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Evaluating NextGen Closely Spaced Parallel Operations Concepts with Validated Human Performance Models: Scenario Development and Results

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April 2013

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Acronyms and Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast (ADS-B) In/Out
AGL	Above ground level (height in feet above the ground)
ANSP	Air Navigation Service Provider
ATC	Air traffic control
ATM	Air Traffic Management
CA	Captain (pilot in left seat)
CSPO	Closely Spaced Parallel Operations
CONOPS	Concept of Operations
DFW	Dallas-Fort Worth airport
EICAS	Engine indication and crew alerting system (cockpit display)
EMM	Electronic moving map (cockpit display)
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FAF	Final approach fix
FMS	Flight Management System
FO	First officer (pilot in right seat)
GPS	Global Positioning System
HPM	Human Performance Model
HITL	Human in the loop
ILS	Instrument landing system
IFR	Instrument Flight Rules
JPDO	Joint Planning and Development Office
MCP	Mode control panel
MIDAS	Man-machine Integration Design and Analysis System
MSL	mean sea level (height in feet above the global mean sea level)
NASA	National Aeronautics and Space Administration
NAS	National Airspace System
Nav	navigation display (cockpit display)
NextGen	Next Generation Air Transportation System
OTW	Out the window
PF	pilot flying (either by hand or using the auto-pilot controls)
PM	pilot not flying
PFD	Primary Flight Display
RNP	Required Navigation Performance
RNAV	Area Navigation
SA	situation awareness
SEEV	SA model (salience, effort, expectancy, value)
SFO	San Francisco airport
SOIA	simultaneous offset instrument approach
TACEK	Terminal Automation
TOGA	Take-off/Go-around
TBO	Trajectory-based Operations
VCSPA	Very Closely Spaced Parallel Approach
VMC	Visual Meteorological Conditions

Executive Summary

To meet the expected increases in air traffic demands, the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and their industry and academic partners are researching and developing Next Generation Air Transportation System (NextGen) concepts. It is expected that these NextGen concepts will include substantial increases to the data available to pilots on the flight deck (e.g., weather, wake, traffic trajectory projections, etc.) to support more precise and closely coordinated operations (e.g., self-separation, RNAV/RNP, and closely spaced parallel operations, CSPO). These NextGen procedures and operations, along with the pilots' roles and responsibilities and information requirements, must be designed with consideration of the pilots' capabilities and limitations. Failure to do so will leave the pilots, and thus the entire aviation system, vulnerable if errors are made.

The objectives of the current research were to develop valid human performance models (HPMs) of approach and land operations; use these models to evaluate the impact of NextGen Closely Spaced Parallel Operations (CSPO) on pilot performance; and draw conclusions regarding flight deck displays and pilot roles and responsibilities for NextGen CSPO concepts. This research represents the results of a two-year effort that was accomplished in two phases. In phase 1 (2010) CSPO models were developed and validated (see below). In the second phase (reported in this document), the phase 1 models were augmented to evaluate NextGen operations and flight deck guidelines were developed.

<u>Phase 1.</u> Using NASA's Man-machine Integration Design and Analysis System v5 (MIDAS v5), a high-fidelity model of a two-pilot commercial crew flying current-day area navigation (RNAV) approach and land operations was developed and validated using a methodical, multi-dimensional approach. The model inputs, including the task trace and input parameters, were validated using focus group sessions comprised of a total of eight commercial pilots with glass-cockpit aircraft and RNAV flying experience. The pilot-centric, scenario-based, cognitive walkthrough approach captured the context of operations from 10,000 ft to Touchdown and enabled pilots to assess the modeled tasks and identify tasks that were missing, or in the wrong sequence. The pilots also completed quantitative rating scales, which were used to validate the model input parameters for workload and visual attention. The model was refined based on the results of this input validation process. Next, the model outputs, workload and visual attention, of the refined model were statistically compared to existing human-in-the-loop (HITL) data. The workload model output correlated with a comparable HITL study with r^2 of .54 for overall workload. The individual workload dimensions (visual, auditory, cognitive, psychomotor) also correlated positively with the HITL study with r^2 ranging from .55 to .94. Visual percent dwell time correlated with three independent HITL studies with $r^2 = .99$. These validation results provide confidence that the model validly represents pilot performance. The summary of the model development and validation effort can be found in:

> *Gore, B.F., Hooey, B.L., Socash, C.M., Haan, N., Mahlstedt, E., Bakowski, D.L., Gacy, A.M., Wickens, C.D., Gosakan, M., and Foyle, D.C. (2011). Evaluating NextGen closely spaced parallel operations concepts with validated human performance models. HCSL Technical Report (HCSL-11-01). Human Centered Systems Laboratory (HCSL), Moffett Field, CA: NASA Ames Research Center.*

<u>Phase 2:</u> The MIDAS CSPO scenarios were then used to evaluate proposed changes to flight deck technologies, pilot procedures, operations, and roles and responsibilities to support the development of the NextGen CSPO technologies and concepts and to explore "what-if" scenarios about the impact of the CSPO concept on pilot performance in both nominal and off-nominal scenarios. Full

details including model assumptions, model implementation, scenarios, and results can be found in the current report; while the entire task network model and the reverse engineered model that was encoded in MIDAS can be found in Gore, Hooey, Haan, Socash, Mahlstedt, and Foyle (2013). A subset of the current report was used to analyze pilot performance measures, including time required to complete tasks, workload, scan patterns and responses to off-nominal events to develop guidelines regarding the flight deck requirements necessary to support NextGen CSPO concepts. The guidelines report (Hooey, Gore, Mahlstedt & Foyle, 2013) summarizes the main findings, operational implications, and future research requirements for the following issues related to blunder detection, wake monitoring and spacing management on the flight deck:

I. *Operational Concept*
   a. *Aircraft separation responsibility (ATC vs. Flight Deck)*
II. *Wake and Blunder Detection Displays*
   a. *Wake and blunder avionics requirements*
   b. *Wake display format (predicted vs. real-time)*
   c. *Wake display location (PFD, Nav Display, or Both)*
   d. *Blunder alert styles (One-stage vs. two-stage alerts)*
III. *Spacing Management Automation*
   a. *Spacing management automation (Current vs. NextGen)*
   b. *Spacing management display locations (PFD, Nav Display, or Both)*

The CSPO guidelines can be found in both the current report and in the following companion report:

> *Hooey, B.L., Gore, B.F., Mahlstedt, E.A., & Foyle, D.C. (2013). Evaluating NextGen Closely Space Parallel Operations Concepts with validated human performance models: Flight deck guidelines. HCSL Technical Report (HCSL-13-01). Human Centered Systems Laboratory (HCSL), Moffett Field, CA: NASA Ames Research Center.*

In summary, a methodical and comprehensive process was undertaken to develop and validate models of current-day RNAV and NextGen CSPO operations. The models were extended to examine "what-if" off-nominal scenarios. The off-nominal scenarios were then extended to examine candidate roles and responsibilities that could be expected to occur in full implementation of the NextGen. The findings yielded seven primary guidelines and implications for candidate NextGen roles and responsibilities and flight deck displays and automation.

1. Introduction

The National Airspace System (NAS) in the United States is currently being redesigned because it is anticipated that the current air traffic control (ATC) system will not be able to manage the predicted two to three times growth in air traffic in the NAS (JPDO, 2009). To meet the expected increases in air traffic demands, the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) and their industry and academic partners are researching and developing Next Generation Air Transportation System (NextGen) concepts to alleviate bottlenecks caused by the anticipated growth.

One such bottleneck is anticipated to be in the decent, approach, and landing phases of flight. Closely Spaced Parallel Operations (CSPO) are expected to enable paired approaches to minimum runway spacing in instrument meteorological conditions (IMC) while maintaining an acceptable level of risk (Cox, 2010). The current requirement for landings in IMC is at least 4,300 ft of lateral runway spacing (as close as 3,000 ft for runways with a Precision Runway Monitor), whereas operations in visual meteorological conditions (VMC) require lateral runway spacing to be equal to or greater than 750 ft. It is feasible for aircraft to perform both arrival and departure operations in IMC using VMC parallel separation standards as advanced navigation technology, sophisticated wake avoidance algorithms, advanced flight management systems, and augmented flight deck displays become more widely available (Rutishauser et al., 2003). A range of CSPO concepts exist. Examples include the Simplified Aircraft-based Paired Approach (SAPA; Guerreiro et al., 2010), and the Very Closely Spaced Parallel Approach (VCSPA) concept (Verma et al., 2008) using Terminal Area Capacity Enhancement Technology (TACEC; Trott et al., 2007). These build off of earlier concepts including Airborne Information for Lateral Spacing (AILS; Abbott & Elliott, 2001), MITRE's paired approach concept (Bone, 2000), and Simultaneous Offset Instrument Approaches (SOIA), in use at several airports today.

The VCSPA concept was the basis for the present human performance model. In this concept, aircraft are paired by ATC approximately 30 nm from the runway threshold. Pairs are based on aircraft performance, arrival direction, and aircraft weight. The trailing aircraft is slewed 6 deg from runway (Figure 1). At approximately 12 to 17 nm from runway threshold, ATC initiates self-separation operations by datalink message, and the pilot engages the speed-coupling automation mode on the mode control panel (MCP). Once this action is taken, the flight mode annunciator (FMA) shows C–SPD, C-LNAV, C-VNAV. The trailing aircraft maintains 12 sec spacing behind the lead aircraft using speed-algorithms and advanced FMS automation. At approximately 2 nm from the runway threshold, or 1,100 ft, the trailing aircraft then aligns with the runway and is parallel with the lead aircraft.

