1                  NASA2>
INTRVL ERR          INTRVL ERR
ON GOAL         BEHIND 4.2NM
------------------------------
                    TERMINATE>
```

```
      IM-S ACFT 1         2/3
CALLSIGN            ACHIEVE BY
NASA1                    R-17C
GOAL TYPE         TERMINATE AT
<PRECISION<>NCT          R-17C
IM-S GOAL             APPR SPD
95SEC                    130KT
ROUTE
GGG CQY6 PENNY ILS17C
ROUTE CONT

------------------------------
<ERASE                   IM-S>
```

```
      IM-S ACFT 2         3/3
CALLSIGN            ACHIEVE BY
NASA2                    R-17C
GOAL TYPE         TERMINATE AT
<PRECISION<>NCT          R-17C
IM-S GOAL             APPR SPD
2.2NM                    130KT
ROUTE
INK JEN9 YOHAN ILS18R
ROUTE CONT

------------------------------
<ERASE                   IM-S>
```

Figure 3.4. Three MCDU pages added in support of the spacing operation.

Three pages were added to the MCDU to support the IM operation (Figure 3.4). There were considerable data available in the MCDU; however, it was desired that pilots would only use the MCDU to activate the spacing operation, and not have to reference it afterward. The first page contained information about the IM or RTA operations, such as the callsigns of the lead aircraft, the control method being used, the commanded end speed, the time error (for the aircraft going to the same runway), a distance error (for an aircraft going to the parallel runway), and the spacing aircraft’s final approach speed. It should be noted that the first MCDU page is the only location where the time error appeared. The reasoning behind this decision was suspected that the numerical representation of the time error would be misleading and result in confusion. The second and third pages of the MCDU contain additional information about the lead aircraft, such as their route, callsign, achieve by point, terminate point, and spacing interval.

The EICAS display provided advisories, warnings, and cautions to the flight crew (Table 3.1). Cautions could indicate the loss of ADS-B data, that a lead aircraft was off path, or that the time error passed the ‘excess error’ bounds. Advisories could indicate that the spacing aircraft’s path had errors, the spacing aircraft was off path, or if the lead aircraft had bad path information. Messages were designed to provide the flightcrew with increased awareness of the IM operation, and help them stay on track if they deviated too far from the commanded speed. The “IM DRAG REQUIRED“ message indicated if drag was required to conform with the commanded speed, and the “IM SPEED LIMITED” message notified the crew that the speed ASTAR was commanding was limited at 10% of the profile speed. The “IM AC 1/2 SPACING” message was used in the IM scenarios to notify the crew when they were in ADS-B range of their lead aircraft, and transitioned from an RTA operation to an IM operation.

Table 3.1: IM EICAS cautions, advisories, and memos

EICAS Message	Alert Level
IM DISENGAGED	Caution
IM AC 1/2 OFF PATH	Caution
IM AC 1/2 ADSB LOST	Caution
IM ERROR EXCESS	Caution
IM OWN BAD PATH	Advisory
IM OWN OFF PATH	Advisory
IM AC 1/2 BAD PATH	Advisory
IM DRAG REQUIRED	Memo
IM SPEED LIMITED	Memo
IM AC 1/2 SPACING	Memo

3.2.4. Experiment Design and Independent Variables

Experiment Design

The experiment investigated the effect of three error sources (no error, offset error, and wind error) and two control methods (RTA and IM) on arrivals to dependent parallel runways [63]. In total, each group of pilots flew six distinct scenarios, and one exploratory scenario was conducted after the nominal scenarios were completed. Two replicates of each scenario containing an offset error or wind error were conducted, resulting in ten nominal runs and one exploratory run. Within this experiment, the scenarios without error served as a baseline, the offset error consisted of an impulse disturbance, and the wind error consisted of a discrepancy between forecast winds and actual winds.

Table 3.2. The experiment design matrix (Data from RTA scenarios are ignored for this thesis)

CONTROL METHOD

		RTA	**IM**
ERROR SOURCE	**None**	Scenario 1 (Replicate 1)	Scenario 2 (Replicate 1)
	Wind	Scenario 3 (Replicate 1) (Replicate 2)	Scenario 4 (Replicate 1) (Replicate 2)
	Offset	Scenario 5 (Replicate 1) (Replicate 2)	Scenario 6 (Replicate 1) (Replicate 2)

The experiment utilized a split plot design [63]. Each crew was designated as a *whole plot*, and each simulator type was a *whole-plot factor*. Since each crew flew all of the scenarios, the scenarios were considered a *subplot*. Both the control method (RTA and IM), and the error source (no error, offset error, and wind error) were *sub-plot factors* (Table 3.2).

Independent Variables

The RTA control method's goal was to help the aircraft arrive at the runway threshold at a precise time, and the IM control method's goal was to achieve a precise interval behind one or two lead aircraft at the runway threshold. The RTA algorithm was identical to the IM algorithm, with the dependency of the lead aircraft removed and replaced by an arrival time.

The *wind error* was comprised of a discrepancy between the actual winds and the forecast winds (Figure 3.5). The discrepancy included a difference in both magnitude and direction, and was derived using actual NOAA winds and a Rapid Update Cycle weather model. The forecast winds were derived from the Rapid Update Cycle weather model with 13km resolution (RUC-13). This experiment used the RUC-13 error associated with a three hour forecast to simulate an event where flightcrew did not update the wind forecast prior to reaching TOD. Furthermore, the three hour forecast was multiplied by 1.5 to simulate an instance where the RUC-13 model is less accurate due to rapidly changing weather conditions. The RUC-13 wind model (forecast winds) was compared to actual NOAA winds to obtain the difference between the actual winds and forecast winds for the wind error scenarios, and an additional wind shear was added at 5,000ft. The final wind speed error was approximately one standard deviation away from the mean forecast error at the surface and three standard deviations away at an altitude of 40,000 ft. Thus, this wind error is one that pilots are rarely expected to experience.

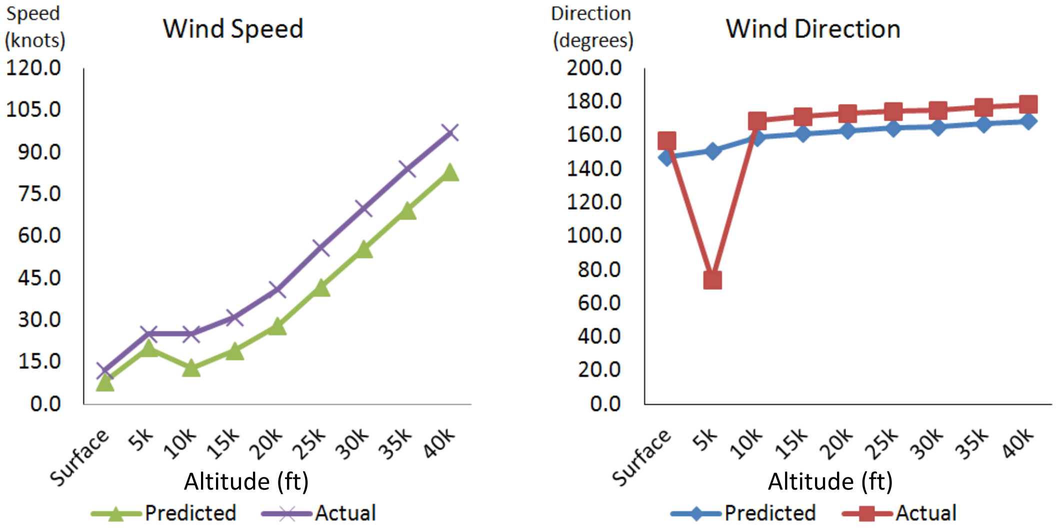


Figure 3.5: The difference between the actual winds and forecast winds used in the wind error scenarios

The *offset error* was a disturbance that was injected into the system when the first piloted aircraft's lead descended below 9,000ft. The offset error was implemented differently in the IM scenarios and the RTA scenarios. In the IM scenarios, the aircraft in front of the first human piloted aircraft had its spacing interval increased by 30 seconds. This increase was allowed to propagate backwards through the stream. In the RTA scenarios, the aircraft in front of the first human piloted aircraft, and all of the aircraft arriving later than this aircraft, had their arrival times moved 30 seconds earlier. This involved sending an updated RTA CPDLC clearance to each aircraft. The offset error was designed to simulate an instance where ATC had to modify a spacing interval to fit an additional aircraft into the flow.

The final scenario was an exploratory scenario, designed to examine various off-nominal events. The exploratory scenario had a number of differences from the nominal scenarios. First, the spacing interval was decreased from 120 seconds to 75 seconds to simulate an arrival flow with greater density. Secondly, a new display element, the 'conformance box,' was added. The conformance box is a green box that appears around the spacing aircraft on the ND (Figure 2.1). The purpose of the conformance box was to provide pilots with a way to easily see how well the spacing operation was proceeding. Lastly, there were a number of events that were included in the exploratory scenario. The most notable event was a go-around that pilots in a high fidelity two-crew simulator were required to conduct due to insufficient spacing. Events other simulators encountered included a clearance to space off an aircraft landing on runway 13R and an instance where a lead aircraft, who was originally on the same route, switched to a parallel runway. Pilots were briefed that this scenario was different than the rest, but were not told of specific circumstances that would occur during the scenario.

3.3. Experiment Results

Results from the experiment were collected and analyzed for statistical significance and indications of operations that did not go according to plan. Since this thesis is primarily concerned with IM, the RTA results were not included in the analysis. However, the RTA results along with the IM results can be found in [63], [72]. Despite the best efforts to concentrate on the IM results, the RTA results may have influenced the post-experiment questionnaire results. This is considered acceptable because the RTA and IM control methods used almost identical displays, the procedures were almost identical, and the comments that were observes were similar across the IM and RTA scenarios. The largest difference between the RTA and IM scenarios may have been the length of the CPDLC message that was sent. The RTA scenarios contained a significantly shorter CPDLC message.

This section will discusses the results of the experiment in four categories: workload and acceptance of IM, procedures and operational issues, interfaces, and the time it took pilots to complete time critical tasks.

3.3.1. Workload and Acceptance of IM

Before examining the interface and procedures, it is useful to ensure the pilots were able to achieve the desired performance. The main indicator of performance in the IM operation is the time error at the runway threshold. Table 3.3 shows that the time error at the runway threshold had mean values under three seconds and standard deviations below four seconds for all error sources. A statistical difference was found between the offset error and the wind error scenarios when the signed time error values were used (p=0.008). However, when the absolute value of the error was taken there were no statistically significant differences found, demonstrating that the spacing algorithm is able to achieve a high degree of precision even when large error sources are present.

Table 3.3: Time error at the runway threshold

Error Source	Mean (sec)	SD (sec)
No Error	-1.81	3.87
Wind Error	0.90	3.91
Offset Error	-2.16	3.29

Ratings of average and peak workload were collected, along with the phase of flight where the peak workload occurred. Pilots used the Modified Cooper Harper workload rating scale to rate their average and peak workloads on a scale from 1 (favorable) to 10 (unfavorable). The results showed that the median pilot rating of their average workload was 2.0 ($N = 120$), and the median rating of their mean "peak" workload was 2.0 ($N=120$). A workload value of 2.0 indicates the task the pilots were asked to perform was easy/desirable, their mental effort was low, and the desired performance was attainable. The data were averaged across replicates, blocked by crewmember, and a Friedman test was conducted to examine the data for statistical differences between error sources (using a 95% confidence interval). When the average workload was examined, no statistically significant effects were found between error source conditions (*p*=0.074); however, statistically significant effects were found when the peak workload was examined (*p*=0.032). Tukey simultaneous pairwise comparisons were used to determine which conditions were significantly different from each other. The results demonstrate that there were significant differences between the wind error scenarios and the scenarios without error, and significant differences between wind error scenarios and offset error scenarios.

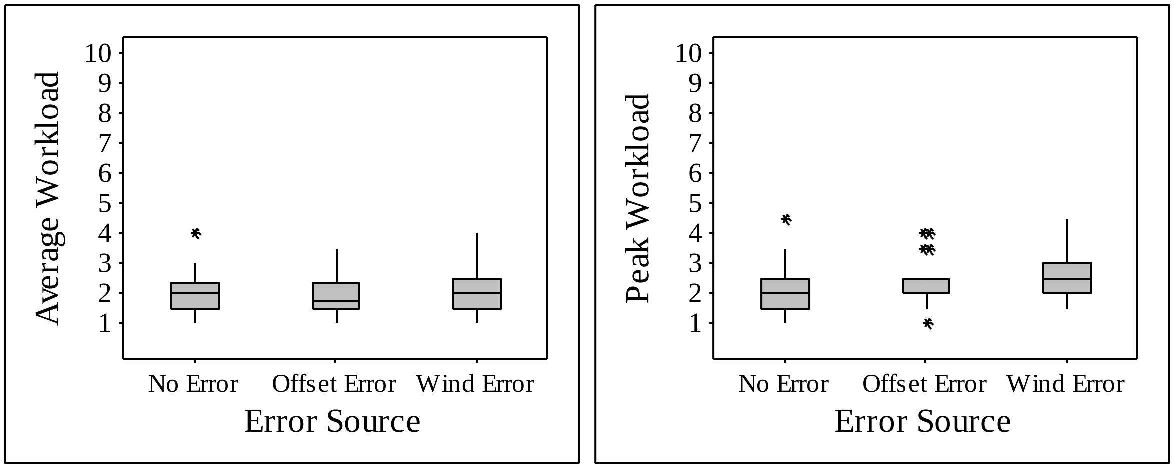


Figure 3.6: From left to right; (a) a boxplot of the pilots' ratings of their average workload, (b) a boxplot of the pilots' ratings of their peak workload

In addition to rating their average and peak workloads, pilots were asked to select the phase of flight where their peak workload occurred. The results showed that 70% of pilots’ peak workload occurred when they were on final approach and configuring their aircraft. These numbers were relatively consistent across all error conditions, and consistent with the number of speed changes encountered during each of these phases of flight. However, it is unclear how the peak workload compares to current day operations.

Table 3.4: Flight segment associated with peak workload (IM and RTA data combined)

Segment of Flight	Responses (N=191)
>18,000ft (cruise, initial descent, CPDLC)	10%
18,000ft – 11,000ft (descent, approach check)	3%
11,000ft - 5,000ft (TRACON, low altitude merge)	17%
<5,000ft (final approach, configure aircraft)	70%

One measure of taskload is the number of speed changes that the pilots are given. The experiment results demonstrated that the number of speed changes provided to pilots tended to increase substantially when errors were introduced into the system. Statistically significant differences were found in the number of speed changes presented to the flightcrew for different error sources ($p<0.001$). A Tukey pairwise comparison test demonstrated that the number of speed changes was significantly different between each of the error sources, with the scenarios without error having the lowest number of speed changes and the scenarios with wind error having the highest number (Table 3.5). Furthermore, the results in Figure 3.7 (right) show that a significant portion of speed changes occurred within 30NM of the runway, explaining the workload results that indicated that the peak workloads occurred during the final phase of flight. Lastly, Figure 3.7 (left) shows that a majority of speed changes occurred within one minute of the previous speed change, indicating that there are periods when multiple speed changes can occur during a short period of time. This is a function of the wind error and the design of the ASTAR speed control algorithm. Since the ASTAR speed control algorithm provides pilots with speed changes in 5 knot speed increments, when a very large error is encountered (such as the wind shear in the wind error scenarios), the algorithm will command a sequence of 5 knot speed changes. The total number of speed changes varied depending on the error source and control method; however, the probability distributions shown in Figure 3.7 maintained a relatively similar shape.

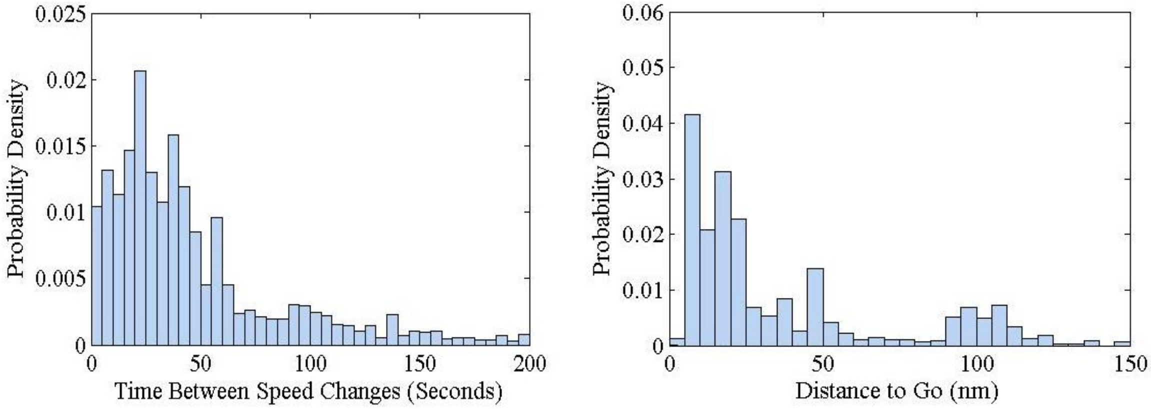


Figure 3.7: From left to right, a) a histogram of the time between consecutive speed changes, b) a histogram of where speed changes occurred as a function of distance from the runway (right).

Table 3.5: Number of speed changes per treatment condition.