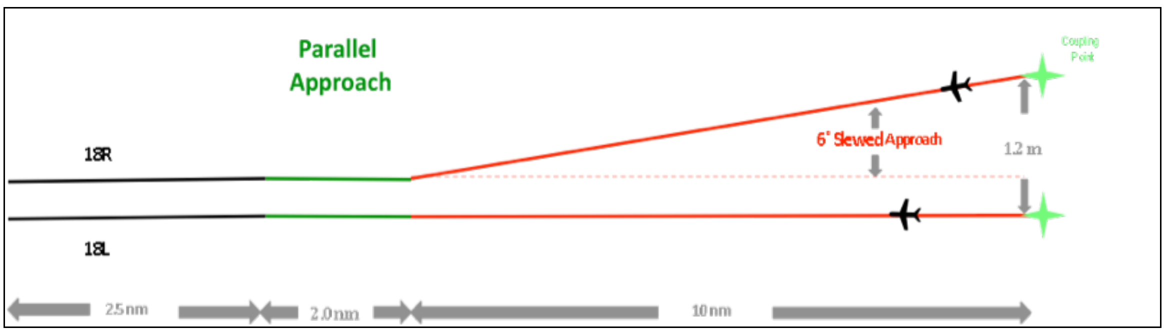

Figure 1. Closely Spaced Parallel Operations (CSPO) concept

In the highly automated CSPO environment envisioned by NextGen, a paradigm shift might be required that would transfer the responsibility for separation from ATC, as is currently the case, to the flight deck. As flight decks are modified to accommodate the new suite of automation tools and displays required to support this, research must be conducted to ensure that they are designed and implemented in a safe manner without leaving pilots vulnerable to errors or excess workload. These NextGen procedures and operations, along with the pilots' roles and responsibilities must be designed with consideration of the pilots' capabilities. Failure to do so will leave the pilots, and thus the entire aviation system, vulnerable to performance inefficiencies caused by error. This is a particular concern in the CSPO environment where wake threats become an important issue for trailing aircraft on approach and landing operations.

1.1 Using HPMs to Evaluate NextGen Concepts

There are large challenges associated with evaluating novel NextGen concepts such as CSPO and changes to pilot / ATC roles and responsibilities. Because NextGen concepts are still in the early stages of the design lifecycle, operator roles and tasks are often not well defined, and NextGen technologies have not necessarily reached a level of sufficient maturity to allow for physical prototypes. These factors limit the feasibility of full-mission human-in-the-loop (HITL) simulations. However, human performance models (HPMs) can be used to make meaningful contributions early in the design lifecycle, particularly for concepts that have high consequences associated with their failure. Models can be advantageous because they are cost effective, and eliminate concerns often associated with HITL testing of new concepts such as novelty and training effects. Furthermore, models are advantageous as compared to HITL simulations where you have to build physical prototypes because HPMs represent the location and nature of information symbolically (i.e., one can classify flight deck information as text or symbol, without defining the exact text phraseology or designing the symbol) and therefore allow rapid prototypes of concepts to be generated and tested early in the design phase. One such HPM tool, the Man-machine Integration Design and Analysis System (MIDAS), is discussed next.

1.2 The Man-Machine Integration Design and Analysis System

NASA's MIDAS is a dynamic, integrated HPM that facilitates the design, visualization, and computational evaluation of complex man–machine system concepts in simulated operational environments (Gore, 2008). MIDAS symbolically represents many mechanisms that underlie and cause human behavior including the manner that the operator receives/detects information from an environment, comprehends and registers this information in a memory store, decides on a response, and responds to the information within the context of operational rules and human performance capacities. MIDAS combines these symbolic representations of cognition with graphical equipment prototyping, dynamic simulation, and procedures/tasks to support quantitative predictions of human-system effectiveness, and improve the design of crew stations and their associated operating procedures. MIDAS provides an easy to use and cost-effective means to conduct experiments that explore "what-if" questions about domains of interest.

2. A Process for Evaluating NextGen Concepts using HPMs

One challenge associated with developing valid models of NextGen concepts is the lack of HITL data with which to validate the models. In this paper we propose a candidate process for developing and validating HPMs for the evaluation of NextGen concepts. The process includes four steps: 1) Develop a baseline (current-day) model; 2) Validate the baseline (current-day) model; 3) Extend the baseline scenario to NextGen based on empirical input from domain experts; and 4) Conduct iterative what-if scenarios to explore early design concepts. This process addresses the validation challenge by first developing models of known, current-day, operations, which are well-defined and proceduralized, and for which HITL data exist to enable validation. Then, the validated model platform is modified by integrating assumptions about likely NextGen changes that will be made to the flight deck equipage and pilot tasks (JPDO, 2009). Confidence is attained that the validity of the model is preserved through the documentation of assumptions and through the small iterative model changes to the validated model. This process, as applied to the CSPO concept, is discussed next.

2.1 Develop the Baseline (Current-Day) Model

A MIDAS v5 high-fidelity model of a two-pilot commercial crew flying current-day area navigation (RNAV) approach and landing operations was developed using a methodical, multi-dimensional approach (Gore et al., 2011). The model represented a Boeing 777 flying from 10,000 ft to touchdown at Dallas-Fort Worth (DFW) airport. Table 1 lists all aircraft controls that were modeled and Table 2 lists the cockpit displays and windows used by the model for visual fixations.

Table 1. Boeing 777 flight deck controls included in the model

Flight deck controls	
Tiller	Auto-brake knob
Yoke	MCP altitude control
Rudder pedals (and brakes)	Flap lever
Throttles	Radio tuning panel
Speed brake lever	Radio transmit button

Table 2. Boeing 777 flight deck displays and windows included in the model

Flight deck displays	
Air Speed	Engine Systems
Ground Speed	Cabin Systems
Pitch	Paper Chart
Bank	MCP
Angle of Attack	CDU
Vertical Speed	Headset (internal and external)
Altitude	Left window
Heading (PFD)	Left-front window
Route	Right-front window
Heading (Nav)	Right window
Traffic	
Terrain	

Figure 2 presents a pictorial representation of the areas of interest on the instruments used by the crew for visual fixations and control actions in the simulations:

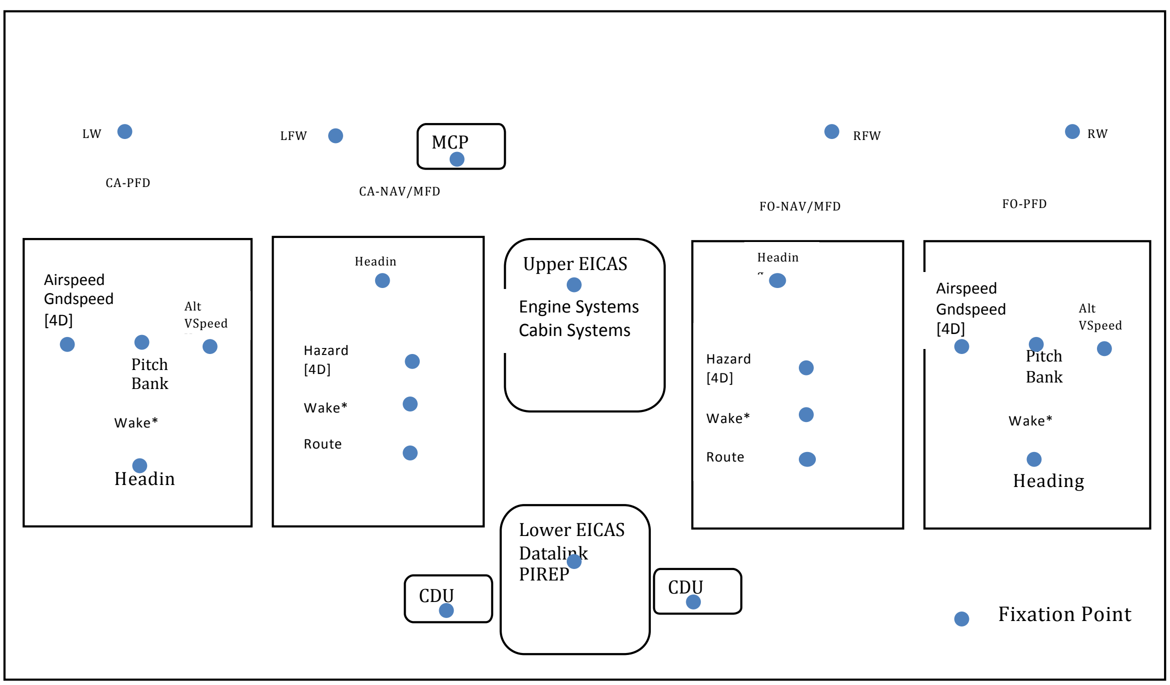

Figure 2. Flight deck layout

*Note: Datalink, wake, and 4D displays were used in the NextGen scenarios, but not included in the current-day (baseline) scenario.