Error Source	Mean (sec)	SD (sec)
No Error	9.72	1.87
Wind Error	16.11	3.32
Offset Error	13.14	1.81

Overall, pilots found the IM concept acceptable; however, pilots found some behaviors of the automation less than desirable. These behaviors included multiple speed changes within a short period of time, speed increases shortly followed by speed decreases, and speed increases when pilots were in the process of configuring the aircraft for landing. Pilots were asked to rate series of questions about their perceptions of the IM speeds using a scale that ranged from “1” (completely disagree) to “7” (completely agree), with “1” being the most favorable response and “7” being the most unfavorable response. The data was averaged across replicates, and a Friedman test was conducted to examine the data for statistical differences using a 95% confidence interval. The Freedman test was blocked by crew member, and examined whether the answers to the questions changed when different error sources were present. No statistically significant differences were found between any of the experimental factors (*p*>0.05). However, both the question asking if IM was an interruption (*p*=0.068), and the question asking if the IM speed frustrated the crew (*p*=0.053) were close to being significant. For the IM scenarios, the wind error scenarios received the worst ratings for both the frustration question (*M*=2.5, *SD*=1.7) and the question asking about interruptions (*M*=2.7, *SD*=1.4). The non-error conditions received the most favorable ratings for both the frustration question (*M*=1.7, *SD*=1.1), and the question asking if pilots were interrupted (*M*=2.2, *SD*=1.1). While the difference in means may be small, they appear to be indicative of a greater number of outliers with unfavorable responses during the scenarios containing wind error (Figure 3.8). The results are also consistent with many comments pilots provided that stated that the speed guidance was too twitchy, or that the gains should be turned down. In general, the data suggests that the IM operation was acceptable during all of the error condition circumstances; nevertheless, the wind error and offset error scenarios had a greater chance of creating outlier ratings that were unacceptable. It is suspected that this occurred because of the large number of speed changes that were present in these conditions. It may be possible to decrease the frustration and interruptions by providing pilots with displays and procedures that show them why the algorithm is commanding specific speed changes, and increase their ability to predict the spacing algorithm's behavior in the near future. Despite the frustration, there were only a few instances where pilots thought IM was unsafe.

Table 3.6: Pilot ratings of speed commands across all conditions (IM Only)
(1 = favorable, 7 = unfavorable)

Question	Mean	SD	Median	P Value
10 a) Unsafe	1.35	0.84	1	0.223
10 b) Incorrect	1.47	0.99	1	0.282

10 c) Interruption	2.48	1.55	2	0.068
10 d) Unexpected	2.12	1.57	1	0.247
10 e) Conflicted With Other Information	1.68	1.18	1	0.793
10 f) Uncomfortable	1.56	1.24	1	0.341
10 g) Frustrated	2.08	1.49	1	0.053

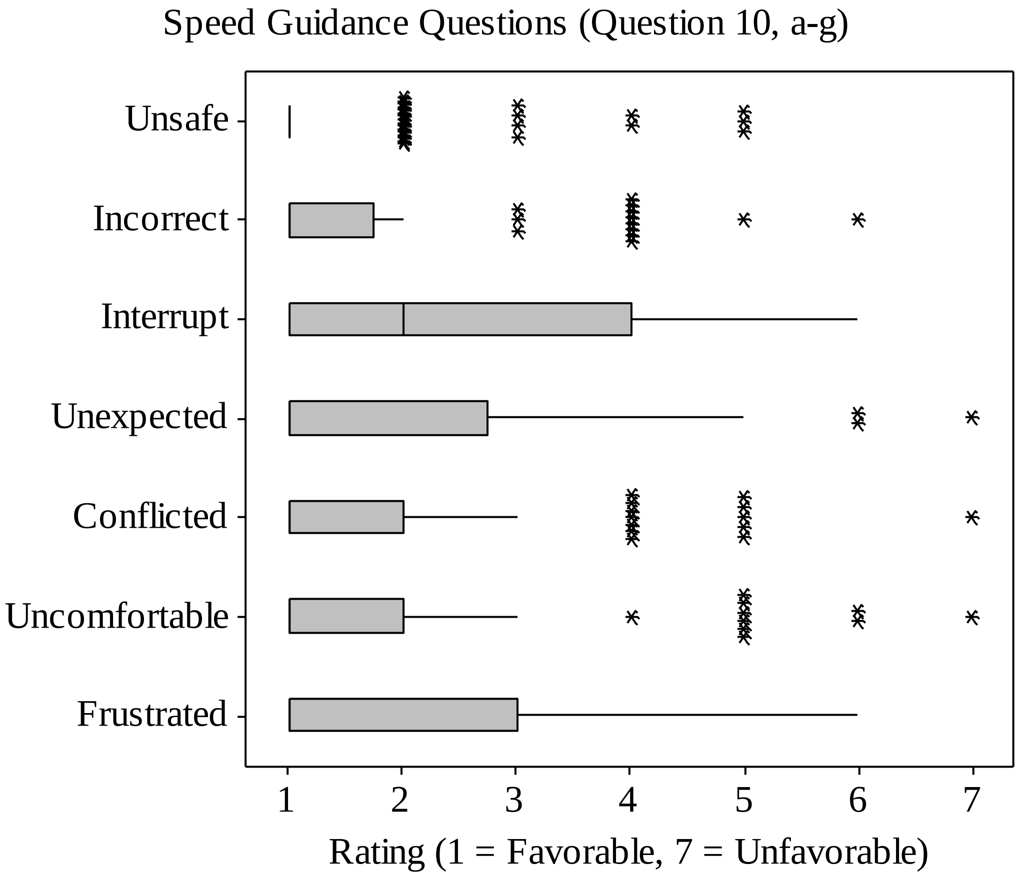


Figure 3.8: Pilot responses to post run question ten regarding the acceptability of the commanded speeds (IM only)

It is useful to understand some of the outliers in the ratings provided by pilots. Of particular interest are the three instances where the flightcrew slightly agreed that the IM operation was unsafe and the two instances when they provided a neutral rating. Some of these ratings were caused by a simulator glitch, which commanded the pilots to fly at Mach 0.85 prior to their TOD. Other comments indicated that ASTAR waited until a point after the FAF to command the aircraft’s final approach speed (this will occur if the aircraft is below the profile speed), and because pilots were not given adequate time to slow their aircraft to meet the 250 knot speed limit at 10,000 ft. The two neutral comments were provided because pilots had to reconfigure the aircraft to achieve the commanded speed, and because they spent too much time monitoring the PFD for commanded speed changes.

The ratings that indicated that the commanded speeds were incorrect were provided because of commanded speed increases that were shortly followed by speed decreases, ASTAR commanding the final approach speed after the FAF, and because speed changes occurred too frequently. The ratings that stated that speed changes occurred too frequently occurred during wind error scenarios and to a lesser extent during the offset error scenarios. It is possible that providing pilots with displays that showed how ASTAR works, and why they were given speed commands could decrease the perception that some speed changes are incorrect.

There were also ratings that indicated that the spacing algorithm could interrupt pilots. This interruption can be caused by pilots' inability to predict commanded speed changes. The ratings that were often provided because of frequent speed changes, and speed changes that did not allow the flightcrew to configure their aircraft as early as they would have liked.

Ratings that indicated the commanded speeds were unexpected, conflicted with information available from other sources, and caused discomfort were often provided because the pilots thought there were too many speed changes within a short period of time.

Ratings indicating that pilots were frustrated included speed changes that were very frequent, speed changes that did not make sense to the flight crew, speed changes that forced pilots to reconfigure their aircraft, and the need to use an excessive amount to speed brakes.

It should be remembered the poor ratings represented a small number of runs, and that many of them were instigated by large error sources that pilots are not expected to encounter very often. Nevertheless, these ratings can provide insight into what behavior pilots find unacceptable.

3.3.2. Procedures and Operational Issues

Overall, pilots rated the procedures used in this experiment as acceptable; however, there were a number of instances where flight crews did not follow the procedures, or they used less than desirable behavior to follow the procedures. When asked if the IM procedures used during this experiment were complete, accurate, and logical, 92% of the pilots answered positively. However, when asked to use a scale of 1 (Very Difficult) to 7 (Very Easy) to rate the ease with which the spacing procedures could be integrated with current day procedures, the pilots' mean response was 4.58 (SD = 1.56, N = 24), indicating that they were somewhat undecided. Problems that were seen with the procedures included tasks associated with activating the IM operation, instances where the flightcrew did not follow the procedures, and instances where pilots followed the procedures, but found the behavior non-ideal.

Pilot comments indicated that there were two problems with the procedures used in this experiment: both of which occurred when accepting a new clearance and activating ASTAR. When pilots were asked to amend the spacing operation, they were required to terminate the existing clearance, and then go through the process of loading the new clearance. Many pilots mixed up the order of this task, and suggested that the old clearance should automatically terminate when new or amended information was entered. The main reason for not implementing this feature in the first place was that it required two instances of ASTAR running; one to compute the commanded speeds for the existing operation, and one to compute an initial commanded speed for the appended operation to allow the flightcrew to determine if it is acceptable or not. In the full crew simulators, pilot coordination was needed to set up the spacing operation, because they were required to have the IM MCDUU page and the CPDLC MCDU page open at the same time. The PNF was expected to read and respond to the CPDLC clearance, and the PF was expected to activate the spacing algorithm and execute it if the initial commanded speed looked acceptable. Pilots felt this entire operation should be able to be completed by the PNF on a single MCDU. One flight crew even worked around the procedures by having the PNF reach across the center console to input commands into the PF's MCDU.

In some scenarios, the use of IM caused less than desirable behavior when pilots were configuring their aircraft. In 10 out of 180 runs, pilots either reconfigured their aircraft to conform to a new commanded speed (as instructed by the procedures), or used improper landing flaps. Of these instances, only one occurred in a high fidelity two-crew simulator, indicating that the simulation environment may have played a role in this behavior. Nevertheless, it is useful to examine these incidents. Many of the flap reconfigurations were caused by ASTAR speed approaching the flap limit speeds. Additionally, pilot comments in the questionnaires and group debrief suggested that some of them had used their flaps as a mechanism to create enough drag to slow the aircraft. One pilot, who flew one of the single-crew desktop simulators with the commanded speed automatically managed by the FMS, over sped his flaps because he momentarily paid attention to something other than his commanded speed. There was also at least one case where pilot flying in the high fidelity two-crew IFD simulator did not follow the commanded speed to keep them from having to reconfigure their aircraft, as described by the pilot comment:

> "*Computer commanded a speed above my current maximum Flaps 30 speed. I increase my speed to within 5kts of max F30 speed, but still well below the commanded speed.*"

ASTAR has a flap protection feature that was turned off for this experiment. It may be useful to use the flap limiting feature when the FMS is automatically controlling the commanded speeds. Otherwise, there is the potential for small lapses in attention to result in the aircraft over speeding the flaps. Flap protection may also be useful in implementations where pilots are required to dial the commanded speed into the MCP speed window and if the procedures dictate that pilots fly the commanded speed, because it might increase speed conformance.

One important operational and procedural issue is that pilots did not always follow the speed guidance commanded by ASTAR, as dictated by the procedures. Approximately ten instances were found where pilots did not dial a new commanded speed into their MCDU for an extended period of time during the ILS portion of their approach. As with the flap deployment problems, many of these instances occurred in the single pilot simulators, indicating that the simulation environment may have played a role. The procedures and training told pilots that they should follow the speed commands unless they did not think they were appropriate, in which case they were required to cancel the operation. The pilots who did deviate from the commanded speeds did not contact ATC to cancel the operation. It is unclear if this is a function of the simulation environments (i.e. that they did not want to ruin a data run), or an issue that would be encountered in the real world. One of the IFD pilots commented on his rationale for not following his commanded speed:

> *"Between ZINGG and JIFFY, the IM speed called for a 5 knot speed increase followed by another 5 knot increase just outside of JIFFY FAF. I did not try to chase the speed because it was over JIFFY, we prepared for landing and speed reduction."*

It is hypothesized that the OPDs used in this experiment contributed to some of the behavior that pilots found undesirable. The OPDs used in this experiment were designed as near idle descents. If a spacing aircraft developed a positive time error (projecting they would arrive late), the aircraft would be given a commanded speed that is faster than the nominal speed of the 4D trajectory. These faster speeds would often require the flightcrew to use drag to slow the aircraft in time to achieve a stabilized approach. Pilot comments during the verbal debrief indicated that some pilots thought they had to use speed brakes too often to slow their aircraft, causing concern about passenger comfort. It is possible that some of the use of speed brakes could have been avoided if pilots had better awareness of their aircraft's energy.

3.3.3. Pilot Interface

Qualitative data was collected on the pilot's use of the IM displays. Most of this data was gathered from the ratings and comments pilots provided in the post-run questionnaire; however, some of the comments were also taken from the post-experiment questionnaire. Since the post-experiment questionnaire only included 24 responses, statistical analysis was not used on that data.

Pilots were asked to rate the usefulness of each display element on a scale ranging from *Detrimental* to *Required for IM* (Figure 3.9). Pilots generally provided high usefulness ratings to all of the IM displays on the PFD. This was expected, because the IM operating procedure used in this experiment dictated that pilots act off of information that was presented on the PFD. The green box that appeared around the commanded end speed to indicate a speed change received lower ratings than the other indications on the PFD. Pilot comments suggested that the lower ratings were provided because pilots did not find the green box salient enough, and found themselves watching the commanded end speed on the PFD to try and catch any speed changes. Of the 24 pilot participants, 23 stated that better alerting of changes to the commanded speed were needed.

The highest rated display element on the ND was the visual representation of the lead aircraft (i.e. the double chevron or diamond depicting the lead aircraft). With the exception of visual representations of the lead aircraft, the IM displays on the ND were rated as less useful than those on the PFD; however, pilots still found them moderately useful to highly useful.

The displays on the MCDU were also given lower usefulness ratings than the displays on the PFD. The intent was that the pilots would use the information on the MCDU to activate the IM operation, and not have to reference it afterwards. To support this, a lot of the important information present on the MCDU was also present on the PFD or ND. Thus, the lower ratings of the MCDU display elements were expected. The EICAS messages also received lower ratings. Pilot comments indicate that this was caused by a number of factors. The “IM DRAG REQUIRED” message appeared when the airspeed of the aircraft was greater than six knots above the instantaneous commanded speed (shown by the speed bug), and turned off when they were within four knots of the commanded speed. Pilot comments indicated that there were a number of instances when the “IM DRAG REQUIRED” message appeared, but they thought their aircraft were slowing at an adequate rate. Additionally, a number of pilots seemed to view the “IM SPD LIMITED” message, which notified them when the commanded speed deviation was limited to ±10% of the profile speed, as a nuisance alert.

To determine how often pilots used each display, they were asked to rate how frequently they referenced each of the major aircraft displays containing IM information using a scale ranging from 1” (Never) to “5” (All the Time). Ratings provided by the participants indicated that they monitored the PFD more frequently than any other display. This is consistent with the usefulness ratings that were previously discussed. IM information on the ND was referenced less often than the PFD, but more often than the MCDU. This is also consistent with the usefulness ratings previously discussed. The MCDU was only referenced slightly to moderately often. A design goal of the MCDU interface was that pilots should not have to reference it very often after the spacing operation was activated to allow pilots to use the MCDU for other tasks; thus, limited monitoring of the MCDU was seen as a desirable characteristic.

In addition to describing how often they referenced different displays, the pilots who flew in the two-crew simulators were asked how often they referenced the information out the window, and how often they referenced information from their crewmember. In general, pilots did not reference information out the window very often. This was probably due to the fact that a majority of the arrival was flown in IFR conditions. However, pilots in the two-crew simulators did reference information from their crew members very often. This was apparent when observing the experiment, as pilots would often call out speed changes when they occurred to ensure that both the PNF and PF had consistent information.