The modeled scenario began with the aircraft at an altitude of 10,000 ft and 30 nm from the runway threshold (see Figure 3). The cloud ceiling was 800 ft, with a decision height (DH) of 650 ft at which point the modeled pilots disconnected the autopilot and manually flew the aircraft to touchdown. The model assumed that the "pilot flying" (PF) was in the cockpit's left seat and the "pilot monitoring" (PM) was in the right seat. The model scenario included communications with DFW Regional Approach Control, tower, and ground control, as well as intra-cockpit communications. In total, over 970 pilot tasks were included in the model.

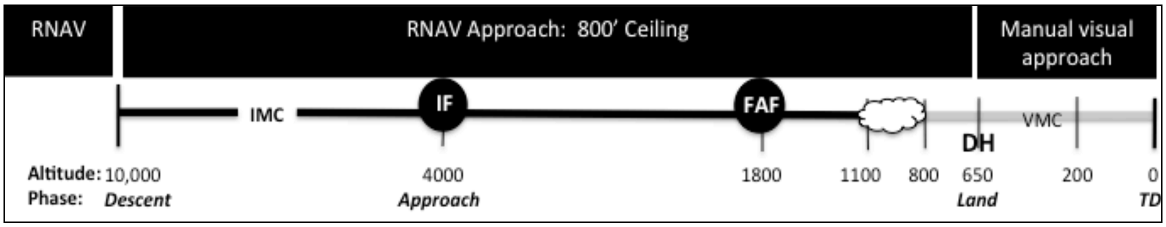

Figure 3. Baseline Current-Day RNAV model of approach and landing
Notes: DH = Decision Height; FAF = Final Approach Fix; IF = Initial Fix; IMC Instrument Meteorological Conditions; RNAV = Area Navigation; TD = touchdown; VMC = Visual Meteorological Conditions

A task network model architecture such as the one embedded in MIDAS contains top level tasks (e.g., land) that are subsequently decomposed into finer-grained tasks, generally to the button-press level for physical control input tasks, scan fixation points for the visual system, and verbal strings for the vocal communication output. The tasks in the network are then tied to a set of behavioral primitives. These tasks then wait for release conditions to be satisfied by the environment, the operators, the controls, or the displays. The behavioral tasks in MIDAS are termed the operator primitives. The task network model illustrated in Figure 4 is a subset of the task network model, a snapshot of the flight deck's flap-setting procedure required when landing the aircraft in the simulation. The full set of task network models is available in Gore, Hooey, Haan, Socash, Mahlstedt, and Foyle (2013).

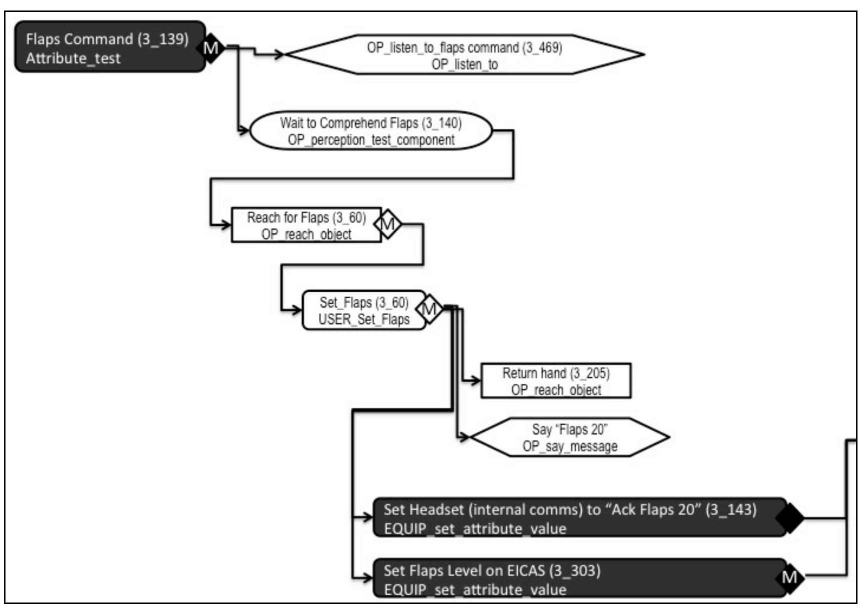

Figure 4. Task network model implementation of a set flaps sequence

2.2 Validate the Baseline (Current-Day) Model

The model inputs, including the task trace and input parameters, were validated using focus group sessions comprised of a total of eight commercial pilots with glass-cockpit aircraft and RNAV flying experience. The pilot-centric, scenario-based cognitive walkthrough approach captured the context of operations from 10,000 ft to touchdown and enabled pilots to assess the modeled tasks and identify tasks that were missing, or in the wrong sequence. Out of 74 tasks in the MIDAS RNAV application presented to the focus group pilots, 12 tasks were identified that should be removed, reordered, or added. The pilots also completed quantitative rating scales, which were used to validate the model input parameters for workload and visual attention. Thirty-nine tasks were rated on the visual, auditory, cognitive, and motor workload dimensions (as relevant for the task). The workload of four of the pilot tasks was modified and three new primitives were created based on the pilots' ratings. The model was refined based on the results of this input validation process. Next the model outputs, workload and visual attention, of the refined model were statistically compared to existing HITL data (Hüttig, Anders, & Tautz, 1999; Mumaw, Sarter & Wickens, 2001; Anders, 2001; Hooey & Foyle, 2009). The workload model output correlated (r^2=.54) along the overall workload dimension. The individual workload dimensions also correlated positively with the HITL study (r^2=.55 to .94). Visual scan time correlated with three HITL studies (r^2 = .99). These results provide confidence that the model validly represents pilot performance. The full validation process and results are presented in Gore, Hooey, Socash, Haan…, Foyle, (2011).

2.3 Extend Validated Model to CSPO Scenarios

The validated RNAV model was modified to reflect the CSPO concept based on assumptions about changes to: 1) Flight deck equipage; and, 2) Flight crew tasks. The flight deck equipage (as presented in Table 2) was modified to include NextGen functions including data communications (DataComm), wake depctions and alerts on the PFD and/or Nav Dislay, and speed maintenance and spacing management displays on the PFD and Nav Display.

Two models were developed: 1) CSPO – 800 ft cloud ceiling and 2) CSPO – 200 ft cloud ceiling. The first model scenario (CSPO – 800 ft ceiling) maintained the assumptions of the current-day Simultaneous Offset Instrument Approaches (SOIAs) approach landing minima, specifically, a cloud ceiling of 800 ft and a DH of 650 ft (see Figure 5). The assumptions were made based on interviews with NextGen concept developers and scenario-based focus groups with pilots experienced with current-day Simultaneous Offset Instrument Approaches (SOIAs). This model scenario was generated and verified with domain experts. The full task network model can be found in Gore, Hooey, Haan, Socash, Mahlstedt, & Foyle (2013).

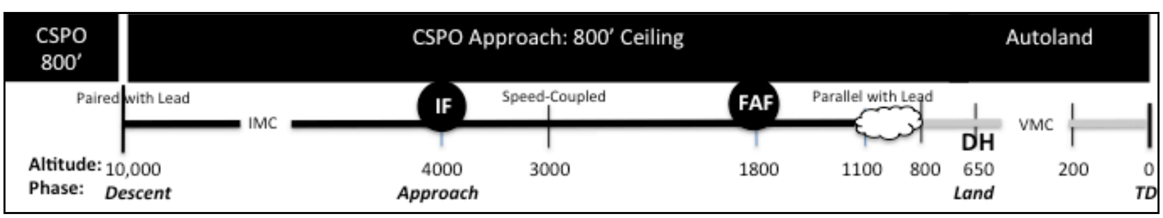

Figure 5. CSPO 800 ft ceiling scenario timeline

Notes: IF = Initial Fix, FAF = Final Approach Fix, DH = Decision Height, IMC = Instrument Meteorological Conditions, VMC = Visual Meteorological Conditions, TD = Touchdown

The second model scenario (CSPO – 200 ft ceiling) assumed an operational environment consistent with NextGen goals of reduced landing minima, specifically, a cloud ceiling of 200 ft and a DH of 100 ft (see Figure 6). The assumptions were made based on interviews with NextGen concept developers and scenario-based focus groups with pilots experienced with current-day Simultaneous

Offset Instrument Approaches (SOIAs), which are similar to CSPO but conducted in VFR conditions and with larger runway separations.

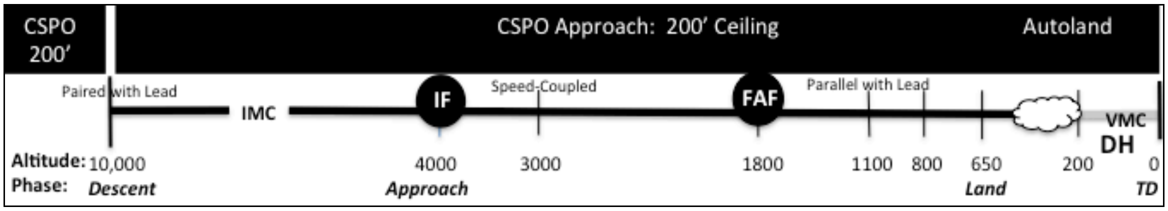

Figure 6. CSPO 200 ft. ceiling scenario timeline

Notes: IF = Initial Fix, FAF = Final Approach Fix, DH = Decision Height, IMC = Instrument Meteorological Conditions, VMC = Visual Meteorological Conditions, TD = Touchdown

In order to ensure the verifiability and validity of the CSPO model, the specific CSPO task changes and input parameters were validated using the same pilot focus group sessions described previously. In the focus group sessions, after the pilots completed the task trace and input parameter rating scales for the RNAV model, the CSPO concept was introduced. The pilots were briefed on the goals of NextGen, expected changes to flight deck equipage, and pilot procedures. Examples of the wake displays on both the PFD and Nav Display and the visual and auditory wake warnings and alerts were presented. A video of two pilots completing CSPO procedures from a HITL simulation (Verma et al., 2008) was also presented. Pilots completed the task trace and input parameter rating scales for the new tasks of the CSPO model.