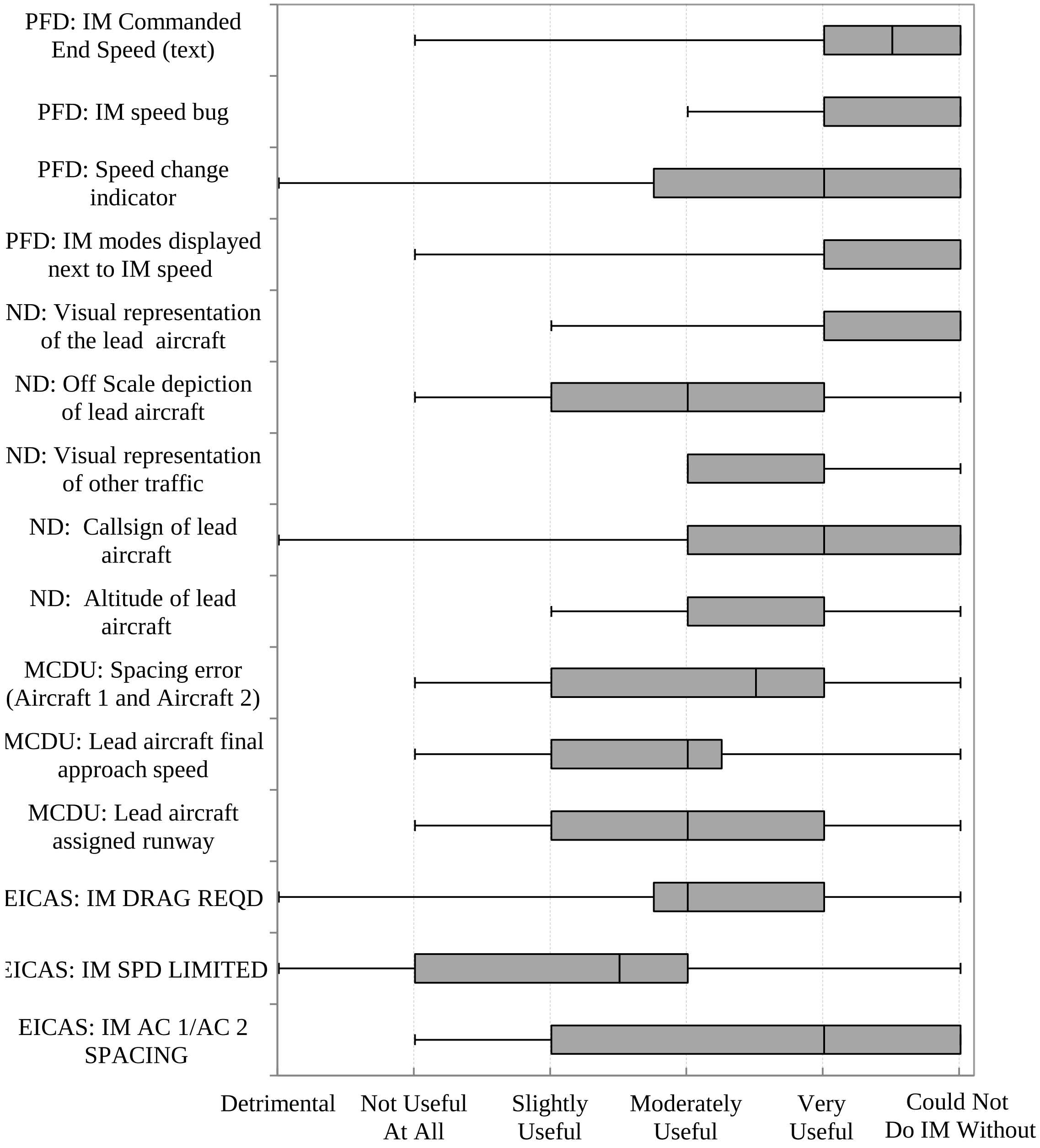


Figure 3.9: Pilot ratings of display elements used in the experiment (N=24)

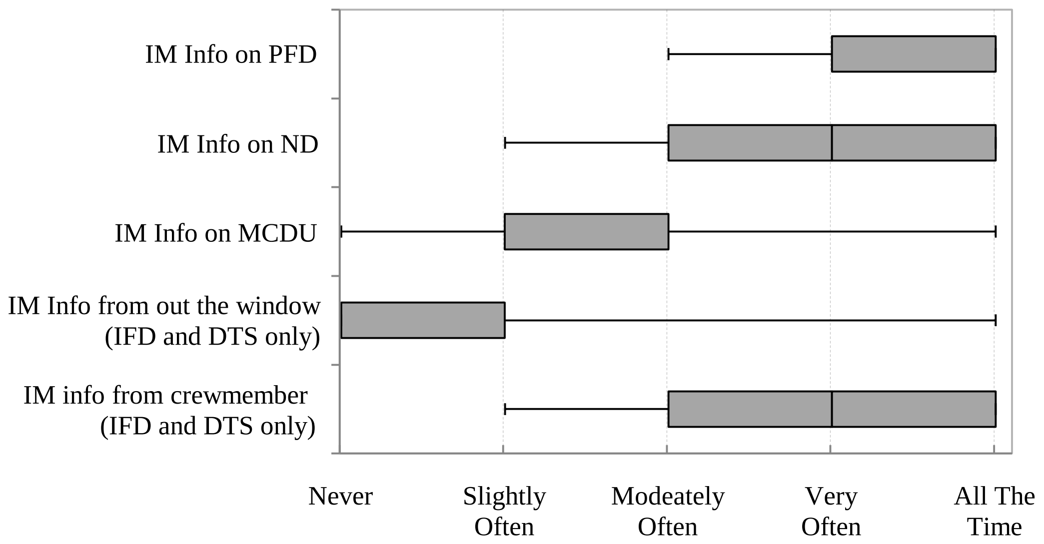


Figure 3.10: Pilots ratings regarding how often they monitored particular displays while conducting IM

In addition to the usefulness and frequency of use of the IM displays, pilots were asked whether they were able to predict the behavior of the spacing algorithm. Using a scale of scale of 1 (Completely Disagree) to 7 (Completely Agree), pilots moderately agreed that the spacing tool behaves in a predictable manner (*M*=6.04, *SD*=0.55, *N*=24), and that they were able to predict commanded speeds before they occurred (*M*=5.36, *SD*=1.37, *N*=180). Pilots were asked to describe the information that helped them predict the spacing algorithm, and their answers were binned by their content. 46% of pilots stated that they used the first IM MCDU page to help predict the algorithm’s behavior, which was the only location that contained the spacing error values. 46% used published speed profiles, scheduled speed decreases, and general flight rules to predict the IM spacing algorithm. Lastly, 29% used the visual representation of their lead aircraft on the ND. Fully predicting impending speed changes is not possible with the ASTAR algorithm because it uses the current state of the aircraft to calculate the commanded speed; however, pilots felt they were able to predict general behavior that the algorithm used, including scheduled speed decreases, what constituted a high or low spacing error, general trends between the time error and the commanded speed, and general trends between the pilots actions and the commanded speed. Nevertheless, pilot comments indicated that may not have formed an accurate mental model of the ASTAR algorithm. Thus, it is possible that pilots thought they were able to predict the ASTAR algorithm, but in actuality, their predictions were incorrect.

A number of the comments that pilots provided suggested that they were attempting to understand the relationship between the time error that was displayed on the MCDU and the speeds commands generated by ASTAR. The following comments demonstrate that pilots often had an incorrect or incomplete mental model of the relationship between the time error displayed on the MCDU and the commanded speed changes.

- *"Maybe with more experience I'd have a better feel for what speed will be coming next, but even when we seem to be ahead of our goal (time) we still get commands to speed up."*
- *"Lots of airspeed changes on final some of which seemed inappropriate. Several IM airspeed changes around FAF. I didn't understand why it was asking for 165 then 150 then 155 and back to 165 (I think that was the order) when we were still showing 10 sec early."*
- *"The conformance box was the easiest method to predict performance and trends. Without it I had to refer to the IM page in the CDU. Even then it was difficult to predict the next commanded speed. On several occasions when I checked the IM page it showed me as much as 23 sec ahead of schedule and yet it subsequently commanded a speed increase."*

- *"I was looking at the IM page and noting error in the progress. For example, if I noticed it was late and trending later, it was easy to expect that there was a change coming for an increase."*

Based on these comments, it appears as if some pilots thought that speed changes would only increase if the time error was positive (arriving late), and only decrease if the time error was negative (arriving early). In reality, the commanded speed will move toward the nominal profile speed as the time error moves toward zero. This means that if the time error is increasing, the commanded speed will increase, and if the time error is decreasing, the commanded speed will decrease (regardless of the value of the time error). The pilot that provided the final comment was close to figuring this relationship out; however, the commanded speed will increase if the time error increases, even if the aircraft is early. Overall, the pilots' confusion appears to be centered on the relationship between the ASTAR commanded speed and the time error. The subject of chapters four and five will describe a set of rules that can explain ASTAR's behavior, and chapter five will explore how these rules can be conveyed to the flightcrew to help them understand ASTAR's behavior.

The conformance box was created to show pilots a snapshot of how well they were completing the spacing operation. The conformance box is a green box that appears around the depiction of the spacing aircraft on the ND during the exploratory scenario (see Figure 3.3), and was designed to indicate excessive error bounds (i.e. error values where the flightcrew would be expected to cancel the operation). The pilots were asked a number of questions about the conformance box in the post-experiment questionnaire. In general, the results showed that pilots liked the conformance box. Using a scale of

1(Completely Disagree) to 7 (Completely Agree), pilots slightly to moderately agreed that the conformance box helped them monitor the IM operation (*M*=5.29, *SD*=1.78, *N*=24) and that the conformance box should be part of any display designed to support IM operations (*M*=5.36, *SD*=1.62, *N*=24). However, the pilots were only neutral to slightly in agreement with the statements that the conformance box helped them predict speed changes (*M*=4.75, *SD*=1.80, *N*=24), that it increased the level of safety of IM (*M*=4.75, *SD*=1.78, *N*=24), or that it increased their comfort with IM (*M*=4.88, *SD*=1.98, *N*=24). This data is consistent with what Volk found when he investigate a number of IM displays: pilots liked the conformance box, but it was not clear how it helped them [64].

Comments from the post run questionnaire also showed problems with the conformance box. Most notably, when pilots changed the scale on the ND, the conformance box changed its size; there were a small number of pilots who flew or wanted to fly (and were stopped by their crewmember) speeds that were different than the commanded speed to decrease their time error more quickly. Lastly, some pilots interpreted the conformance box as a separation box, and attempted to keep other aircraft out. Some of these effects may have been cause by the delay between the training (on the first day) and the exploratory scenario (on the third day). In the end, the conformance box provided pilots a snapshot of their time error relative to the “excessive error” bounds. However, it did not help pilots understand why they were receiving particular speed commands, or help the pilots obtain an accurate mental model of ASTAR. This is demonstrated by the following quote:

> *“The conformance box was the easiest method to predict performance and trends. Without it I had to refer to the IM page in the CDU. Even then it was difficult to*

> *predict the next commanded speed. On several occasions when I checked the IM page it showed me as much as 23 sec ahead of schedule and yet it subsequently commanded a speed increase."*

This comment suggests that while the conformance box provided pilots with an easy way to determine how well the spacing operation was proceeding, it did not help them understand the rationale behind the commanded speeds or provide them with a more accurate mental model of IM. The pilot made the same mistake that was present in previous comments: that a negative (early) time error meant that the commanded speeds would always decrease.

3.3.4. Time Sensitive Tasks

In addition to the data on pilot acceptability, procedures, and interfaces, data was collected on the amount of time it took the flight crew to complete specific time sensitive tasks. There are three main time sensitive tasks in the IM system: sending/responding to CPDLC clearance from ATC, responding to commanded speed changes, and controller intervention. Because the IMSPiDR experiment was scripted and did not include actual controllers, the controller intervention point was not examined in this experiment.

Baxley (2011) conducted an extensive analysis of the amount of time it took pilots to read and respond to the CPDLC message [72]. The International Civil Aviation Organization (ICAO) stated that the time for the entire CPDLC process should be less than 210 or 350 seconds, depending on the equipage of the aircraft [77]. The time allocated for the aircraft to send a response is 60 seconds. Data from the IMSPiDR experiment showed that the mean response time for all of the IM runs was 52 seconds (SD=19, N=60) for the two crew simulators, and 40 seconds (*SD*=10, *N*=118) for the single-crew simulators [72]. Significant difference in response time were found between the ATOL and the IFD/DTS (p=0.002). The ATOL had the lower response time (*M*=40, *SD*=10, N=118), and IFD and DTS had a mean response time of 52 seconds (*SD*=19, *N*=60). It is suspected that this difference occurred because the pilots in the two-crew simulators had to coordinate efforts to read the CPDLC message, activate ASTAR, and respond to the message; whereas the pilots in the single-crew simulators did not have to coordinate with a crewmember. The time taken for the two crew simulators to respond to the IM CPDLC message was fairly close to the 60 second limit discussed by the ICAO. The initial hypothesis was that this was caused by the complicated message sent during the IM scenarios that contained IM clearances for two aircraft (including their trajectories), and an RTA clearance that the spacing aircraft was expected to fly until it was in range of its lead aircraft. However, no statistical differences were found between the response times for the IM scenarios and the RTA scenarios, which had a significantly shorter CPDLC clearance.

The time pilots took to notice and respond to commanded speeds were examined, and compared with assumptions made by ASTAR. To complete the analysis, the response time data was averaged for each run. If a new speed change occurred before the pilot reacted to the old speed change, the reaction time for that particular speed change was considered to be the time between the two speed changes. The square root of the response data was taken to transform it into a normal distribution. Normally reaction times would be transformed using a logarithmic transformation; however, a square root transformation provided a better, though not perfect, approximation of a normal distribution in this case (Figure 3.11, b). When the square root of the reaction time was analyzed, significant differences were found between the error source and the simulator type. A Tukey pairwise comparison test revealed that the reaction times of the scenarios without error were statistically different than the reaction times of the scenarios with offset error and wind error, with the scenarios without error having a higher reaction time (Table 3.7). It is hypothesized that the scenarios without error had a larger reaction time because they had fewer speed changes, and the pilots may not have been looking for them as diligently. In addition to collecting data on the reaction time of pilots to speed changes, pilots were asked to provide the amount of time they thought would be reasonable to notice and implement a speed change. On average, pilots' responses in the post experiment questionnaire stated they would consider noticing the speed change within nine seconds (*SD*=5, *N*=24) of a commanded speed change, and dialing the speed commands into the MCP speed window within seven seconds (*SD*=4, *N*=24) of noticing the speed command as acceptable. These numbers are consistent with the 10 seconds that was assumed.

Table 3.7: The reaction time of the scenarios without error was significantly greater than the wind and offset error scenarios

Error Source	Mean (sec)	SD (sec)
No Error	10.4	10.7
Wind Error	8.8	8.9
Offset Error	8.5	7.2

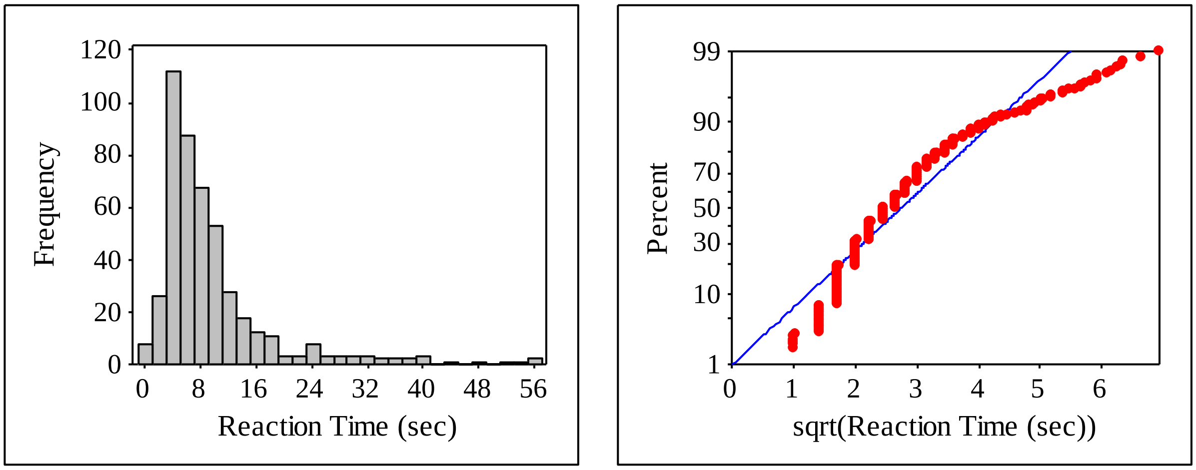


Figure 3.11: From left to right, (a) A histogram of pilot reaction times to commanded speed changes for all scenarios, (b) A plot showing how well the square root of reaction time conformed to a normal distribution (a perfect fit would follow the blue line)

3.4. Summary

An experiment was conducted at NASA Langley, examining the flightdeck implementation of IM. The experiment examined IM and RTA control methods under three different perturbations: No error, an impulse perturbation (offset error), and a discrepancy between actual winds and forecast winds (wind error).The participants in the experiment flew arrivals from a point just prior to the TOD to the runway threshold. During this time, pilots were asked to review and respond to a CPDLC message containing either an IM or RTA clearance. Pilots were expected to accept the clearance and fly speed guidance generated by onboard avionics to the final approach fix, after which they flew their final approach speed. A variety of metrics were collected during the experiment, including aircraft state data, questionnaires administrated to the pilots, and a group debrief session at the end of the experiment.

The results of the experiment demonstrated pilot acceptance of the IM operation and IM procedures. In general, pilots provided positive feedback despite the significant perturbations present in a majority of the scenarios. However, the perturbations instigated some behavior that the pilots found less than acceptable. The less than acceptable behavior included instances where there were multiple speed changes were given within a short period of time, periods where a commanded speed increase was shortly followed by a speed decrease, and instances where achieving the commanded speed forced pilots to reconfigure their aircraft.

Pilot comments also suggested that they were attempting to form a mental model of the relationship between the time error presented on the MCDU and the ASTAR commanded speeds. Their mental model of the IM system was often incorrect and/or incomplete. It is suspected that their incorrect/incomplete mental model made the speed changes look random and indecisive, which could have resulted in increased frustration. It is hypothesized that creating display, procedures, and/or training that helps pilots establish an accurate mental model of the IM system will result in increased acceptability and frustration when significant perturbations are present.

Time data, feedback on the procedures and interface, and knowledge incurred from observing pilots will be used to build a joint HTA and WDA model in the next chapter. The WDA and HTA model will be used to help determine interfaces and procedures that have the potential to help pilots and/or air traffic controllers gain a better understanding of the IM system. It is hypothesized that a more complete and correct mental model of the system will increase the acceptability of IM, increase pilots' understanding of the commanded speeds they are provided, and decrease frustration when perturbations are present.

CHAPTER 4

HTA, CTA, and WDA MODEL OF IM

4.1. Introduction

This section describes a Hierarchical Task Analysis (HTA), Control Task Analysis (CTA), and Work Domain Analysis (WDA) of the Interval Management (IM) system. These models were created using information from the literature review conducted in chapter two and from the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) Human-In-The-Loop (HITL) experiment discussed in the previous chapter. The WDA portion of the model will then be used in chapter 5 to derive representations for the IM system that can help pilots understand the constraints and dynamics of the IM system, aiding them when unforeseen circumstances are encountered. The HTA is used to examine the procedures expected for IM during both normal conditions and foreseen non-normal conditions. The CTA is used to describe the decision making process the human operators use when conducting control tasks, and determine the information needed to support the decision making process. The HTA, CTA, and WDA created in this chapter assume that the ASTAR algorithm is used as the spacing algorithm. Using a different algorithm would likely create different dynamics and procedures requiring changes to the models, and changes to the displays and representations developed next in chapter 5.

This chapter first discusses the HTA, which is used to describe a nominal course of behavior air traffic controllers and flight crews can used to complete the IM operation, followed by a CTA used to describe the information pilots need to make decisions pertaining to IM. Next a WDA is used to describe the dynamics of the IM system. Lastly, the chapter concludes with a discussion of the benefits of using HTA, CTA, and WDA together.

4.2. Hierarchical Task Analysis (HTA)

4.2.1. Task Requirements

An HTA was developed to examine the tasks flightcrews are expected to use during normal and anticipated non-normal conditions. The HTA was developed from referencing a variety of sources, including the IMSPiDR HITL experiment and the literature. The purpose of the HTA is to ensure that tasks are adequately supported, that priority information receives appropriate emphasis, and that displays are placed in the correct locations.