2.4 Conduct "What-if" Evaluations

The validated CSPO model was then exercised to explore a number of CSPO design concepts including varying the flight crew task allocation, pilot-ATC roles and responsibilities, and the format and location of wake and spacing information. In total, 26 model-based scenario manipulations were completed. Analyses of pilot performance measures, including time required to complete tasks, pilot workload, pilot scan patterns, and response times to off-nominal events were used to draw conclusions and develop guidelines regarding the information requirements necessary to support NextGen CSPO concepts

3. CSPO Concept and Technology Model Evaluations

In this section, results of the CSPO concept and technology evaluations are presented. The validated CSPO models (Gore et al., 2011) were augmented to produce three scenarios described below. The three model scenarios were the following: 1) **Crew Roles and Responsibility model**, which manipulated the crew responsibilities *within the cockpit;* where PF and PM roles were shifted from a shared task allocation to a divided task allocation required to manage NextGen technologies and displays; 2) **Separation-responsibility model**, which manipulated whether ATC or pilots were responsible for safe separation between aircraft and evaluated the flight deck equipment to support safe separation; and, 3) **Information Requirements model,** which evaluated the impact of (i) wake information type (predicted versus real-time), (ii) the level of speed-management automation (current automation vs. NextGen automation) and (iii) the placement of the speed/spacing management information (PFD vs. Nav vs. Nav+PFD) on pilot flight performance.

3.1 Evaluation of NextGen Crew Roles and Responsibilities

The *crew roles and responsibilities* model scenario manipulated the responsibilities of the Pilot Flying (PF) and Pilot Monitoring (PM) in a NextGen operational environment. The scenario adjusted the validated NextGen CSPO models (Gore et al., 2011) to shift the PF and PM roles from current-day shared task allocation, in which both pilots similarly prioritize the tasks of Aviate, Separate, Navigate, Communicate, and Systems to a divided task allocation, in which the PF was responsible mostly for aviating, whereas the PM was responsible mostly for separation and navigation. This shift in responsibility would therefore result in the PF being responsible for the displays required to aviate (PFD and OTW in clear visibility) while the PM would be responsible for monitoring wake and traffic (primarily located on the Nav Display, but also OTW depending on altitude and visibility). The validated model was recaptured with these adjustments.

The PF and PM task importance weightings were adjusted in the respective phase of flight given the operator's role in the validated model. These adjustments were applied across all of the flight contexts (descent, approach, and land). A high-level characterization of the changes to the PF and the PM can be found in Table 3.

Table 3. High level overview of task allocation to PF and PM in the CSPO model.

PF Priority	PM Priority
Aviate: High	Aviate: Low
Separate: Low	Separate: High
Navigate: Low	Navigate: High

This first manipulation required that a series of adjustments be made to the information that the operator samples. All adjustments were made to the path: Operator > Context > Scenario > Flight Rule (*e.g., CA > Descent > C800 > Aviate)* as illustrated in Figure 7.

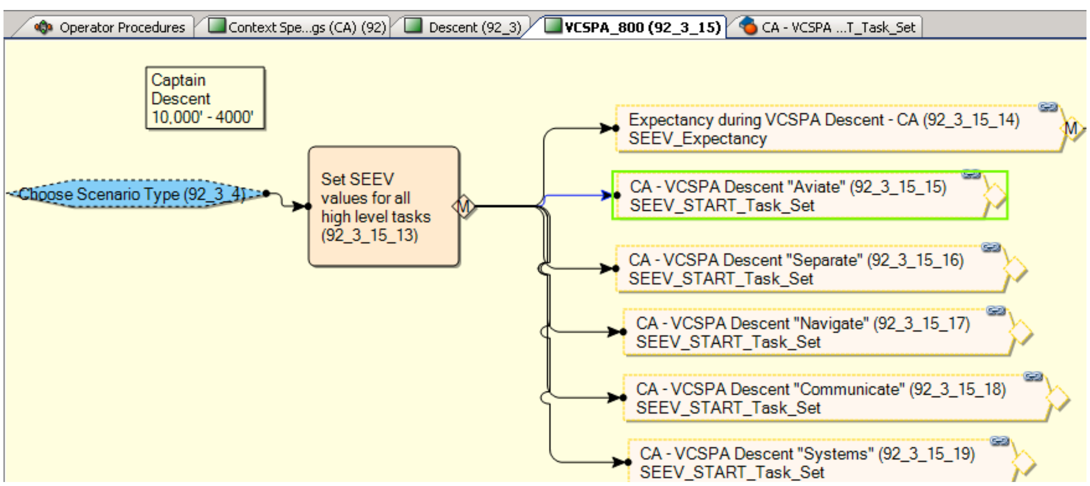

Figure 7. Model adjustments made to the information that the operator samples based on shared and divided task allocations.

Figure 8 illustrates how task importance was manipulated in the MIDAS software. As illustrated in Figure 8, the possible values were None, Low, Moderate, or High.

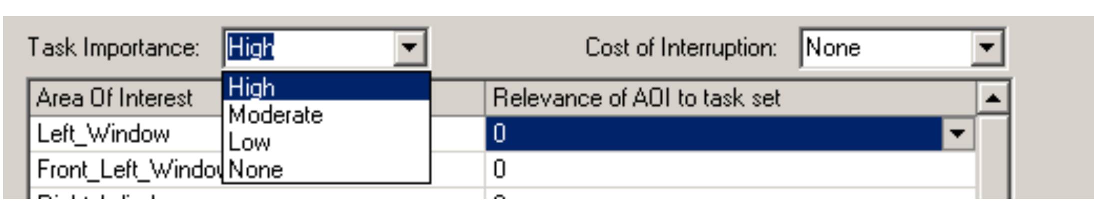

Figure 8. Manipulating task importance in the MIDAS model

The tasks completed by the modeled pilots remained consistent within the scenario but the weightings of the importance of information were manipulated to reflect the differences in the operator role and responsibilities from current-day to NextGen operations.

3.1.1 Crew Roles and Responsibilities Results

Ten Monte Carlo simulation model runs were generated to evaluate the *crew roles and responsibility* through the output of: (a) Visual Scan (Overall and by Flight Phase), (b) Workload (by Channel and by Flight Phase), and (c) Response Time to a Required Navigation Performance (RNP) Alert, a measure of attention distribution across the cockpit. The RNP alert is one of the four most likely off-nominal events in the NextGen approach and land operations (see Gore, Hooey, Wickens, Sebok…Bzostek, 2009 for a complete analysis of the responses to off-nominal events in NextGen). Only the CSPO 200ft condition is reported here.

3.1.1.1 Visual Scan

Figure 9 (left) presents the pilots' visual scan across three main regions (PFD, Nav Display, OTW), or areas of interest (AOI), under both the shared- and divided task allocation conditions. There was a significant interaction between the operators' role on the flight deck (whether they were PM or PF) and the task allocation (shared or divided) ($F(1,18)=53.1$ $p<.05$).

It can be seen that, in the shared task allocation, the PF and the PM spent approximately the same amount of time monitoring the PFD, the Nav Display, and OTW, consistent with shared roles in the cockpit (both PF and PM looked at the same information). In the divided task allocation scenario, however, the data reveal that the PF's scan increased on the PFD and OTW, and decreased on the Nav Display AOI compared to the shared task allocation. Conversely, the PM (Figure 9, right) spent significantly less time monitoring the PFD when operating under the divided responsibility than the shared responsibility, and more time monitoring both the Nav Display and OTW.

These data imply that the divided task allocation allowed for improved distribution of attention of the crew, with the PF spending more time monitoring primary flight status and the PM spending more time monitoring wake and traffic, and both pilots allocating more attention OTW when on parallel approach.

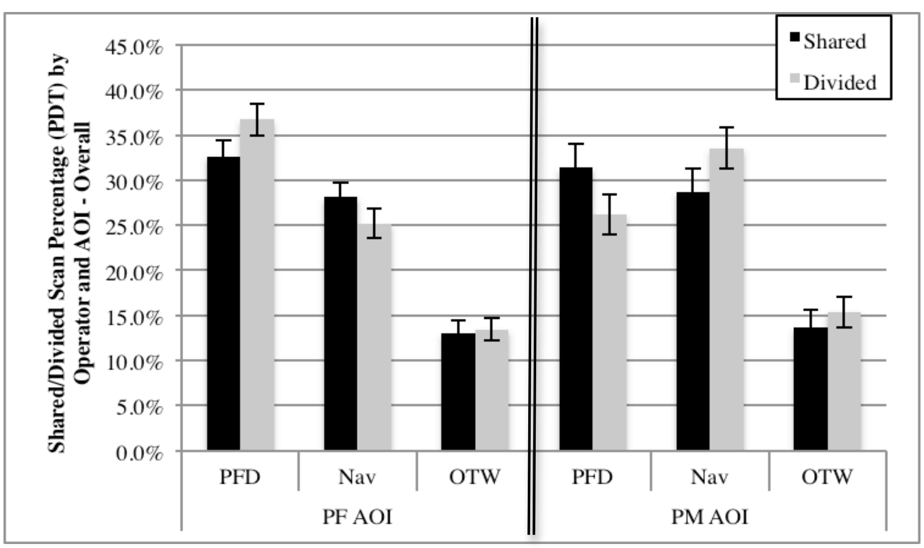

Figure 9. PF (left) and PM (right) scan on the PFD, Nav Display and OTW Areas of Interest across all phases of flight with shared and divided task allocations (+/- 1 SE).

The anticipated changes to the operator roles in the NextGen significantly impacted where the pilot looked depending on their phase of flight ($F(1,18)=52.9$, $p<.05$). However, the overall effect of the divided task allocation did not change from the overall findings presented above. Data for each phase of flight can be found in Appendix A.

3.1.1.2 Workload

Figure 10 presents the overall workload by phase of flight for the PF and for the PM for both the shared and divided task allocation scenarios. In the Descent phase of flight (above 10,000 ft), the PF's and the PM's overall workload did not differ with the introduction of the divided task allocation strategy – as expected because the additional tasks of traffic and wake monitoring have not begun at this altitude. In the Approach phase of flight (4,000 ft to 650 ft), both the PF's and PM's workload declined with the divided task allocation scenario, albeit negligibly, because the divided task allocation scenario allowed each pilot to focus efforts on a separate primary task. In the Land phase of flight (650 ft. and below), the introduction of the divided task allocation revealed that the PF's workload decreased negligibly while the PM's workload increased negligibly as the PM's responsibility for wake and traffic is greatest in this phase of flight. These results are suggestive of a change in workload that could warrant further evaluation in a human-in-the-loop simulation. Data for each separate workload channel and for each phase of flight are presented in Appendix B.

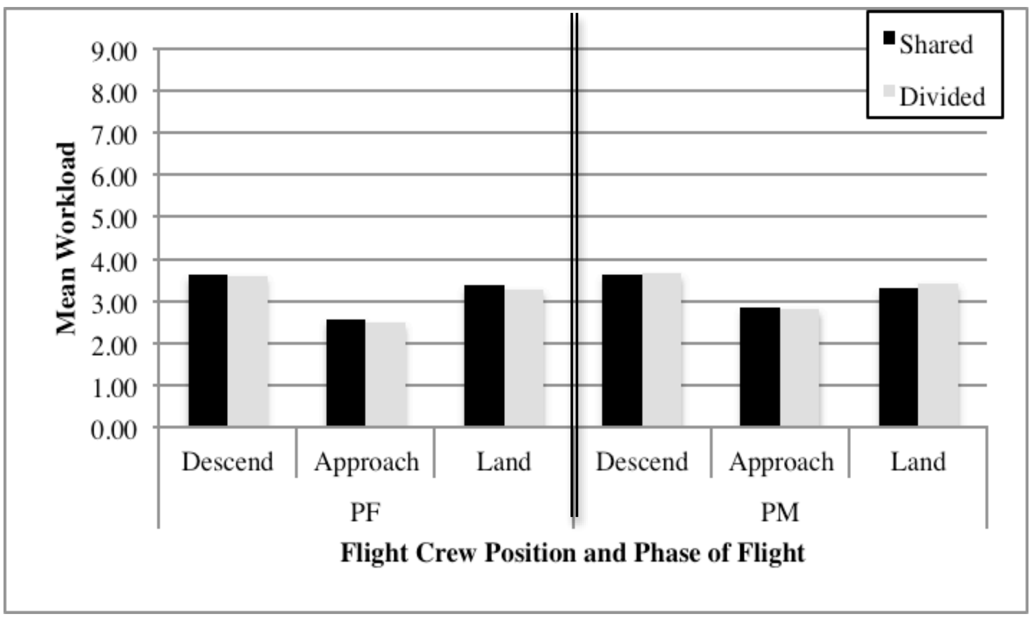

Figure 10. Mean workload by flight crew position per phase of flight in the shared and the divided roles

3.1.1.3 RNP Alert Response Time

The scenario included a visual RNP alert on the EICAS indicating that there was insufficient RNP to continue with the parallel approach. The alert occurred when the aircraft was at the following altitudes: 3,000 ft, 900 ft, and 400 ft and the pilot's time to detect the alert was recorded (see Figure 11).

When the alert occurred at 3,000 ft, the time to detect the RNP alert was faster under the divided task allocation procedures than the shared task allocation ($t(9)=3.5$, $p<.05$). This is expected, since the aircraft is still above the cloud level at this time and the PF was able to allocate additional glances to the EICAS, as the OTW did not provide relevant information to support the primary task of flight monitoring.

However, it can be seen that the detection time was increased in the divided task allocation scenario when the RNP alert occurred at the lower altitudes (900 ft and 400 ft) but the difference was not statistically significant (p>.05). It is expected that these delays occurred in the model because the priority for the PF was to monitor the PFD and OTW, and in this phase the OTW requires more visual attention and competes with scans to the EICAS. Clearly, in actual operations, an alert of this nature would require an auditory component.

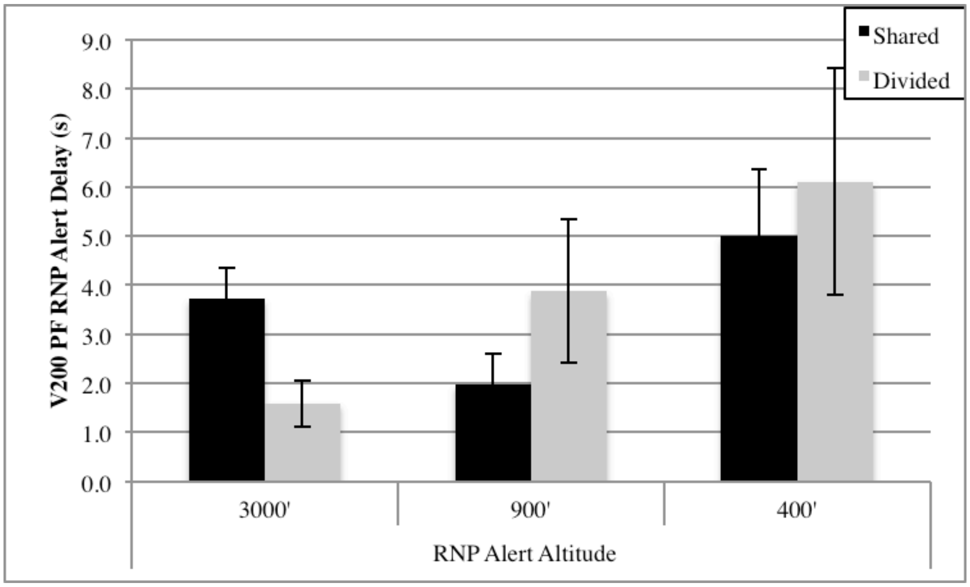

Figure 11. RNP alert latency for the PM at three event altitudes (3,000 ft, 900 ft, and 400 ft) with both shared and divided task allocations (+/-1 SE).

A similar pattern of results was observed for the modeled PM (see Figure 12). However, there was little effect of task allocation strategy on the PM's RNP detection when the alert occurred at 3,000 ft altitude (p>.05). This is likely because the PM's visual attention was directed to tasks inside the cockpit equally at this altitude (the crew was initiating the pairing procedure, including receiving, reading, and accepting datalink and initiating speed-coupling automation; there was no OTW visibility as the aircraft was still in the clouds).

It can be seen that the RNP Alert detection time was delayed in the divided task allocation compared to the shared task allocation scenario when the alert was issued at 900ft and at 400ft (but p>.05 for both). This occurred in the model because the PM's visual attention was directed to the tasks of Separate and Navigate, which exhibited the highest information relevance values for the Nav Display. Again, the crew procedures and alert design must encourage efficient scan of the EICAS during these high workload phases of flight.

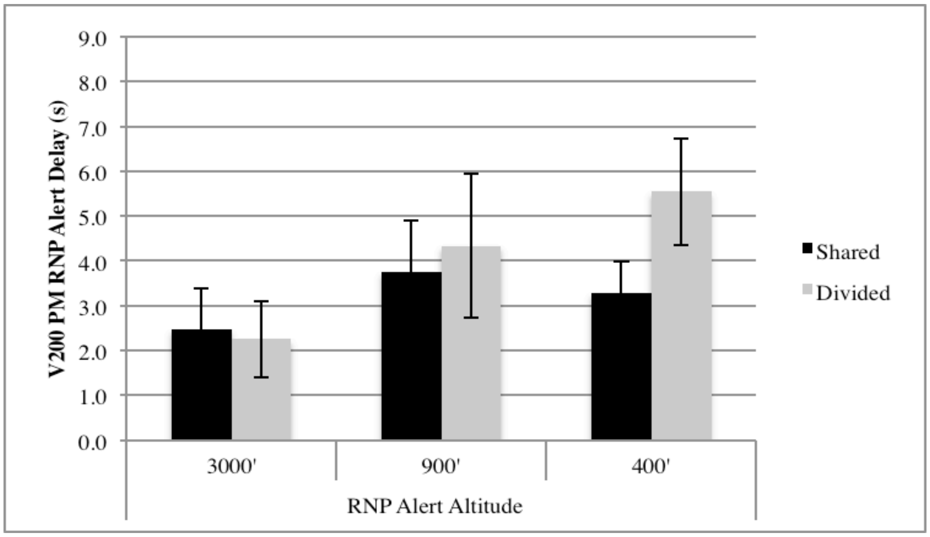

Figure 12. RNP alert latency for the PM at three event altitudes (3,000 ft, 900 ft, and 400 ft) with both shared and divided task allocations (+/-1 SE).