Different definitions have been used in the literature for nominal and off-nominal events. Events can be split into three categories: normal events that occur every day; non-normal events that do not occur every day, but have been anticipated and have defined procedures; and unanticipated non-normal events for which there is no procedure. This thesis uses the term nominal to refer to both normal events and anticipated non-normal events, and the term off-nominal to refer to unanticipated events.

4.2.2. Task Analysis

An HTA of the IM system was completed to describe nominal tasks that the flightcrew and ATC need to complete to operate the IM system (Figure 3.1 and Figure 3.2, respectively). The system goal of the HTA was to achieve a precise spacing interval behind a lead aircraft at the runway threshold. By achieving this goal, IM is expected to complete its functional purpose of increasing the runway throughput and enabling fuel efficient OPD arrivals during periods of high traffic. The system goal was split into three main tasks: initiating IM, conducting IM, and terminating IM.

Initializing IM occurs when an air traffic controller provides an IM clearance (Task 1 in Figure 4.1 and Figure 4.2). The parameters that are included in the clearance include a lead aircraft, an achieve-by point, a spacing interval, the route of the lead aircraft, and the lead aircraft's final approach speed if the achieve-by point is a runway. Once the IM clearance is received, the flightcrew is responsible for entering the information into onboard avionics, which generates an initial commanded speed. Using this information, the flightcrew is expected to determine whether or not the IM clearance is acceptable. If it is acceptable the flightcrew will execute the clearance; if it is not acceptable they cancel the clearance.

Once the IM operation is activated, the flightcrew is responsible for using guidance provided by onboard automation to achieve their assigned spacing interval, and ATC is responsible for monitoring for impending separation violations (Task 2 in Figure 4.1 and Figure 4.2). Nominally, the flightcrew is expected to follow the speed commands provided by onboard guidance. If the flightcrew does not believe the speed commands are acceptable, they can cancel the IM clearance and wait for Air Traffic Control (ATC) to provide further guidance. If there is a problem, ATC can either choose to amend the original IM clearance with a new spacing interval, suspend the IM operation so they can provide temporary speed commands, vectors, or terminate the IM operation.

The IM operation can be terminated if the flightcrew find the commanded speeds unacceptable during any portion of the flight, if there is an ASTAR error that appears, if ATC decides to terminate the operation, or if the achieve-by point is reached (Task 3 in

Figure 4.1 and Figure 4.2). If ATC cancels the clearance, they should immediately provide further instructions to the flightcrew. If the flightcrew terminates the clearance, they are required to notify ATC and wait for further instructions.

Tasks that require communication with ATC and the flightdeck are outlined with an orange box, and the tasks that required pilots and air traffic controllers to make decisions are highlighted with blue shading. All of the communications between ATC and the flightdeck are provided by clearances unless the IM operations is canceled or suspended, in which case ATC is required to provide the flightcrew with speeds and/or vectors.

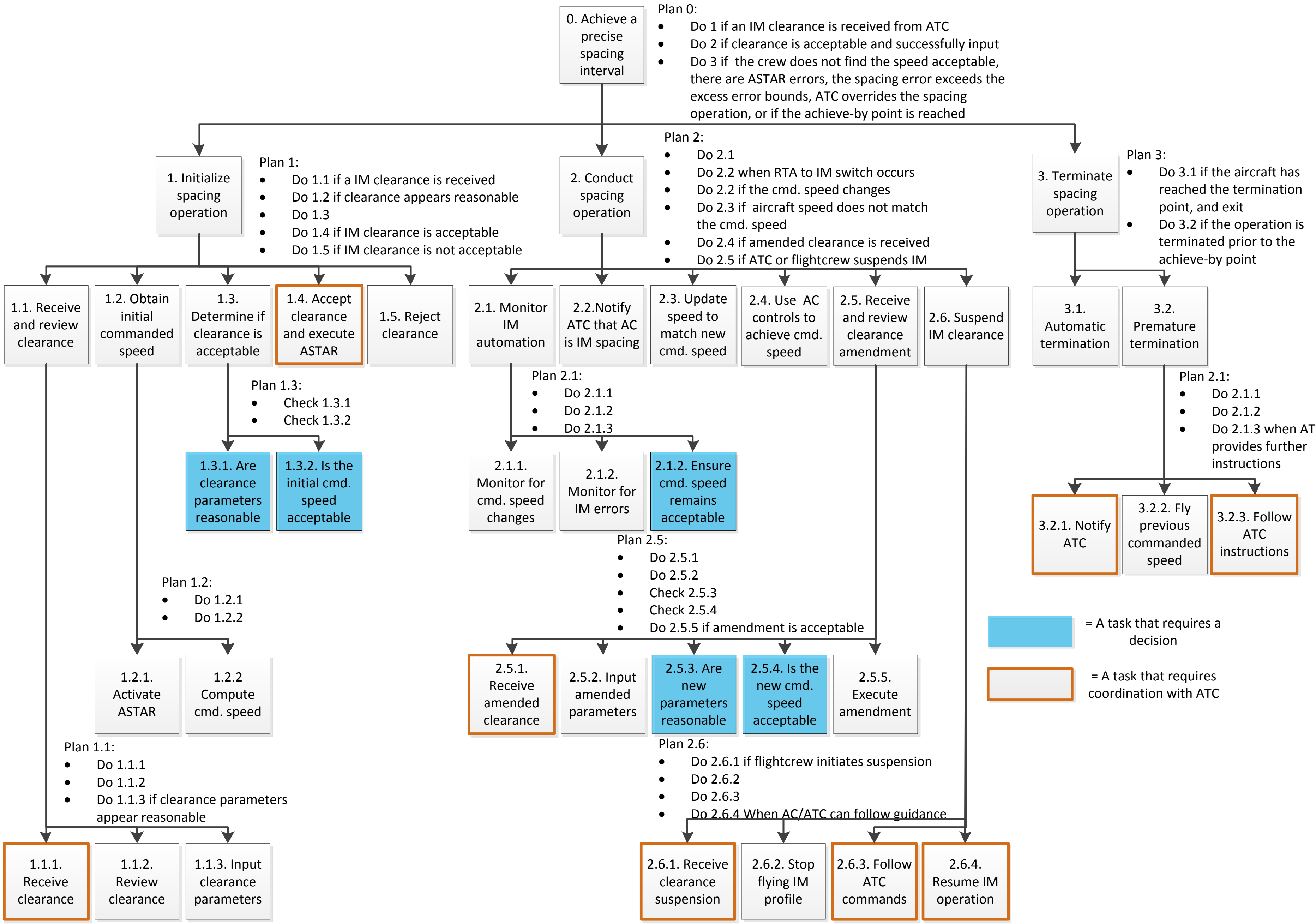
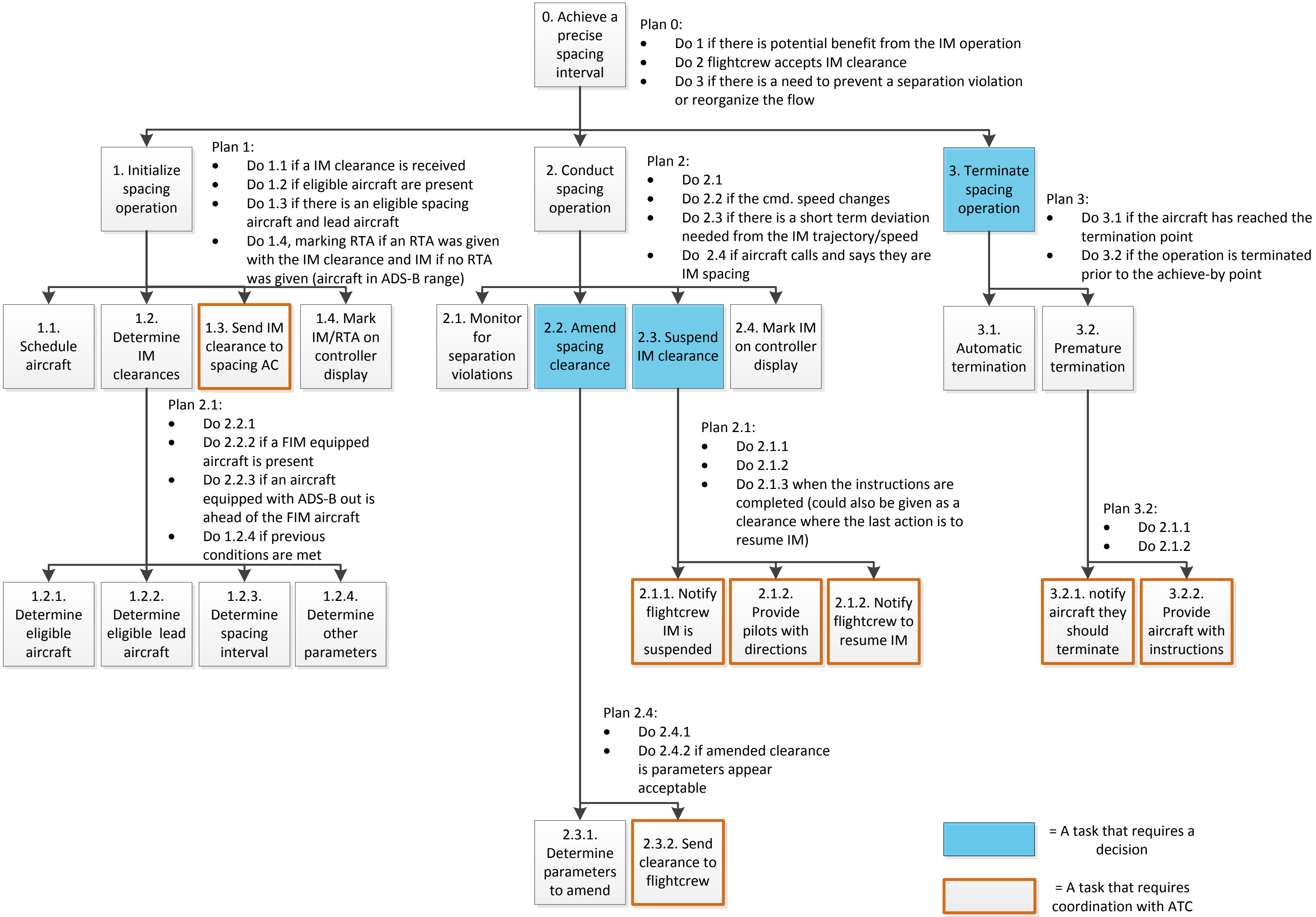


Figure 4.1: Flightdeck task analysis



Plan 0:
- Do 1 if there is potential benefit from the IM operation
- Do 2 flightcrew accepts IM clearance
- Do 3 if there is a need to prevent a separation violation or reorganize the flow

Plan 1:
- Do 1.1 if a IM clearance is received
- Do 1.2 if eligible aircraft are present
- Do 1.3 if there is an eligible spacing aircraft and lead aircraft
- Do 1.4, marking RTA if an RTA was given with the IM clearance and IM if no RTA was given (aircraft in ADS-B range)

Plan 2:
- Do 2.1
- Do 2.2 if the cmd. speed changes
- Do 2.3 if there is a short term deviation needed from the IM trajectory/speed
- Do 2.4 if aircraft calls and says they are IM spacing

Plan 3:
- Do 3.1 if the aircraft has reached the termination point
- Do 3.2 if the operation is terminated prior to the achieve-by point

Plan 2.1:
- Do 2.2.1
- Do 2.2.2 if a FIM equipped aircraft is present
- Do 2.2.3 if an aircraft equipped with ADS-B out is ahead of the FIM aircraft
- Do 1.2.4 if previous conditions are met

Plan 2.1:
- Do 2.1.1
- Do 2.1.2
- Do 2.1.3 when the instructions are completed (could also be given as a clearance where the last action is to resume IM)

Plan 3.2:
- Do 2.1.1
- Do 2.1.2

Plan 2.4:
- Do 2.4.1
- Do 2.4.2 if amended clearance is parameters appear acceptable

Figure 4.2: ATC task analysis

4.3. Control Task Analysis (CTA)

As mentioned in Chapter 2, CTA can be used to examine the decision process that a human decision maker uses, or is expected to use. CTA was originally introduced as the second phase of Cognitive Work Analysis (CWA); however, it can also be used to examine tasks within the HTA. The HTA of the flightdeck demonstrated that there are two major IM tasks that required the flightcrew to make a decision: deciding whether to accept or reject a new or amended IM clearance, and deciding whether the IM commanded speeds are acceptable. It is useful to examine the decision making process that pilots can use when completing these tasks.

The first task that the flightcrew must complete is determining whether an IM clearance is acceptable (Figure 4.3). Moving from the bottom left of the decision ladder, the flightcrew first receives either a full IM clearance or an amendment to a previously provided clearance. The IM clearance contains parameters such as the IM achieve-by point, the callsign of the lead aircraft, its route, the spacing goal, and an RTA time if the aircraft are not in ADS-B range. Depending on the exact implementation of IM, there can also be additional parameters such as the lead aircraft's Mach to Calibrated Airspeed (CAS) transition speed. Once the clearance is received the flightcrew loads it into the IM automation, which generates a commanded speed. At this time the spacing algorithm checks that the lead aircraft is on the selected route and that the aircraft will likely null the time error by the achieve-by point. If either of these conditions are false, the spacing algorithm will provide the flightcrew with an error message. If the commanded speed is within the speed constraints imposed by the aircraft, within any regulatory constraints, if the commanded speed is acceptable to the pilot for the current conditions, and if the spacing algorithm does not generate any errors, the flightcrew should accept the commanded speed (the leap from “alert” to “plan” in Figure 4.3). The top portion of the CTA is mostly undefined because it is expected that the flightcrew will reject the clearance if any knowledge based reasoning is required.

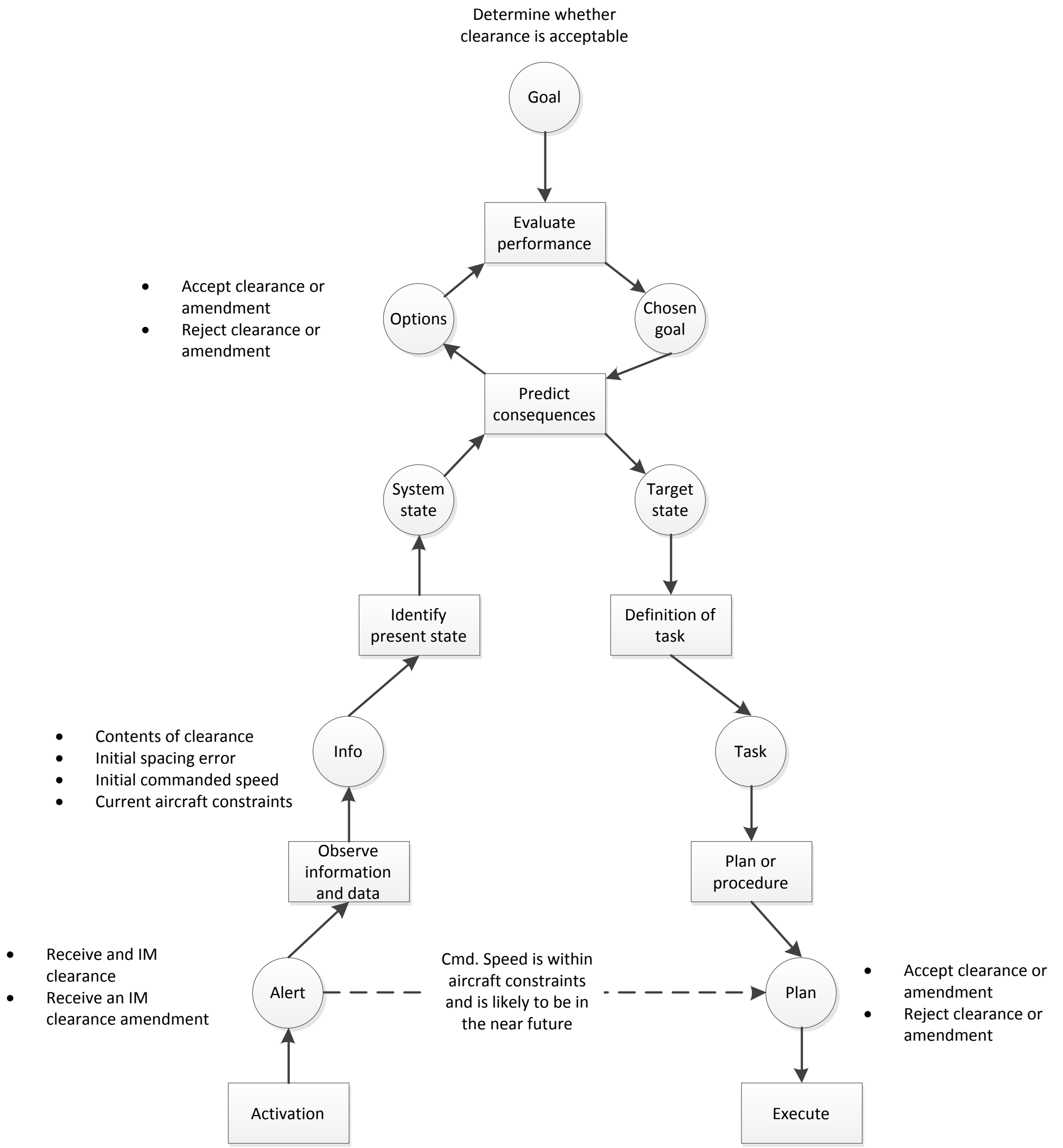


Figure 4.3: The decision ladder showing how pilots are expected to determine if their clearance is acceptable

A second control task the flightcrew must complete is determining whether they should continue with the IM operation (Figure 4.4). This task is a monitoring function that should be conducted whenever a flightcrew is conducting an IM operation. First, the flightcrew should observe pertinent information including current aircraft state, speed constraints, the value of the commanded speed, that the time error is reasonable, and any error messages provided by automated checks the spacing algorithm does. These checks include ensuring that the spacing algorithm is on path, that the lead aircraft is on its path, that a valid ADS-B signal is being received from the lead aircraft, and that the spacing interval is achievable. If a commanded speed change occurs and the flightcrew knows that the commanded speed is acceptable given the aircraft's current state, they can execute the new commanded speed (shown by the shunt from "alert" to "execute" in Figure 4.4). If the spacing algorithm gives an error message, the flightcrew can use the information from that message, look up the appropriate procedure and execute that procedure (shown by the shunt from "info" to "develop plan and use procedures" in Figure 4.4). There may also be cases where the flightcrew may use their judgment to determine whether they should or should not continue with the spacing operation. These cases may be triggered by weather phenomena, non-ideal behavior by the lead aircraft, or a series of questionable speed changes. During these cases, the flightcrew must examine options and determine an appropriate course of action. Once that course of action is chosen, the flightcrew can reference any applicable procedures (shown by the leap from "predict consequences" to "develop plan and use procedures" in Figure 4.4).