3.2 Evaluation of Separation-Responsibility Concepts

This model examined the impact of assigning separation responsibility to either ATC or pilots during an off-nominal blunder scenario. Three scenarios were generated: 1) Current-day, ATC is responsible for separation and flight decks are equipped as they are in current-day modern aircraft; 2) Transition, ATC is responsible for separation with flight deck displays augmented to depict aircraft separation and wake; and, 3) NextGen, pilots are responsible for separation and flight decks are augmented to depict aircraft separation and wake.

The model also assessed two wake alert styles: 1) one-stage; and, 2) two-stage alerts. In the one-stage alert format, the system was either in a nominal no-alert state, or in an alert state (red alert only) that would require an action to initiate a Missed Approach (MA). The two-stage alert format first issued a visual (yellow warning) as the wake threat developed and a final (red) alert commanding an immediate take-off / go-around (TOGA) procedure.

Modeled Tasks

In all three scenarios, as the aircraft was on final approach (1800 ft), a wake threat occurred in which the wake of the lead aircraft extended into the ownship's trajectory. During the nominal condition, the pilots looped through an internal check of flight deck displays in addition to scans outside of the cockpit. When a wake or blunder alert was active, pilots cycled through a four-step sequence to prepare for a missed approach: 1) Detect Alert; 2) Assess Situation; 3) Determine Missed Approach response; and 4) Communicate Missed Approach Response. This four-step "Detect – Assess – Determine Response – Communicate" sequence was defined as follows:

1. One pilot must **Detect** the presence of the alert on the Nav Display and notify the other pilot. In terms of the model implementation, the yellow alert was a medium-salience piece of information whereas the red alert was a high-salience piece of information.
2. Both pilots then must **Assess the Situation.** This required the pilots to **comprehend** the information either on the Nav Display or OTW (or both). If information was available both on the Nav Display and OTW, pilots then confirmed that the Nav Display and OTW were consistent (modeled as a spatial-compare task).

3. Next both pilots must **Determine Missed Approach Response,** or, in other words decide what action would be required if/when the yellow alert turns to red. This was a decision task.
4. Then the pilots **Communicated** this MA plan *within* the cockpit. This entailed a verbal communication between the PF and PM.

In the two-stage alert scenarios, Steps 2 through 4 (Assess Situation - Determine MA response - Communicate) continued to loop while the aircraft was in the 'yellow' alert zone. If the wake display turned to red, and the MA plan had been communicated in the last 10 seconds, the pilots executed the MA plan by pressing TOGA at which point the scenario ended. If the wake display was red, but the MA plan had not been communicated in the last 10 seconds, the pilots re-entered the **Assess Situation – Determine MA Response – Communicate** loop, and then made a TOGA response/maneuver (at which point the scenario ended).

Figures 13, 14, and 15 illustrate a flow chart of the modeled tasks for the Current-day, Transition, and NextGen scenarios respectively. In the current-day scenario (Figure 13), the flight crew received separation information from ATC and no information about wake or blunders was presented on the flight deck. When ATC received a wake alert, they then issued a verbal 'Go-Around' command to the aircraft with a unique MA path that accounted for metroplex traffic, terrain, and wind conditions. The model required that pilots complete a cross check to match the OTW with the pilot's understanding of the traffic situation as indicated by ATC communication before initiating the MA.

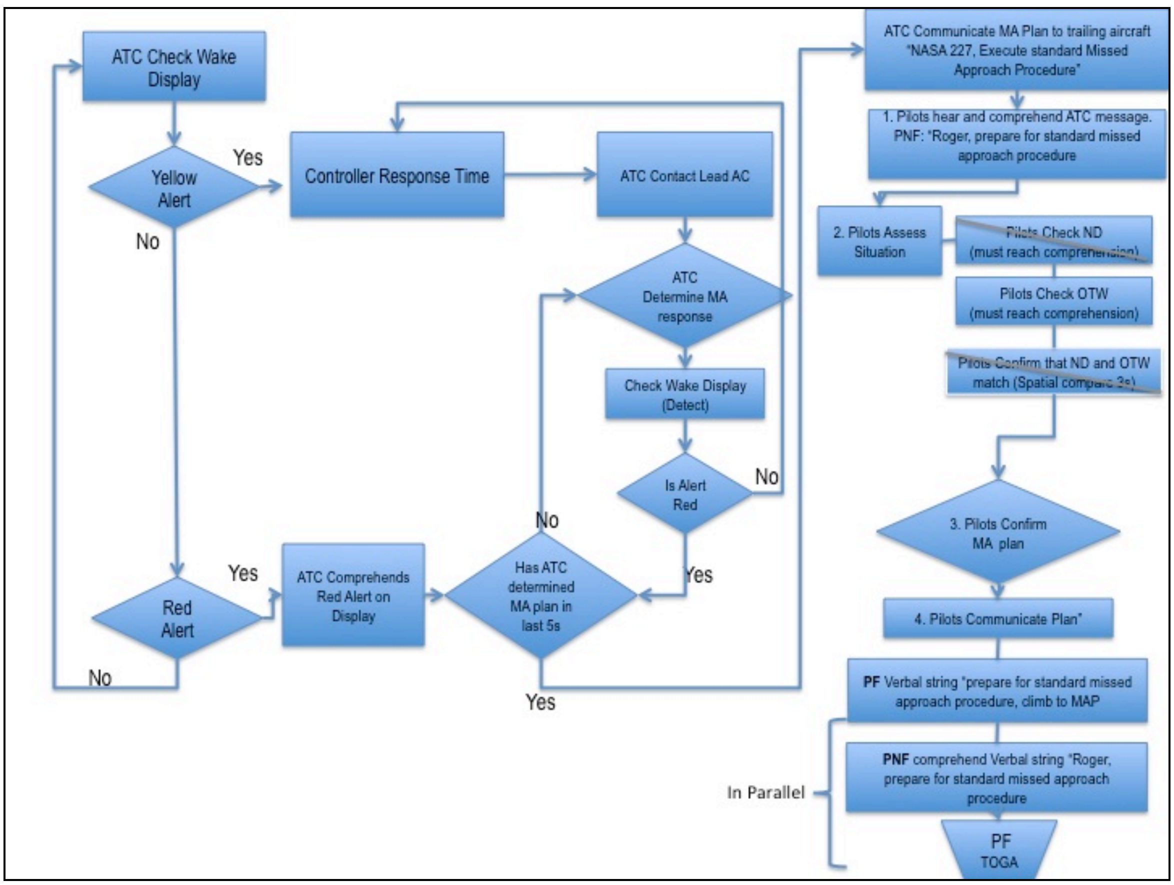

Figure 13. Flowchart of current-day scenario.
NOTE: The tasks "Pilots check ND" and "Pilots confirm that ND and OTW match" were not active in this current-day scenario, but were used in the Transition and NextGen scenarios (described next)

In the Transition scenario (Figure 14), ATC maintains responsibility for separation and is equipped with wake and blunder detection technology with either one- or two-stage alerts as. When ATC received a wake alert, they then issued a verbal 'Go-Around' command to the aircraft with a unique MA path that accounted for metroplex traffic, terrain, and wind conditions. In contrast to the current-day scenario, each pilot's Nav display showed the route, traffic, and wake conformance zones. Once alerted of a blunder or wake threat ATC assessed the situation, contacted the lead aircraft, determined the MA operation, and immediately issued the MA command to the trailing aircraft. The pilots of the trailing aircraft received this MA command and assessed their environment, confirmed that the Nav Display and the OTW provided consistent information, and carried out the TOGA action.