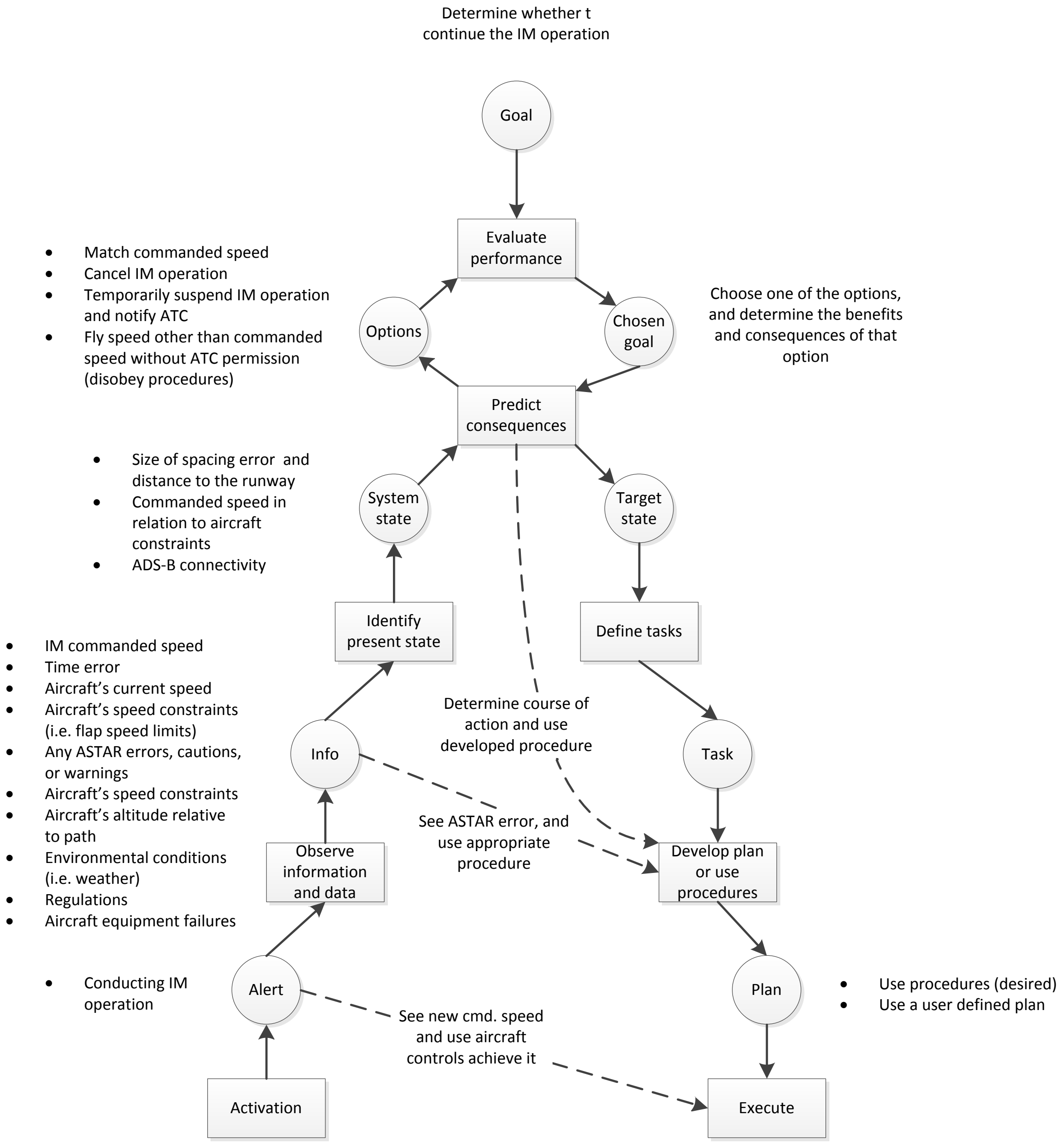


Figure 4.4: The decision ladder showing how pilots are expected to determine if they should continue the IM operation

4.4. Insights into Design from Task Analysis

The HTA showed that the IM operation can be split into three major parts: Activating the spacing operation, conducting the spacing operation, and terminating the spacing operation. This is true for both the flightdeck and ATC. There are a few tasks that involve communications between ATC and the flightdeck. The flightcrew is able to contact ATC and cancel the operation at any time. ATC can contact the flightcrew to provide an update clearance, or suspend a clearance so vectors can be initiated. This clearance may contain a change in spacing interval or trajectory. These updates are expected to occur if speed control is not sufficient to fix the spacing error, or if ATC must make space for an additional aircraft. If the operation is terminated prematurely (prior to reaching the achieve-by point), it is the responsibility of ATC to provide the aircraft with future speed instructions. The flightcrew can terminate the spacing operation because of unacceptable speeds, and ASTAR error, or for excessive time error.

Each of the tasks were examined to determine the interfaces needed to support them (see Appendix A). From this analysis, it was determined that the IM symbology used within the HITL experiment described in Chapter 4 did a good job supporting task based behavior. Furthermore, the IM symbology was placed on the appropriate flightdeck displays. All of the IM speed information was placed with the IM speed information on the PFD, indications of the lead aircraft were placed on the ND, pages for entering information into the algorithm on the MCDU, and cautions and advisories on the EICAS display.

There are three time critical actions involved in the IM system: the time it takes for the flightcrew to respond to a clearance, the time it takes a flightcrew to match a commanded speed and the amount of time an air traffic controller has to recognize and impending separation violation and prevent it. To minimally support the task of matching the commanded speeds, pilots must have timely indication that a speed change has occurred, and indication of any errors. The pilot’s expertise and knowledge of the current flight situation is used to determine whether the ASTAR speeds are acceptable or not. To provide timely indication there must be alerting of changes in the commanded speed. In the IMSPiDR experiment it appeared that the solid green box that appeared around the commanded end speed for ten seconds was not salient enough to adequately capture pilots' attention, and thus the next version of IM displays should have more salient notification of speed changes. The IM clearance is long and complicated, since it includes the spacing interval, lead aircraft's callsign, lead aircraft's route, and the achieve-by point. This suggests it is important to streamline the task of providing the initial IM clearance as much as possible, which can be accomplished by providing an easy way of entering a voice clearance or using a CPDLC clearance.

It is also possible to look at procedural modifications that could potentially make IM run smoother. For instance, under the current procedures the flightcrew is expected to terminate the spacing operation if their time error becomes too large. If this occurs later in the descent, ATC will probably not have sufficient time to provide the flightcrew with a new spacing clearance, and will likely end up having to provide the aircraft with a larger spacing buffer and vectors or speed commands to the runway. If the flightcrew is able to request an amended spacing interval from ATC, it is possible that they would be able to reduce the time error to a manageable value and continue the IM operation to the runway. Additionally, there could be cases where the lead aircraft is vectored off path by ATC. In the current implementation, this will result in the flight crew of the spacing aircraft receiving a "Lead aircraft off path" message, requiring them to cancel the operation. This may not be ideal if ATC is only vectoring the lead aircraft temporarily.

4.5. Work Domain Analysis (WDA)

4.5.1. Work Domain Constraints

The work domain is governed by a number of constraints that the system must operate within. Physical constraints describe the constraints imposed by the laws of nature. They can include natural forces such as aerodynamics and gravity (energy management), the number and size of runways, and aircraft performance, among others. Physical constraints can also include the time it takes to complete certain tasks, constraints on human or machine memory, and limitations of cognitive abilities.

Regulatory constraints describe the rules and regulations that have been put into place to achieve a safe and organized system. Regulatory constraints can be can be put in place so that behavior is predictable, to establish dynamics of teamwork, or to act as more conservative forms of physical constraints. There are many regulatory constraints present in the NAS to ensure the airspace remains safe and orderly. Some of the rules and regulations that are most pertinent to IM include separation constraints, the 250 knot speed limit imposed on aircraft below an altitude of 10,000ft, and speed/altitude constraints at specific waypoints in a route. Furthermore, there are rules that dictate when pilots and air traffic controllers should communicate, the precise phraseology they should use, and instances where following ATC instructions is imperative.

Lastly, automation can be given constraints to help it achieve an ideal behavior. For instance, ASTAR contains constraints to limit the number of speed changes and to increase the probability that the flightcrew will find the commanded speeds acceptable. Some examples of the constraints imposed by ASTAR include limiting the difference between a commanded speed to ±10% of the nominal profile speed, and an “excess error” bound.

4.5.2. Building the Abstraction-Decomposition Space (ADS)

The work domain was described using the Abstraction-Decomposition Space (ADS). Both the abstraction and decomposition dimensions of the ADS were used to describe the IM system. The information from the ADS was gathered from the IMSPiDR experiment discussed in the previous chapter, and from a variety of sources that were discussed in Chapter 2.

The decomposition dimension of the ADS was split into a system level that described the National Air System, a subsystem level that described both Air Traffic Control (ATC) and aircraft, and a component level that described IM. This organization was chosen because the NAS is primarily comprised of aircraft and ATC infrastructure. Each of these subsystems has its own purposes and goals. Furthermore, IM has both a component that integrates with ATC and a component that integrates with the flightdeck. Thus, IM is a component of both the ATC and flightdeck subsystems. Organizing the ADS in this way allows the purposes and functions of the IM system to be compared with the purposes and function of both ATC and the flightdeck.

The abstraction dimension includes the functional purpose, values and priority measures, object related functions, and physical objects [23]. To keep the ADS from becoming overly complicated, the WDA is often filled out primarily along its diagonal (i.e. the purpose related functions are only shown for the system and physical objects are only shown for the component). However, in this thesis each decomposition level was filled out from top down and the lowest level of abstraction was chosen by the level of detail that was deemed to provide significant benefit to the design process in chapter 5. This portrays how ATC and the flightdeck have separate purposes and separate measures of success. In the following paragraphs the ADS of the IM system is described, and is represented in Table 4.1.

The *functional purpose* of the National Airspace System (NAS) is to move people and cargo from one point to another safely and efficiently. As the world has become more globalized, there is an increasing need to make aviation as accessible as possible, as environmentally friendly as possible, and as safe as possible. To accomplish these goals, the NAS must operate at the maximum practical efficiency. To help identify the role of ATC, the flightdeck, and IM, the functional purposes of the NAS were decomposed into the functional purposes of ATC and the flightdeck. ATC is primarily responsible for maintaining a safe and efficient air system. This requires maintaining adequate separation between aircraft, and efficiently controlling the flow of aircraft. ATC also sees it as their duty to promote fairness in the NAS, and will often allow an aircraft a trajectory change as long as the request does not interfere with other aircraft in the NAS or safety. Thus, ATC has the responsibility of promoting the efficiency and safety of all of the aircraft under their control. In contrast, the flightdeck is primarily interested in promoting the safety and efficiency of a particular aircraft. The flightdeck’s main customers are passengers; thus the goals are safe, comfortable, and low cost flights with minimal delays. Lastly, the main purpose of IM is to maximize the runway throughput during periods of high demand. This can help enable OPDs during periods when high runway throughput is required. OPDs have shown an ability to help reduce noise, air pollution, and fuel use. Additionally, IM has the ability to reduce controller workload by minimizing vectoring at low altitudes.

The *values and priority measures* in the ADS describe measures that were used to determine how well the system is achieving its functional purpose. To achieve the functional purposes of moving people/cargo, safety, and efficiency, the NAS must minimize the number of collisions/crashes, its environmental impact, and expenses while transporting people/cargo. ATC achieves some of these objectives by minimizing losses of separation, and maximizing throughput. The flightdeck is concerned with getting their passengers to their destination on time using minimal fuel, while maintaining passenger comfort. The IMSPiDR experiment demonstrated that passenger comfort was a particular concern when pilots were forced to use speedbrakes to achieve their commanded speeds. IM can help achieve a number of these values by helping regulate the flow of traffic, helping aircraft achieve and/or maintain adequate spacing intervals, and enabling more fuel efficient, lower emissions, and lower noise arrivals during busy periods.

The *purpose-related functions* were used to describe the general functions that are needed to operate the system. The functional purpose of ATC is to manage the air traffic, ensure that aircraft maintain adequate separation from each other, and to ensure each aircraft is able to get to their destination with minimal delay. To maintain an efficient and safe traffic flow, ATC must first understand the current state of the traffic, and be able to predict what the state of the traffic will be in the near future. To maximize the efficiency of the traffic flow, ATC must make sure that there is a well-conditioned flow of traffic arriving to the runway that maintains proper separation intervals and does not contain large differences in speeds. To monitor for separation violations, ATC must use their picture of the traffic along with automated decision aids to predict and prevent impending separation violations. Lastly, air traffic controllers must communicate with aircraft and other controllers to make sure that they have a clear understanding of the traffic, and to control the traffic to maintain a safe and efficient traffic flow. Similarly, pilots are often told that their purpose related functions are, in priority order starting with the most important to aviate (control the aircraft), communicate, navigate, and then manage systems. Aviate refers to avoiding obstructions and managing the aircraft's energy to keep it in the air. However, aviating can be expanded to include controlling an aircraft's speed, controlling the aircraft's path, and monitoring autoflight systems. Navigating refers to selecting the aircraft's path and tactical maneuvers needed to avoid dangerous flight conditions such as poor weather. Additionally, aircraft must communicate with ATC to determine information about weather conditions, and to receive instructions to avoid conflicts with other aircraft. To conduct an IM operation, there are a number of additional functions that must be completed by the pilots and controllers. There must be a schedule created so spacing intervals can be chosen, eligible aircraft identified, information communicated between ATC and the flightdeck, a control mechanism to minimize the spacing error, and finally there must be a method of ending the operation.

The *object related functions* were used to describe the systems and constraints used to meet the purpose-related functions. ATC uses automation in conjunction with human expertise to help monitor for separation violations and maintain a smooth arrival flow. Monitoring for separation violation necessitates knowing the locations of aircraft now and in the near future. ATC gathers the positions of aircraft through radar, and is expected to have access to more precise position and velocity data provided by ADS-B.

ATC then uses this information to communicate instructions to aircraft to ensure a smooth arrival stream. Furthermore, ATC uses STARs to help funnel aircraft into the runway. Likewise, modern commercial flightdecks have a number of systems that help the flightcrew aviate, navigate, and communicate. These systems include an autopilot, a Traffic Collision Avoidance System (TCAS) to help prevent collisions with other aircraft, crew alerting systems, communication systems, and navigation systems. Additionally, the aircraft itself can be considered an object related function, since its performance characteristics can have an impact on the IM operation. Lastly, pilots use published charts and procedures, such as STARS and approach plates, to understand the actions they will have to do to perform a safe arrival. The IM concept that is discussed in this paper uses two major pieces of automation: TMA and ASTAR. TMA generates a runway schedule, and ASTAR is in charge of tracking the lead aircraft and controlling the interval between the spacing aircraft and the lead aircraft.

The *physical objects* category was used to describe the display elements, physical locations of the aircraft, and the other physical attributes. The physical objects are only described here for equipment that ATC and pilots use for IM. The IM physical objects include the IM displays in ATC stations and on the flightdeck, procedures, aircraft performance, the locations of the spacing aircraft and lead aircraft to enable a spacing algorithm to provide guidance to the aircraft. The weather is also considered a physical object of interest, as storms can force aircraft to deviate from their nominal course, or and non-forecast winds can cause additional speed changes.

Lastly, means-end relationships were created to describe the relationships between the different elements in the ADS. There are many means-end relationships that can be discussed. This thesis concentrates on those that are deemed the most important. The means-end relationships present in the ADS can be generally be described by the physics of the trajectory and the speed control law. The physics of following the trajectory includes the performance of the aircraft, aerodynamics and the dynamics of the sensors used to determine the aircraft’s location with respect to the trajectory, which includes latency, update rate, and error. For the purposes of discussion, a subset of the entire ADS described in Table 4.1 is portrayed in Figure 4.5: A subset of the ADS with means-end relationships. Means-end relationships were drawn between elements of the ADS that had dependencies. From this process, it was determined that many of the means-end relationships present in the ADS described the ASTAR control law.

Table 4.1: The Abstraction-Decomposition Space (ADS) of the IM system

Decomposition → ↓ Abstraction	System	Subsystems		Component
	National Airspace System	**Air Traffic Control**	**Aircraft**	**IM**
Functional Purpose	Move people and/or cargo from point A to point B, Safety, Efficiency	Manage air traffic, Ensure separation, Promote fairness among aircraft, Minimize delay	Safe transportation of people/cargo, Provide passenger comfort, Minimize cost	Maximize runway throughput during periods of high demand
Values and Priority Measures	Minimize expenses, Minimize environmental impact, Minimize the number of collisions/crashes, Adherence to regulations, Number of people moved	Maximize runway throughput, Maximize the efficiency of the traffic flow, Minimize separation violations	Aerodynamics and balance of forces, Minimize fuel used, Maximize passenger comfort, Management of physical and attention resources	Maximize arrival precision behind one or more lead aircraft at the runway threshold
Purpose-related Functions		Maintain a picture of the traffic situation, Monitor for separation violations, Monitor the weather, Streamline flow, Handoffs, Communicate with aircraft and other controllers	Navigate, Communicate, Control speed, Control path, Energy management, Manage aircraft's systems, Adhere to ATC instructions, Avoid obstructions, Avoid weather,	Runway scheduling, Communication and coordination, Trajectory generation, Tracking lead aircraft, Controlling spacing interval, Ending spacing operation
Object-related Functions		TMA, Communications systems, Radar System, Arrival routes, Airport configuration, Weather	Navigation systems, Communication systems, Autopilot, Crew alerting system, TCAS, Aircraft performance, Arrival diagrams (STARS, approach plates, etc.)	ASTAR, TMA/TAPSS, ADS-B
Physical Objects		CPDLC, Radio	MCP speed window, VNAV and LNAV buttons, FMS page containing the route, ND, PFD, MCDU, flaps, landing gear, throttle	Ownship position, Lead aircraft position, Ownship 4D trajectory, Lead aircraft 4D trajectory, Spacing error, Aircraft performance, IM clearance, Commanded speeds, Radio, Datacom, Procedures and checklists, Aircraft flap configuration, Runway schedule, IM flightdeck displays (Display of lead aircraft, Display of commanded speed, Display of changes to the, commanded speed, Pilot alerting, Display of route, Display of weather), IM ATC displays (timeline, Indication of ATC intervene point, Indication of CPDLC equipped aircraft, Indication of IM equipped aircraft, Method of generating IM clearances)

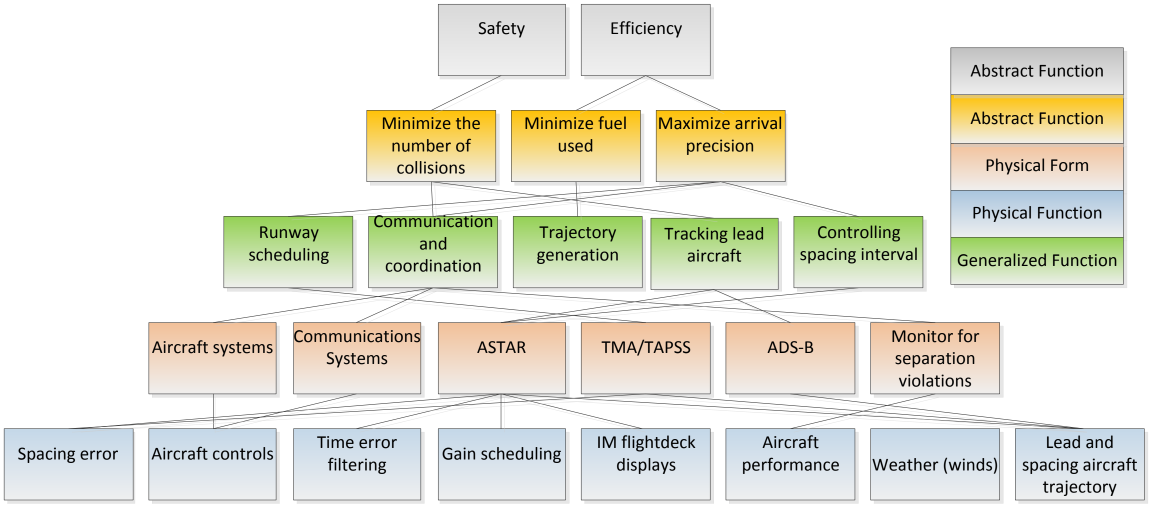


Figure 4.5: A subset of the ADS with means-end relationships

Many of the physical objects discussed in the IM portion of the ADS are connected together by the ASTAR speed control algorithm [76], [74]. Furthermore, the ASTAR speed control algorithm is described in. The ASTAR speed control algorithm begins by using the spacing aircraft’s Time-To-Go (TTG) to the achieve-by point, along with the lead aircraft’s TTG and a spacing interval to generate a raw time error. The raw time error provides a projection of how far ahead or behind the spacing aircraft will be at the achieve-by point. Next a filter artificially decreases the value of the time error when the aircraft is far from the runway to prevent unnecessary control actions. A gain is applied to the filtered time error to create a raw speed error, which is limited to ±10% of the nominal profile speed. Next, this speed error is chunked into five knot increments and added to the nominal profile. Thus, the speed control algorithm uses the 4D trajectories of the spacing aircraft and lead aircraft, along with the spacing interval, to compute an error. A proportional gain is applied to that error and used to produce a speed correction. The speed correction is implemented by the flightcrew and the difference between the nominal profile speed and commanded speed causes a change to its ETA, acting as the feedback loop. The filter that limits the commanded speed to ±10% of the nominal profile speed bounds the reachability of the assigned spacing goal.

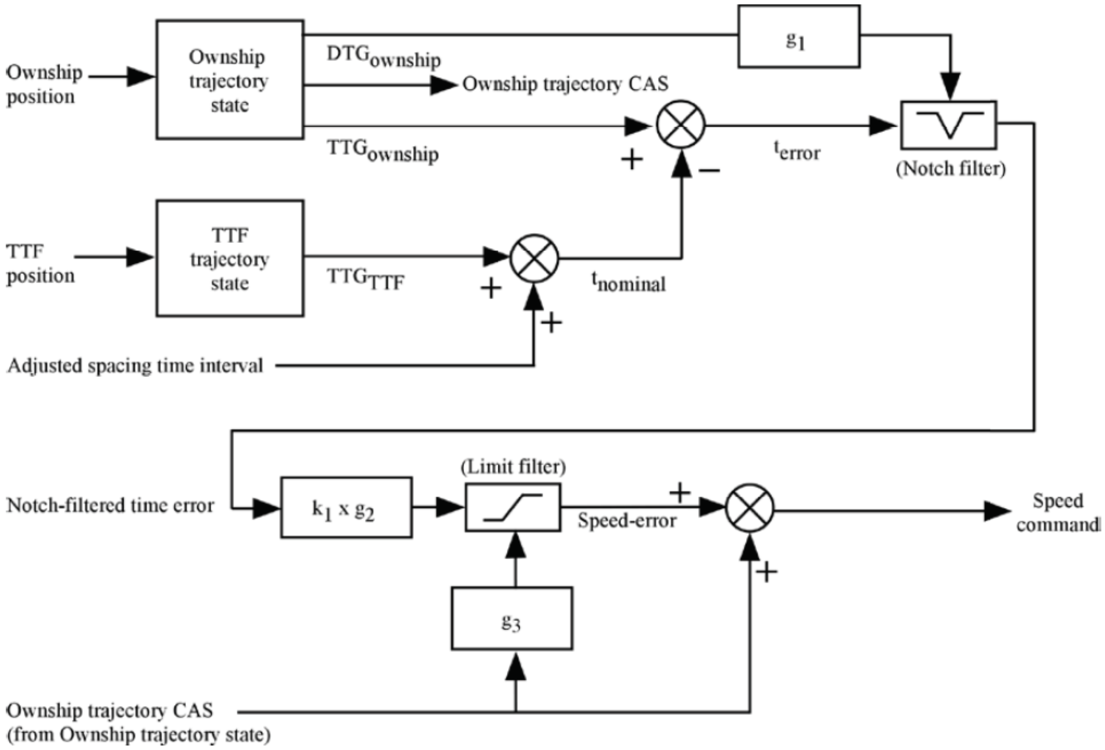


Figure 4.6: The ASTAR speed control algorithm [76]

Further insights can be gained by examining the ASTAR control algorithm. For instance, there are three major factors that affect the time error: error between forecast winds and actual winds, the lead aircraft's deviation from its nominal profile, and the spacing aircraft's deviations from its nominal profile. These deviations will impact the ETA of the spacing aircraft or the lead aircraft causing either an increase or decrease in spacing error. Additionally, as the aircraft approache the runway, filtering and gain scheduling make the speed changes more sensitive to a given time error.

There were also periods where speed changes are inhibited to help the commanded speed meet regulations and to make them more acceptable to pilots. In the IMSPiDR HITL experiment discussed in the previous chapter there were three conditions that could inhibit a speed change, limiting the controllability of the algorithm: the commanded speed was inhibited if it would violate the 250 knot speed limit below an altitude of 10,000ft, if the deviation of the commanded speed from the nominal profile speed would be greater than 10% of the nominal profile speed, and if the speed change would cause the commanded speed to increase less than ten seconds prior to a scheduled (profile) speed decrease. These limits constrain the controllability of the algorithm and can impact whether the assigned spacing goal is reachable.

4.6. Insights into Design

From the process of completing the WDA it was found that the higher levels of abstraction can be examined to ensure the system has the correct objectives: in this case, the functional purpose and values and priority measures of IM align with those of the NAS, ATC, and the aircraft indicating that IM has appropriate objectives. The lower levels of abstraction can be used to identify important domain constraints and relationships. Once these constraints and relationships are identified, EID can be used to design interfaces that convey them to the operator using easy to understand representations.

EID principals were applied using the ADS to determine appropriate interfaces. The basic idea behind EID is to develop interfaces that serve as an external model of the system. The operator can use this external mental model to understand the state of the system in relation to its constraints, and how the system will react to a given input.

Additionally, the goal of EID is to develop displays that support all three modes of human cognition: skill based behavior, rule based behavior, and knowledge based behavior. By supporting each of these modes, EID interfaces can help support operators during both nominal and off-nominal circumstances.

The implementation of IM used in the IMSPiDR HITL experiment did a good job supporting task based behavior; however, experiment results demonstrated that the interfaces and procedures often conveyed an incomplete or inaccurate mental model of the how ASTAR works, and may have contributed to increased frustration when speed changes were unexpected. The IM displays supported skill based behavior by allowing pilots to directly act by referencing the displays. This includes seeing a commanded speed change on the PFD and dialing that speed into the MCP window, as well as controlling the throttles and speed brakes to track the commanded speed bug during accelerations and decelerations. The displays and procedures used in the HITL experiment supported rule based behavior by providing the flightcrew with a series of EICAS messages when they were required to take a specific action. However, the experiment demonstrated that the displays and procedures had difficulty supporting knowledge based behavior and conveying an accurate mental model of the system to the pilots. The data from the IMSPiDR experiment in chapter 3 showed that some pilots used the information available to them to develop a mental model of the relationship between the aircraft’s position, the time error on the MCDU, and the speed commands they were receiving; however, this information often misled the flightcrew, resulting in an incomplete or inaccurate mental model. If the relationship between spacing and lead aircraft’s state can be communicated through the interface, it is hypothesized that pilots will gain a greater understanding of why particular speed commands are provided and of how their conformance to the commanded speed affects their ability to achieve a precise spacing interval behind a lead aircraft.

The means-end relationships in the WDA show that changes to the time error are composed of the spacing aircraft's deviation from its profile speed, the lead aircraft's deviation from its profile speed, and differences between the actual winds and forecast winds. In the previous chapter, pilot comments indicated that they did not have a good understanding of the relationship between the time error provided by ASTAR and the commanded speed. This relationship can be broken into a few simple rules.

- As the magnitude of the time error decreases, ASTAR will return the aircraft to its nominal profile speed.
- If the time error is increasing (arriving earlier), the commanded speed will increase.
- If the time error is decreasing (arriving later), the commanded speed will decrease.
- If the time error is positive (arriving early), the commanded speed will be below the nominal profile speed.
- If the time error is negative (arriving late) the commanded speed will be above the nominal profile speed.

Additionally, the cause of changes to the time error can be provided to pilots by separating the rate of change of the time error into different components. ASTAR calculates the Time-To-Go (TTG) of the spacing aircraft and lead aircraft along their respective 4D trajectories and uses this information in conjunction with the spacing interval to generate a time error. Assuming no trajectory recalculations, the rate of change of the Time-To-Go for each aircraft can be computed by looking at the difference in the profile ground speed and the actual ground speed at the aircraft's location along the 4D trajectory. If the forecast winds and actual winds are known, the rate of change in the TTG can be decomposed into a wind component and component that is caused by the flightcrew flying off their nominal speed.

In addition to the relationships between the physical world and the commanded speed, there are constraints on ASTAR's commanded speed as noted earlier. These constraints include excess error bounds which are used to determine if the spacing interval is reachable, the point where controllers are expected to intervene to prevent a separation violation, and the ±10% speed bound that ASTAR uses to limit the controllability and ensure commanded speeds remain acceptable. Providing pilots with the aircraft state in relation to these constraints, or otherwise illustrating when these constraints are limiting the commanded speed, could provide pilots with greater situational awareness.

4.7. The Combination of HTA and WDA

The previous sections discussed both the results from the HTA, CTA, and WDA. In this section, further insights are found by juxtaposing the three models. Initially the results of the WDA and HTA were combined by connecting the physical forms required to complete each task to the physical forms in the WDA, effectively providing a link between the WDA and HTA. However, this was time consuming, and there was little insight gained. Instead, the tasks associated with the rules and constraints were determined from the WDA. The idea is that providing operators with thorough knowledge of a system can change the way they operate the system, and could change the way tasks should be allocated.

The tasks associated with the rules and constraints derived from the WDA are presented in Table 4.2. Most of the rules/constraints are associated with the tasks of monitoring for speed changes and updating the commanded speed. The task of updating the commanded speed is included because providing the flightcrew with additional information might influence whether or not they choose to should follow a new commanded speed. The only two constraints that are different are the ‘excessive error’ constraint and the controller intervention bound. These two constraints are associated with the tasks of terminating the spacing operation and amending a clearance.

There are two issues that were identified from examining the rules and constraints from the WDA and their associated tasks. The first issue is that providing the flightcrew with information of the time error and the rate at which it is increasing or decreasing could cause the flightcrew to disobey the commanded speed. The second issue was that providing pilots with knowledge of the controller intervention point may cause them to modify their speeds to avoid it. If they are part of a string of aircraft there is the possibility that this could cause stream instabilities. Additionally, the flightcrew could try to contact ATC to cancel the spacing operation. If the flightcrew and ATC simultaneously see that the aircraft is past the controller intervention point, they may try to contact each other at the same time. This could potentially be mitigated with a clear procedure for communication.

Table 4.2: Rules and constraints from the WDA and their associated tasks from the HTA

Rule or Constraint (From WDA)	Associated Task(s) (From HTA)
If the time error is increasing, the commanded speed will increase	Monitor for changes to the commanded speed, Update commanded speed
If the time error is decreasing, the commanded speed will decrease	Monitor for changes to the commanded speed, Update commanded speed
If the time error is positive, the commanded speed will be greater or equal to the profile speed	Monitor for changes to the commanded speed, Update commanded speed
If the time error is negative, the commanded speed will be less than or equal to the commanded speed	Monitor for changes to the commanded speed, Executing operation
As the aircraft approaches the runway the speed becomes more sensitive to the time error	Monitor for changes to the commanded speed, Executing operation
As the aircraft approaches the runway, the notch filter causes less error to be ignored	Monitor for changes to the commanded speed, Update commanded speed
The commanded speed must stay within ±10% of the profile speed	Monitor for changes to the commanded speed, Update commanded speed
The time error should stay within the 'excess error' bounds (otherwise cancel the operation)	Terminate the spacing operation, Update appended clearance
The speed must remain below 250 knots when the aircraft is below 10,000ft.	Monitor for changes to the commanded speed
The controller intervention bound (If ASTAR is configured to monitor the current spacing between the spacing aircraft and lead aircraft)	Terminate Spacing Operation, Update appended clearance, Monitor for excess spacing bounds

4.8. Summary

This chapter developed a WDA, HTA, and CTA of the IM system. The purpose of the WDA, HTA, and CTA was to determine procedures and interfaces that could enable the flightcrew to fully understand the relationships between the physical world and the commanded speeds they are provided. In general, the purpose of the WDA was to describe the relationships and constraints that are present in IM, the purpose of the HTA was to describe pilots' nominal behavior, and the purpose of the CTA was to identify the decision making process that could be used when conducting tasks that required a decision.

The WDA used an ADS to describe the entire work domain of IM. The ADS was separated into components describing the entire NAS, ATC, the flightdeck, and IM. The WDA indicated that there are two major relationships in the IM system: the relationship between the physical world and the time error computed by the spacing algorithm, and the relationship between the time error and commanded speed changes. The previous chapter demonstrated that some pilots tried to determine these relationships using available information, but often formed an incomplete or incorrect mental model. Thus, there are potential benefits to be gained from providing the flightcrew with interfaces and procedures that act as external representations of the system. The WDA showed that that the behavior of IM can be broken into a few simple rules and constraints. In the next chapter, these rules will be incorporated into proposed interfaces and procedures.

To link the WDA and HTA together, the rules of operations obtained from the WDA were linked with their associated tasks. Some potential problems were identified that could result in non-ideal behavior. For instance, providing the flightcrew with more information could result in them modifying their commanded speed to decrease their error at a faster rate than ASTAR desires. This modification could have a negative impact on any aircraft behind them. Additionally, providing the flightcrew with the controller intervention point has the potential to cause confusion as to whether it is the flightcrew’s job to avoid the constraint or ATC’s job. It is important for the interfaces to the show pilots whether the spacing algorithm is working correctly, and procedures that provide a clear delegation of responsibility.

Lastly, two major control tasks were identified from the HTA: determining whether or not to accept an IM clearance, and determining whether to continue the IM operation. Information needs, leaps, and shunts for each control task were determined. The CTA determined that there is a lot of information that pilots must integrate together when determining whether they should continue the spacing operation.

In the next chapter, the rules and task knowledge that was generated by the WDA, HTA, and CTA will be used to design interface representations and procedures. It is hypothesized that the proposed interface and procedures additions will help pilots build an accurate mental model of the relationships between the physical world and the time error, and between the time error and the commanded speed.