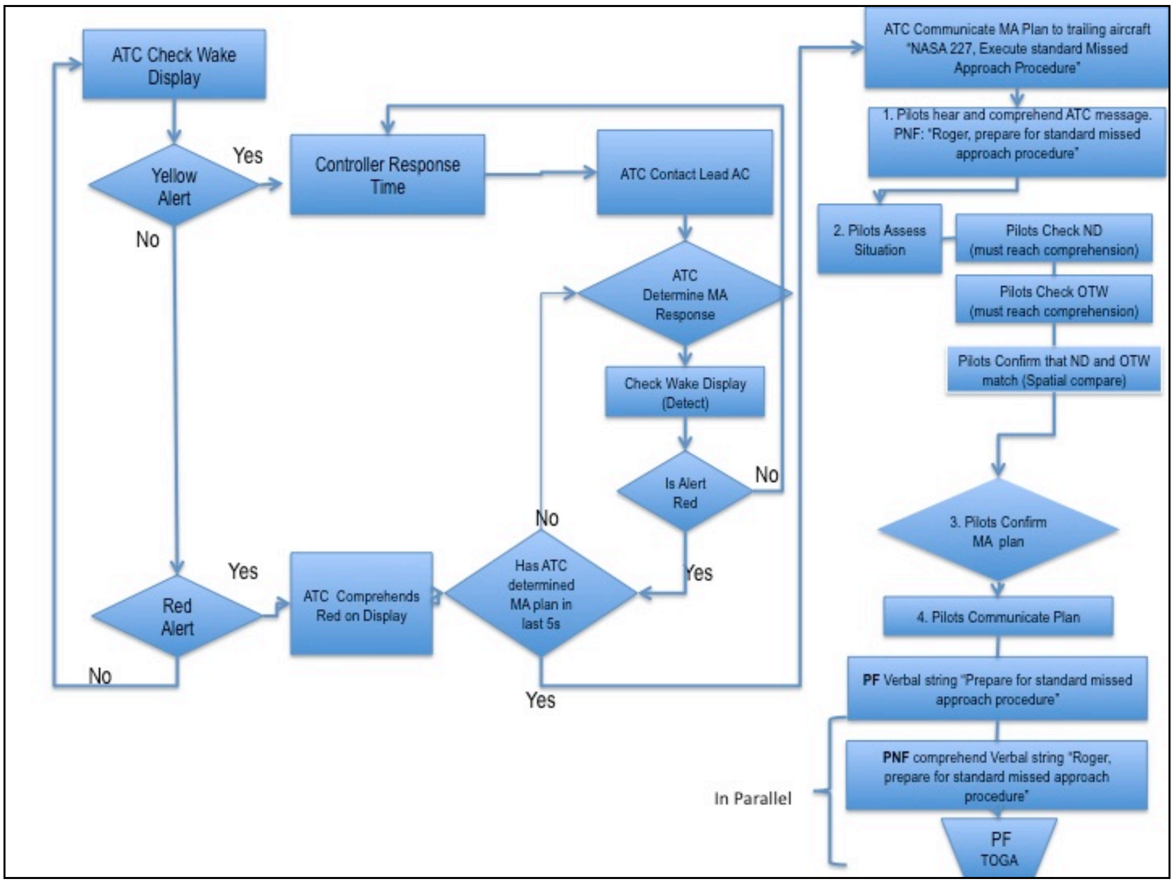

Figure 14. Flowchart of the transition scenario

In the NextGen Scenario (Figure 15), the flight deck was equipped with the same depictions of route, traffic, and wake conformance zones as the Transition Scenario, as well as either one- or two-stage blunder and wake alerts. Upon receiving a blunder or wake alert, pilots cross-checked the information on their Nav and OTW, and initiated the MA.

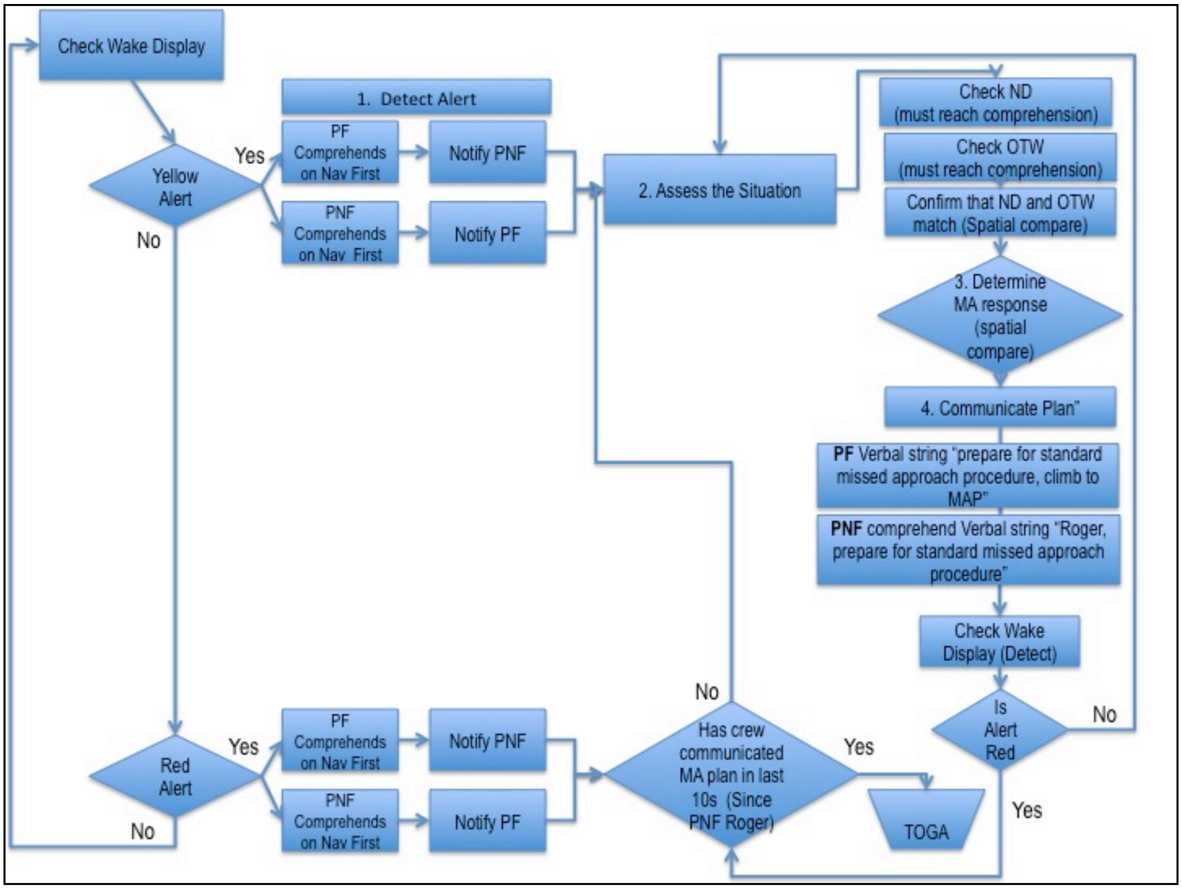

Figure 15. Flowchart of the NextGen scenario.

3.2.1 Separation Responsibility Results

Ten Monte Carlo simulation runs were generated to evaluate the pilots' time to initiate the emergency escape maneuver in response to the wake threat alert (as presented either by flight deck automation or ATC), the pilots' visual scan (percent dwell time, PDT) performance, and the pilots' workload. This section contains summaries for both the one- and the two-stage alert conditions.

3.2.1.1 Response Time to Threat Alert

The time to initiate TOGA in response to the blunder alert can be found in Figure 16. This figure illustrates that the slowest TOGA responses occurred when the flight deck was equipped with advanced wake and traffic displays (in both the Transition and NextGen scenarios) and with one-stage alerts. The fastest TOGA response occurred in the NextGen two-stage alert condition ($F(2,18)=36.21$, $p<.01$).

Looking at the one-stage alert data (grey bars) illustrated in Figure 16, there was no significant difference in response time to the wake threat alert between the Transition and NextGen scenarios ($p>.05$). This figure illustrates that pilots took significantly longer to respond to the threat alert in either the NextGen or Transition as compared to the current-day scenario ($t(9)=10.84$, $p<.05$).

Looking at the two-stage alert data (dark bars) in Figure 16, the response time to the wake threat alert illustrates that pilots were only negligibly faster to initiate the emergency escape maneuver in the NextGen scenario (2.9s) than in the Current-day condition (3.2s); ($p>.05$). Compared to the Transition condition, the time to TOGA was significantly faster in the NextGen scenario when pilots were responsible for separation ($t(9)=7.43$, $p<.05$) and the Current-day scenario ($t(9)=6.47$, $p<.05$).

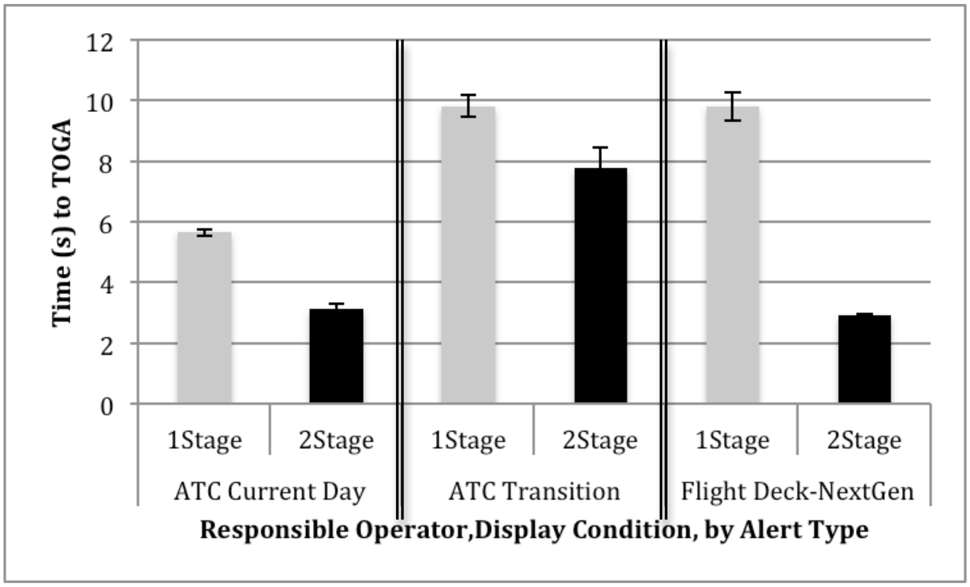

Figure 16. Time to TOGA by responsible operator, display condition and alert type (+/- 1 SE).