CHAPTER 5

INTERFACE AND PROCEDURE MODIFICATIONS

5.1. Introduction

The Human-In-The-Loop (HITL) experiment discussed in Chapter 3 was used to complete a Work Domain Analysis (WDA), Control Task Analysis (CTA), and Hierarchical Task Analysis (HTA) of the Interval Management (IM) system. The WDA and HTA both contain complete information of the IM system that conveys different, but complementary, information to the operator. The WDA was used to describe the constraints imposed on IM, as well as relationships describing how the IM algorithm works. The results from the WDA were used to determine rules that the IM automation follows to generate speed commands. Furthermore, an HTA was used to describe both the normal, and anticipated non-normal events that pilots and air traffic controllers may encounter. Within this chapter, the information gathered from the WDA and HTA will be used to recommend displays and procedures that have the potential to support pilots during both nominal and off-nominal circumstances.

Insights from the WDA can be used to create representations that convey the dynamics of the system to the operator. These can be either external representations provided by displays or written procedures, or they can be internal representations that are provided through training. The idea behind these representations is to help operators develop a thorough understanding of how the spacing algorithm works, and provide the operator with the ability to monitor the dynamics of the operation. By understanding why a particular speed change is occurring, it is hypothesized that operators will be able to identify off-nominal conditions, and determine appropriate plans of action. Furthermore, understanding why the automation is producing specific speed changes could decrease pilot frustration and increase acceptability.

The information from the HTA can be used to describe a nominal course of behavior from which procedures can be systematically designed, resulting in increased usability of IM. Ideally, the procedures will provide pilots with general rules of thumb and guidelines that they can use during both normal and anticipated non-normal events.

This chapter will describe the creation of representations and procedures for the IM system. First, information gained from the WDA will be used to build representations that describe the dynamics of the system. Second, information gained from the HTA will be used to describe a nominal course of behavior.

5.2. Using the WDA to Build Representations

When EID principals were applied to the WDA in the previous chapter, a number of pieces of information were identified that could help pilots understand the relationships that ASTAR uses to compute a time error and generate a commanded speed. From the ASTAR speed control law, it was determined that the rate of change of the time error was the best indication of changes in the commanded speed. Furthermore, to help pilots understand the relationship between the physical world and the time error generated by ASTAR, the rate of change of the time error can be decomposed into the rate of change of the time error caused by the spacing aircraft, the lead aircraft, and wind error. ASTAR also has a number of constraints designed to generate more acceptable speeds. These constraints include limits to the commanded speed, excess error bounds, and suppressed speed changes that would violate the 250 knot speed limit below an altitude of 10,000ft.

In the following sections, IM interfaces will be discussed in terms of skill, rule, and knowledge based behavior. Rasmussen stated that there are certain representations that are associated with each of these behaviors [13]. Specifically, skill based behavior can be associated with signals, rule based behavior with signs, and knowledge based behavior with symbols. Signals are considered as time-space variables that humans can process as continuous variables, and that humans can act on using automatic skill based behavior. Signs are indications that trigger rule based actions a human operator has learned, or point the operator to a procedure containing rule based information. Symbols are abstract representations that display the relationships and constraints within a system and between the system and the environment. Since symbols provide the operator with relationships and constraints, they can be useful when there is no rule based information or automatic behavior applicable to a situation.

5.2.1. Supporting Skill Based Behavior

Skill based behavior is automatic behavior that requires little or no thought, and often consists of highly practiced tasks. Skill based behavior can be supported by providing operators with information that they can directly act on, enabling them to use learned skills immediately.

IM contains a number of tasks that can be completed using skill based behavior. For instance, pilots are asked to achieve new speeds as new commanded speeds are issued. This can require using the throttle and/or speedbrake to maintain an appropriate speed and stay on their path.

The displays and interfaces used in the IMSPiDR experiment are well suited to supporting skill based behavior. For instance, the IM commanded speed was placed just above the FMS commanded speed, allowing the flightcrew to easily ensure that they match. Additionally, a speed bug was placed on the speed tape, providing pilots with an additional method of determining whether their aircraft's speed matched their commanded speed. When a new commanded speed was given, pilots were either required to monitor the commanded speed to make sure it was acceptable (if they had an autothrottle managed mode), or update the FMS speed using the MCP speed window (if they did not have an autothrottle managed mode).

5.2.2. Supporting Rule Based Behavior

Rule based behavior can be thought of as a series of IF/THEN statements. The rules can either be conveyed through the interface, written as procedures, taught through training, or learned observing a system during operation. EID states that interfaces should provide a one-to-one mapping between the constraints present in the work domain and the representations displayed on the interface, meaning that the interface should describe the aircraft's relation to the constraints that were identified in the WDA.

The IM procedures and interfaces used on the flightdeck have been designed to support rule based behavior. Many of these operations can be placed into a series of IF/THEN statements. For instance, if a speed change occurs then pilots are expected to update their commanded speed; if the commanded speed is not acceptable then pilots are required to cancel the IM operation; and if a IM clearance is received the pilots are expected to go through the process of accepting or rejecting the clearance. If the flightcrew receives a warning or caution, they are required to follow the appropriate procedure. The interface, procedures, and automation used in the IMSPiDR experiment supported rule based behavior by providing pilots with cues notifying them which procedure to complete. For instance, EICAS messages were used to notify the flightcrew when there was a problem and procedures associated with the EICAS messages notified them of actions they should take. Furthermore, the process of accepting and rejecting a clearance is a rule based process. The pilots are expected to receive the clearance, load it into onboard avionics, and then determine if the commanded speed that is generated is acceptable at that particular time (i.e. if it within the aircraft's speed constraints).

The rules that were not supported by the procedures and interfaces used in the IMSPiDR HITL experiment included relationships that described the dynamics of the system and rules of thumb for determining if a clearance or commanded speed was acceptable. These rules were described in Table 4.2, and can be provided to pilots through internal representations (training and memory), or through external representations (displays, procedures). In section 5.2.4. , some of the rules described in Table 4.2 will be designed into a new trend indicator. These rules include the IM excess error bounds, the controller intervention bounds, and rules of thumb regarding how the commanded speed reacts to an increase or decrease in the time error. It is hypothesized that providing flightcrew with rules of thumb regarding ASTAR's operation will help pilots understand the relationships between the physical world and the commanded speeds they are provided.

5.2.3. Supporting Knowledge Based Behavior

Knowledge based behavior occurs when there are no skills or rules that are applicable to a particular situation. Knowledge based behavior is more effortful than skill and rule based behavior, and involves improvisation and experimentation to determine an appropriate course of action. Supporting knowledge based behavior also has the potential to help the operator gain a deep understanding of the system. Providing pilots with the information needed to understand the speed constraints may help decrease their frustration and increase their acceptance of IM operations, particularly when there are errors present that cause non-ideal speed changes or frequent speed changes.

To support knowledge based behavior and a deep understanding of IM, it is necessary to convey the constraints and dynamics of the IM operation to the flightcrews identified in the WDA. One way of doing this is to use EID principles to develop displays that serve as an external mental model of IM. It is hypothesized that the doing this will help the pilots understand why particular speed changes were given and encourage correct conformance.

5.2.4. Proposed Display Features

Within this section, the focus is placed on developing EID displays that can fit into the current flightdeck, as well as EID displays that could be used if the displays were not constrained to a current flightdeck.

Several papers have proposed different trend indicators to help determine how well the spacing operation is proceeding (Figure 5.1). Many of these trend indicators were developed for algorithms other than ASTAR and thus may have different underlying logic. Nevertheless, it is useful to examine previous work that has been completed. NLR developed a trend indicator that included the spacing error and the rate of change of the spacing error [78]. CoSpace developed a trend indicator for their particular spacing algorithm that showed the spacing error, rate of change of the spacing error, and constraints imposed on the spacing error [49]; the CoSpace trend indicator received high acceptability ratings from pilots. A usability study conducted at NASA

Langley investigated two trend indicators designed to support the IM interface. The bounds of these two trend indicators showed the time error relative to ASTAR's "excess error" bounds [64]. The intent of the trend indicator was to help pilots understand the dynamics of the operation, and why they are being told to fly a particular speed.

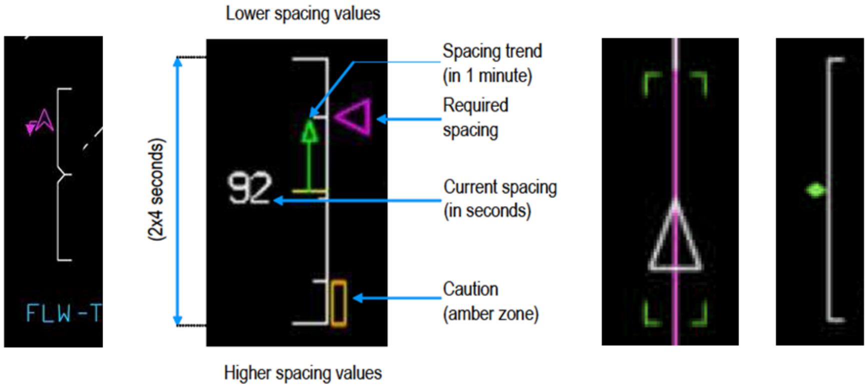


Figure 5.1: Spacing trend indicators from the literature (from left to right), (a) A spacing trend indicator developed by NLR [78], (b) A spacing trend indicator developed by CoSpace [49], (c) A spacing trend indicator developed at NASA Langley for ASTAR [64], (d) A second representation of the trend indicator developed at NASA Langley [64]

Figure 5.2 shows the process that was used to create a new trend indicator that has the potential to convey the relationship between the time error and commanded speeds, and a number of constraints used by the spacing algorithm. The elements of the trend indicator were derived from the constraints and relationships identified using the WDA, and spacing trend indicator examined by Volk was used as a starting point (Figure 2.1, d) [64]. From this basis and the WDA, the following display features were identified:

a) A trend indicator showing the "excess spacing" bounds was used as a starting point for the new trend indicator. The black caret depicts the time error, and the ends of the indicator depict the excess error bounds. When the caret moves to the top or bottom of the of the trend indicator it indicated that the assigned spacing interval at the designated achieve-by point was not reachable.

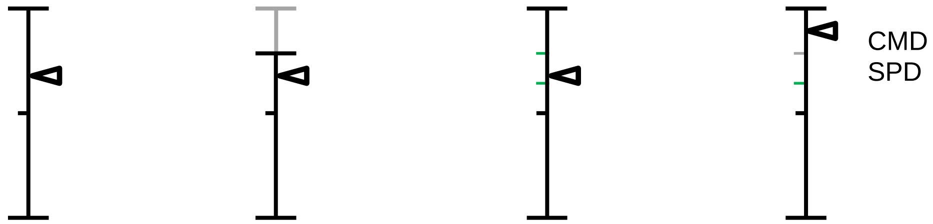
b) Indication of the time error at which a controller would intervene are shown by displaying the constraint and graying out the other portion of the trend indicator. If this feature is used, it will be necessary for ATC and the flightdeck to share the same constraints (i.e. they could be standardized). The discussion of the joint HTA and WDA model also identifies that the procedures would have to clearly identify responsibilities if the time error moved beyond this threshold. For example, while the flightcrew is waiting for ATC to contact them, can they modify their speed to avoid this bound?

c) Two green lines were added to indicate the time error needed to cause a speed change. If the time error moved past the upper or lower green line a speed change would occur. Additionally, the green lines will move closer together as the aircraft approaches the runway showing the pilot the increase in the proportional gain.

d) The green speed change indicators can be grayed to show instances where commanded speed changes are suppressed, such as when the aircraft is below 10,000ft and subject to a 250 knot speed limit or when the commanded speed's deviation from the nominal profile speed is greater than ±10% of the profile speed. In addition to graying the speed change indicators, a message could be provided to pilots notifying them why a particular speed change was suppressed.

e) A green arrow was added to depict the rate of change of the interval error between the spacing aircraft and lead aircraft to provide additional predictability, or feed forward knowledge of the system to pilots. The arrow would change its length based on the magnitude of the rate of change of the time error. It is also possible to give the length of the arrow a physical meaning, such as having it indicate the projected time error after 30 seconds if the same rate of change was maintained. Pilots could use this feature in conjunction with the green speed change indicators to determine feed-forward knowledge of the system: for instance, whether they were likely to receive a non-scheduled speed increase or speed decrease in the near future.

f) An outlined green bar was added to depict the notch filter that ASTAR uses to decrease the number of speed changes when the aircraft is far from the runway. The notch filter subtracts a certain amount of error from the unfiltered time error. For instance, if the spacing aircraft's raw time error was 20 seconds, and the filter value was 15 seconds, the filtered time error would be 5 seconds. If the raw time error was less than 15 seconds, the filtered time error will be zero. The notch filter value decreases as the aircraft approaches the runway. The depiction of the notch filter can help pilots better understand why ASTAR does not completely null their time error when they are far from the runway. Furthermore, as long as the time error is within the green bar, the commanded speed will be the same as the nominal profile speed.

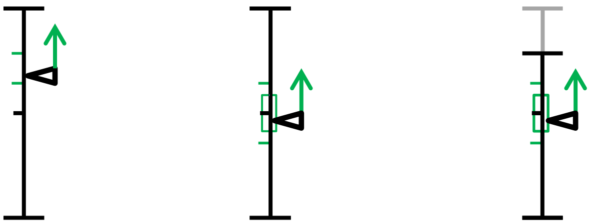


(a) Spacing Excess

(b) Controller Intervention Bound

(c) Speed Change Indication

(d) Indication of Suppressed Speed Change



(e) Indication of Time Error Rate of Change

(f) Notch Filter

(g) Complete Trend Indicator

Figure 5.2: Trend indicator developed by EID to help pilots build an accurate mental model of the ASTAR algorithm and to help the pilots understand why they were receiving particular speed changes

One of the challenges of creating the trend indicator shown in Figure 5.2 is that ASTAR does not generate or use the rate of change of the time error. The rate of change of the time error can be computed in one of two ways: the time error can be numerically differentiated, or the rate of change of the time error can be determined by examining the difference between the nominal ground speed and the actual ground speed. Numerical differentiation often amplifies noise, and filters intended to decrease the noise, such as the Savitzky–Golay smoothing filter, can cause a time delay; thus, the desired approach is to determine the rate of change of the time error using the difference between the nominal ground speed and actual ground speed. This approach can also be used to separate the rate of change of the time error into components of spacing aircraft performance, lead aircraft performance, and error caused by wind errors. The details of these calculations are shown in Appendix A. However, ASTAR periodically re-computes the trajectory due to updates to its wind model. When a trajectory update is completed, there can be a discrete jump in the time error, which causes the rate of change of the time error to become a large value for a short period of time. The effects of the trajectory regenerations are discussed in greater detail in Appendix B. Despite efforts of smoothing the discontinuities out using a first order low pass filter, moving average, and Savitzky–Golay smoothing filter, the jump discontinuities caused by trajectory regenerations caused undesirable display behavior. If a trend indicator similar to the one depicted in Figure 5.1 is used in the future, the ASTAR algorithm may need to be modified so that trajectory regenerations do not cause discontinuities in the time error.

The final spacing trend indicator (Figure 5.2, h) contains both rule and knowledge based information, and minimizes the need for internal representations. The rule based information shows the pilots their relationship to the excess error constraint and the controller intervention bound (if this feature is used), and notifies them when a speed change is suppressed. Furthermore, the trend indicator has various features that show the flightcrew the dynamics of the system. For instance, an arrow indicating the rate of change of the time error was added so that pilots can determine whether error was moving toward a speed increase or a speed decrease. Additionally, indication of the time error needed for a change in the commanded speed was added. With this indication, along with the arrow depicting the rate of change of the time error, pilots can predict a speed increase or decrease. Lastly, the notch filter value is shown and the gain scheduling is shown by the distance between the speed change indicators (the green lines), allowing pilots to see that the spacing algorithm becomes more sensitive to a given time error as the aircraft approaches the runway.

The previously discussed trend indicator was created using the requirement that it can be incorporated into current day flightdecks. There may be ways of better representing the system in future flightdecks. For instance, the spacing trend could be placed on a plot of the nominal profile speed to show pilots where scheduled profile speed decreases occur and to show them that the commanded speeds are simply deviations from the nominal profile. Additionally, a trend indicator could use depictions of aircraft moving closer to or farther from each other to indicate changes to the spacing interval. Since the work in this thesis is focused on a nearer term interface, these ideas are not investigated further.

5.3. Using the HTA to Determine Nominal Course of Behavior

The HTA developed in the previous chapter can be used to determine procedures for the IM operations. The procedures described below have many similarities to those described by RTCA in DO-328 [4]. The place where the procedures diverge from those that were previously described is the addition of a “nominal behavior” section that describes the behavior of ASTAR. The sections below describe the IM procedures that have been proposed as well as additions to the procedures.

5.3.1. Initialize IM Operation

IM initializes when ATC provides a clearance to the flightcrew. The method used to input the clearance into the system is not considered, as it will depend on the whether the clearance is provided by CPDLC or voice, as well as the equipage of the aircraft.

1. Review clearance (confirm the clearance is acceptable)
2. Input clearance parameters
3. Activate ASTAR, producing an initial commanded speed
4. Determine if the aircraft is capable of flying the initial commanded speed
    a. If the aircraft is able to fly the commanded speed is acceptable to the flightcrew, execute the IM operation
    b. If the aircraft is not able to match the commanded speed, reject the clearance and follow ATC directions

5.3.2. Conduct IM Operation

1. Monitor IM displays for speed changes and errors
2. If the aircraft transitions from RTA control to IM, notify ATC
3. If a speed change occurs match the new commanded speed

5.3.3. Amend Clearance

1. Review clearance amendment (confirm the clearance is acceptable)
2. Change amended parameters
3. Activate ASTAR, producing an initial commanded speed
4. Determine if the aircraft is capable of flying the initial commanded speed
    a. If the aircraft is able to fly the commanded speed is acceptable to the flightcrew, execute the IM operation
    b. If the aircraft is not able to match the commanded speed, reject the clearance and follow ATC directions

5.3.4. Suspend Clearance

1. If ATC instructs flightcrew to suspends clearance, suspend IM operations (should remove speed guidance)
2. Follow ATC instructions
3. If ATC instructs flightcrew to resume IM, they should resume IM speed guidance

5.3.5. Terminate Clearance

1. If the commanded speed is no longer acceptable, there is an ASTAR error and the time error exceeds the excess spacing bound
   a. Notify ATC that the operation is being terminated
   b. Fly the previous commanded speed until further instructions are received from ATC
   c. Follow ATC instructions
2. If ATC tells the flightcrew to terminate the spacing operation
   a. Follow ATC instructions

5.3.6. Nominal IM Behavior

In addition to the procedures from the HTA, rules from the WDA can be added to the procedures to notify the flightcrew what behavior to expect from ASTAR. This is a portion of the procedures that this thesis contributes to procedures proposed by the RTCA.

Speed change behavior:

1. If the time error is increasing, expect the commanded speed to increase
2. If the time error is decreasing, expect the commanded speed to decrease

3. If the time error is positive (arriving early), expect the commanded speed to be lower than the nominal profile speed
4. If the time error is negative (arriving late), expect the commanded speed to be higher than the nominal profile speed

ASTAR constraints

1. IM will provide speed commanded speeds no more that ±10% of the nominal profile speed from the nominal profile speed
2. As the aircraft approaches the runways, speed changes will become more sensitive to a given time error

5.4. Summary

This chapter discussed how the rules and constraints developed from the WDA and CTA can be turned into representations that show the dynamics of the system, and how the HTA developed in the previous chapter can be used to develop procedures.

CHAPTER 6

CONCLUSIONS

6.1. Summary

Interval Management (IM) has the potential to help increase runway throughput and enable aircraft to fly fuel efficient Optimized Profile Descents (OPDs) by allowing an aircraft to achieve a precise interval behind a lead aircraft. Numerous studies have shown that IM is able to provide its expected benefit in a varsity of circumstances. One implementation of IM that is being investigated at NASA Langley Research Center uses both a ground scheduling system operated by Air Traffic Control (ATC) and flightdeck avionics to provide speeds to the flightcrew to achieve a spacing interval that is designated by ATC.

A Human-In-The-Loop (HITL) experiment was conducted at NASA Langley with the purpose of investigating the use of IM to dependent parallel runways. This particular experiment only concentrated on the flightdeck portion of IM, and examined two control methods (RTA and IM) and three error sources (no error, offset error, and wind error). The results of the experiment determined that, overall, pilots found the spacing operation acceptable. However, there were cases where the large error sources caused less than acceptable behavior, which included too many speed changes within a short period of time, speed changes that forced pilots to reconfigure their flaps, and speed increases that occurred when pilots thought they should be decreasing their speed for landing. Furthermore, pilot comments indicated that pilots had an incorrect or incomplete understanding of how IM works. It is hypothesized that providing pilots with displays and procedures that act as an external mental model of IM will provide pilots with the information needed to better understand the relationships between the physical world and the commanded speeds. Thus, the objective of this thesis was to perform an HTA, CTA, and WDA to evaluate the procedures and interfaces that are being proposed for IM, and to use their insights to design interfaces and procedures.

Previous research has shown that HTA, CTA, and WDA can be used to design systems that support the operator. Furthermore, research has shown that these two methods can provide complementary information. Task analysis is the study of the tasks operators are expected to carry out, and is good at deriving training regimens, procedures, and interfaces that support task completion. Thus, task based interfaces often have high usability in nominal conditions. However, task based interfaces are limited to supporting behavior in anticipated circumstances. WDA uses knowledge of the constraints and dynamics of the work domain. Since WDA models the environment instead of particular tasks, it has been suggested that it can be used to develop interfaces that support operators during unanticipated circumstances. WDA can also provide operators with a deep and accurate knowledge of the system, resulting in increased understanding of changes to the system state caused by automation.

The information learned from the HITL was used to create a WDA, HTA, and CTA, which were used to examine IM from a systems perspective. The WDA was used to develop rules and constraints explaining the dynamics of the IM operation. The rules that were developed indicated that the rate of change of the time error could be used to determine whether the commanded speed would be increasing or decreasing. Furthermore, a number of constraints present in the IM system were identified.

An HTA was used to determine tasks that were required communication between ATC and the flightdeck, as well as tasks that required decision making. A CTA was used to describe the decision making process the flightcrew could take when determining whether or not the IM clearance and the IM commanded speeds are acceptable. Lastly, the rules that describe how ASTAR operates were associated with their corresponding tasks. Hypotheses were formed regarding how tasks affected the rules and constraints they were associated with, and conversely how the rules and constraints affected the tasks. Two potential interactions were discovered. First, there is a possibility that providing deep knowledge of the dynamics of the operation will cause pilots to skip some speed changes (such as a speed increase at an inopportune time). Secondly, there is the possibility that providing the flightcrew with the controller intervention point could cause undesirable behavior: pilots may either try to modify their speed away from the commanded speeds to avoid the conflict, or the flightcrew could attempt to contact ATC to cancel the operation just as ATC was trying to contact them.

The information from the WDA, HTA, and CTA was used to develop representations that have the potential to help the flightcrew obtain a more accurate mental model of how ASTAR works. It is hypothesized that supporting an accurate mental model could decrease frustration and increase the acceptability of the IM operation when less desirable speeds are commanded (such as the wind error and offset error used in the IMSPiDR experiment). The representations were created according to EID principals. Thus, the discussion was split into supporting skill, rule, and knowledge based behavior. It was determined that the displays used in IMSPiDR did a good job supporting skill and based behavior and most rule based behavior. However, there were rules of thumb regarding how the algorithm worked that were not supported by the IMSPiDR interfaces. Additionally, it was determined that the displays used in the IMSPiDR experiment did not support knowledge based behavior very well. Therefore, the rules, constraints, and dynamics of IM as derived from the WDA, were incorporated into a proposed trend indicator, and the procedures were examined relative to the HTA.

6.2. Contributions

The contributions from this thesis can be separated into contributions to the development of IM, and contributions to the combined use of HTA, CTA, and WDA to develop flightdeck displays and procedures.

The broad contribution of this thesis is the joint use of WDA, HTA, and CTA to examine procedures and interfaces for safety critical systems. This thesis demonstrated how a WDA can be used to understand the dynamics and constraints of a system. The dynamics and constraints can then be used to develop rules, which can be used to develop interfaces that provide users with a thorough understanding of the system. Furthermore, the rules that explain the dynamics and constraints of the system can be incorporated into the procedures to provide users with a secondary source of information on the system. An HTA can be used to define a nominal set of procedures, or a plan, that can be used to give a system structure; a CTA can be used to look at tasks that require a decision, and determine the information that the operator needs. This approach to designing interfaces and procedures is a deviation from the task based approach that is often used in aviation, and has the potential to provide pilots with a deeper understanding of the system without substantially increasing their cognitive load.

This thesis also provided new display and procedure ideas for the IM concept being developed at NASA Langley Research Center. The results of this thesis determined that the current flightdeck displays do not provide pilots with a deep understanding of how the IM automation works, and the pilots had difficulty predicting trends in the commanded speeds provided by the automation. By using an ecological design philosophy, important relationships and constraints were identified, and representations were developed to convey this information to pilots. While the results presented in this thesis are specific to the implementation of IM being developed at NASA, the philosophy and methodology of the interface design can be extended to other IM algorithms, and to many other aviation operations.

6.3. Further Research

Future research is needed to better understand the impact of EID displays in the flightdeck. Currently, many flightdeck displays are task based, with the emphasis placed on actions the flightcrew must accomplish. Furthermore, as the budgets of the major airlines continue to be restricted, fewer resources are allocated to training. At the same time, automation on the flightdeck continues to increase and become more complex. EID interfaces have the potential to provide pilots with fundamental understanding of automation on the flightdeck, allowing the flightcrew to gain a deep understanding of the system with minimal training. However, implementing EID interfaces requires a fundamental change in the way designers approach flightdeck design, and there is the potential that there could be unforeseen consequences.

For IM, further tests are needed to determine if the proposed interfaces will be a benefit to pilots. Within this thesis it was hypothesized that that the proposed interfaces would decrease pilot frustration and interruptions caused by IM by enabling better understanding of why speed changes were provided. The largest benefit is expected to occur when large errors are present or when unexpected circumstances occur.

APPENDIX A

Flightdeck Tasks and Associated Displays

Within this section, the flightdeck tasks that were determined in Chapter 5 are listed in Table A.1 along with the displays that are needed achieve each task. Furthermore, a checkmark was placed in the final column in Table A.1 if the interfaces that were listed were present in the Human-In-The-Loop (HITL) experiment that was described in Chapter 3. With the exception of the suspend function that was not used in the HITL experiment, all of the task based IM displays were present.

Table A.1: Flightdeck tasks and associated displays

Task	Task Description	Displays Needed for Task	In HITL Interface
1.1.1.	Receive clearance	- Voice communications or CPDLC	✓
1.1.2.	Review clearance	- Clearance text (if given by CPDLC) or voice communication	✓
1.1.3.	Input clearance parameters	- Method of loading clearance information into onboard automation	✓
1.2.1.	Activate ASTAR	- Activate button	✓
1.2.2.	Compute cmd. speed	- Automation	✓
1.3.1.	Determine clearance parameters are acceptable	- Clearance text	✓
1.3.2.	Determine if initial speed is acceptable	- Initial commanded speed - Aircraft speed constraints - Flap speed limits - Regulatory limits	✓ ✓ ✓ ✓
1.4.	Accept clearance and execute ASTAR	- Method of sending accept message to ATC - Execute button	✓ ✓
1.5.	Reject clearance	- Method of sending reject message to ATC - Method of clearing IM information that was input into automation	✓ ✓

Table A.1: Flightdeck tasks and associated displays (Continued)

2.2.1.	Monitor for cmd. speed changes	- Indication of a new commanded speed	✓
2.1.2.	Monitor for IM errors	- Indications that aircraft are not flying their expected profile - Indication that the spacing goal in the IM clearance is not reachable - Indication of hardware failures	✓ ✓ ✓
2.1.2.	Ensure commanded speed remains acceptable	- Commanded speed - Aircraft speed constraints - Flap speed limits - Regulatory limits	✓ ✓ ✓ ✓
2.2.	Notify ATC that AC is IM spacing	- Indication of when aircraft is spacing off its lead aircraft	✓
2.3.	Update speed to match new cmd. speed	- Method of inputting commanded speed into aircraft or automation	✓
2.4.	Use AC controls to achieve cmd. speed	- Throttle - Speedbrake - Indication of deviation from commanded speed	✓ ✓ ✓
2.5.1.	Receive amended clearance	- Voice communications or CPDLC	✓
2.5.2.	Input amended parameters	- Method of loading clearance information into onboard automation	✓
2.5.3.	Determine if new parameters are reasonable	- Initial commanded speed - Aircraft speed constraints - Flap speed limits - Regulatory limits	✓ ✓ ✓ ✓
2.5.4.	Is the new cmd. Speed acceptable	- Commanded speed - Aircraft speed constraints	✓ ✓
2.5.5.	Accept and execute amendment	- Execute button	✓
2.6.1.	Receive clearance suspension	- Voice communications - Suspend button (that removes IM symbology from displays)	✓
2.6.2.	Stop flying IM profile	- Aircraft controls	✓
2.6.3.	Follow ATC commands	- ATC commands via voice clearance or CPDLC	✓
2.6.4.	Resume IM operation	- Button that resumes IM (should place IM symbology back on aircraft displays)	

Table A.1: Flightdeck tasks and associated displays (Continued)

3.1.	Automatic termination	- Automation must know aircraft has reached achieve-by point	✓
3.2.1.	Notify ATC of termination	- Voice or CPDLC communications with ATC	✓
3.2.2.	Fly previous commanded speed	- Indication of previous commanded speed	✓
3.2.3.	Follow ATC instructions	- ATC instructions via CPDLC or voice	✓

APPENDIX B

Designing the Spacing Trend Indicator

In Chapter 5, a trend indicator was described that has the potential to help flight crews better understand the commanded speeds generated by ASTAR. This appendix discusses some of the challenges with implementing the trend indicator.

The trend indicator discussed in Chapter 5 contained the rate of change of the time error. Since ASTAR calculates the time error based on estimates of the Time-To-Go (TTG) to the achieve-by point for both the spacing aircraft and lead aircraft, it does not produce a value indicating the rate of change of the time error. Thus, it must it calculated. One way of calculating the rate of change of the time error is to take a numerical derivative of the actual time error. A common method of taking the numerical derivative of a noisy signal is to use a Savitzky-Golay smoothing filter, which performs local polynomial regression to both smooth data and determine the derivative. Another approach is to use both the spacing and lead aircrafts' deviations from their predicted ground speed. If both the spacing aircraft and lead aircraft begin the spacing operation with zero time error and maintain their predicted ground speeds throughout the entire flight, they will arrive at the runway with zero time error. If either of the aircraft deviates from their predicted groundspeed, their time error will change. Deviations from the predicted ground speed can be caused by a wind error, a commanded speed change (designed to decrease the time error), or a pilot who is not following the speeds commanded by ASTAR.

The following equations can be used to determine the rate of change of the time error. Equation 1 provides rate of change of the timer error of the spacing aircraft using the Distance-To-Go (DTG) of the spacing aircraft, as well as the Ground Speed (GS) of the spacing and its predicted GS. Equation 2 describes the rate of change of the time error caused by the lead aircraft using its DTG, GS, and profile GS.

$$\vartriangle \tau_S(i) = \frac{DTG_S(i-1) - DTG_S(i)}{GS_{S_{actual}}(i)} - \frac{DTG_S(i-1) - DTG_S(i)}{GS_{S_{profile}}(i)} \tag{1}$$

$$\vartriangle \tau_L(i) = \frac{DTG_L(i-1) - DTG_L(i)}{GS_{L_{actual}}(i)} - \frac{DTG_L(i-1) - DTG_L(i)}{GS_{L_{profile}}(i)} \tag{2}$$

$$\vartriangle \tau_T(i) = \vartriangle \tau_S(i) - \vartriangle \tau_L(i) \tag{3}$$

Next, these equations were used to compute the rate of change of the time error, using data from the IMSPiDR experiment. Using this method creates smooth signals for the rate of change of the time error. However, when the rate of change of the time error was integrated, it did not align with the actual unfiltered time error produced by ASTAR. This occurred because the actual unfiltered time error contains discontinuities caused by ASTAR trajectory updates. These discontinuities are not captured in the equations listed above, and cause a discrepancy between the actual unfiltered time error and the time error found by integrating the rate of change of the time error that was calculated.

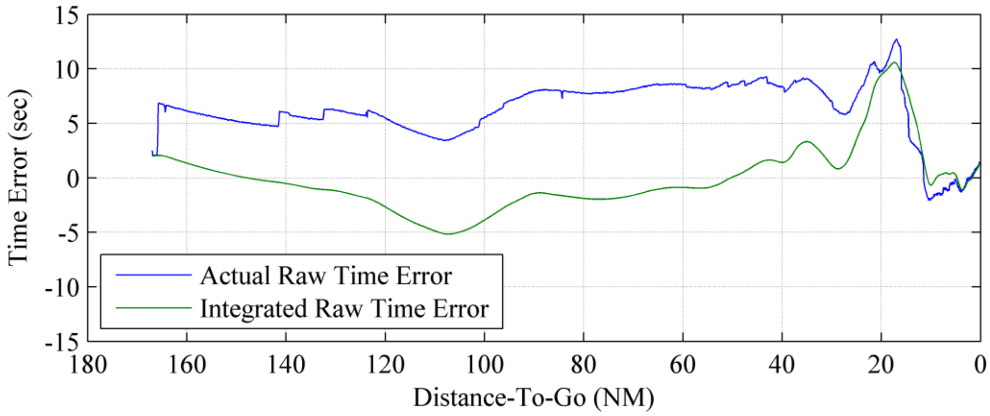


Figure B.1: Time error and rate of change of the time error when trajectory updates were not included

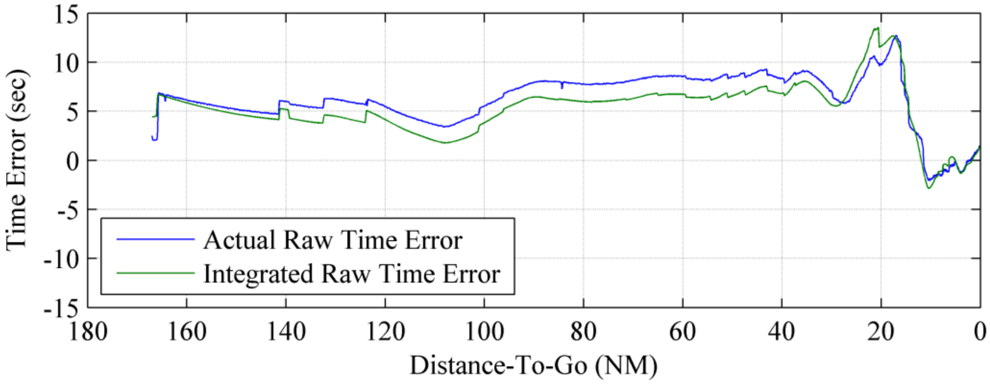


Figure B.2:Time error and rate of change of the time error when trajectory updates were included

Including the discontinuities caused by trajectory updates helped align the unfiltered time error with the value determined by integrating the rate of change of the error. However, the rate of change of the time error was not a smooth continuous signal, which causes problems when trying to drive a continuous display. Various filtering and averaging techniques were implemented in an attempt to lessen the impact of the discontinuities, including: a Savitzky-Golay smoothing filter, and a low pass filter. These methods did not reduce the discontinuities sufficiently, provided too much time delay, or smoothed the actual signal too much.

If there is a desire to implement this trend indicator, ASTAR may need a method of conducting trajectory updates that do not result in discontinuities in the time error signal.

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