3.2.1.2 Pilot Visual Scan

The model output of the pilot visual scan performance was analyzed to determine the impact that shifting the responsibility for separation from ATC to the pilots has on the pilots' visual scan pattern when on a CSPO approach with a blunder threat event. The scan performance (percent dwell time, PDT) was assessed for the three main displays (Nav Display, PFD and OTW) for the PF and the PM given the two alert conditions (one-stage versus two-stage alert) under the three concepts (Current-day, Transition, and NextGen), see Figure 17 (one-stage alert scenario) and Figure 18 (two-stage alert scenario). The model data showed that the pilots' visual scan pattern would be different across the three operational concepts ($F(2,18)=50.9$ $p<.05$).

The one-stage alert data (Figure 17) shows that the PF and PM scanned the PFD less in the NextGen scenario than in the Transition scenario ($t(19)=11.4$, $p<.05$) or Current-day scenario ($t(19)=8.6$, $p<.05$). Both the PF and the PM scanned the Nav more during the NextGen scenario as compared to the Current-day scenario ($t(19)=19.8$ $p<.05$), or the Transition scenario ($t(19)=21.5$, $p<.05$). The PF and the PM scanned OTW more in the Current-day scenario as compared to either the NextGen ($t(19)=8.1$, $p<.05$) or Transition ($t(19)=12.0$, $p<.05$).

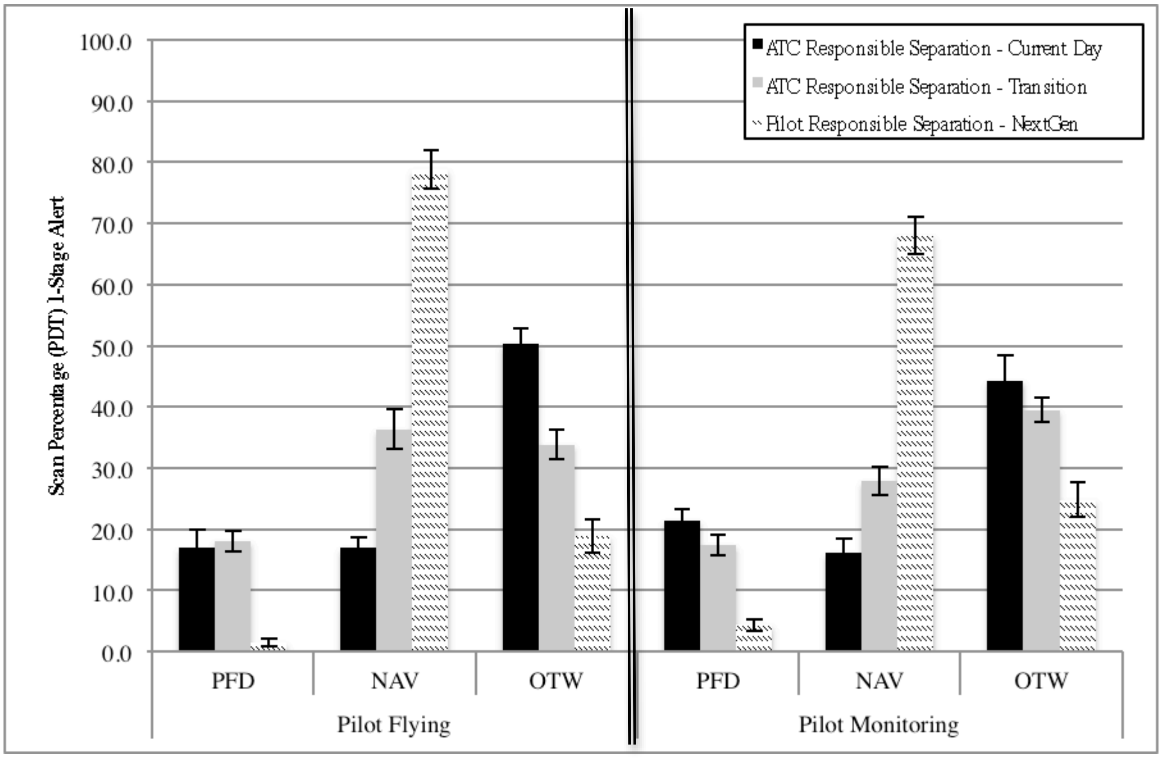

Figure 17. PF and PM PDT in one-stage alert by responsibility and display manipulations (+/- 1 SE).

The two-stage alert data (Figure 18) shows that the PF and PM scanned the PFD less in the NextGen scenario than in the Transition scenario ($t(19)=18.2$, $p<.05$) or Current-day scenario ($t(19)=11.2$, $p<.05$). Contrasting the output from the one-stage alert, it can be seen that the PF and the PM scanned the PFD more in the Transition displays scenario as compared to the Current-day scenario. The PF and the PM scanned the Nav Display more during the NextGen scenario as compared to the Current-day scenario, ($t(19)=27.5$, $p<.05$) or the Transition scenario, ($t(19)=23.8$, $p<.05$). The PF and the PM scanned OTW more in Current-day scenario, as compared to Transition ($t(19)=6.7$, $p<.05$) or NextGen scenarios, ($t(19)=9.0$, $p<.05$).

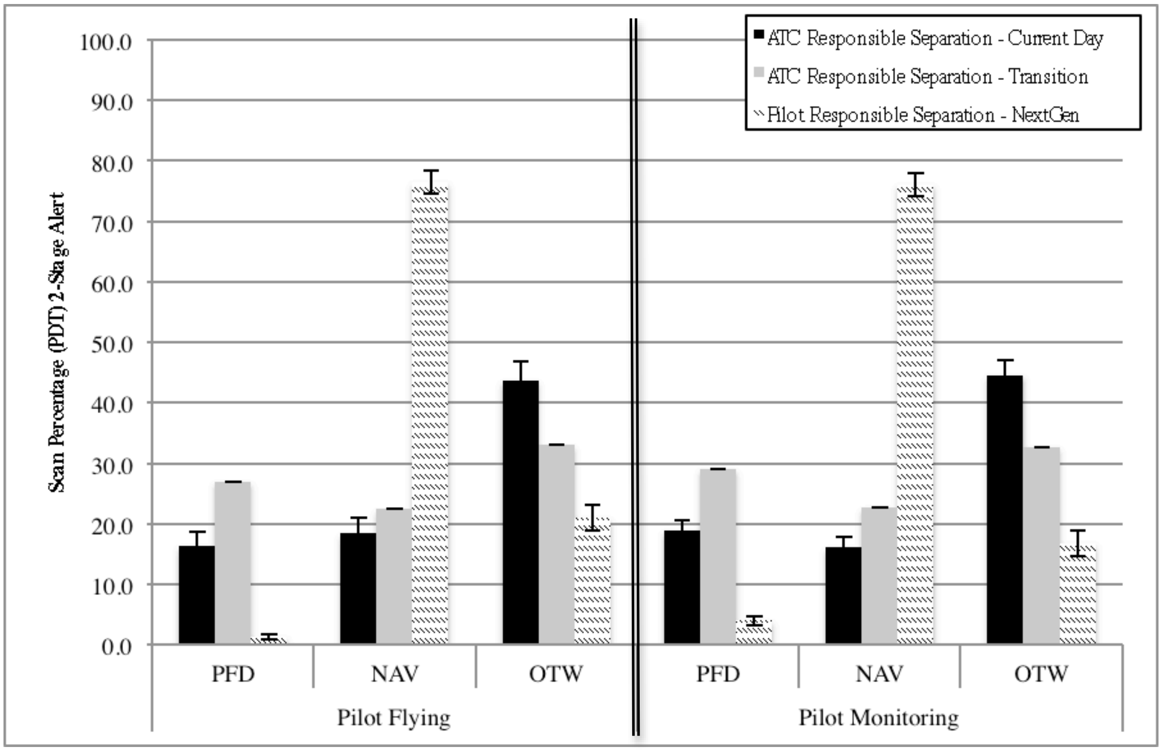

Figure 18. PF and PM PDT in two-stage alert by responsibility and display manipulations (+/- 1 SE).

Summary of Scan Findings

- Pilots' scan to the Nav Display increased by ~50% when separation responsibility was transitioned from ATC to pilots. This was in the expected direction because traffic information, including separation from the lead aircraft, was presented on the Nav Display.
- Pilots' scan OTW decreased by ~50% when pilots were responsible for separation, compared to when ATC was responsible for separation. This occurred because pilots did not have the requirement to determine if a MA was necessary by monitoring the Nav Display. This additional task of separation responsibility decreased monitoring of the external environment.
- The pilots' scan to the PFD decreased when pilots were responsible for separation compared to when ATC was responsible for separation. This additional task reduced the pilots' ability to focus on aviating the aircraft over navigation and separation.

3.2.1.3 Workload Comparisons

Figure 19 presents the mean workload over the total alert phase from alert onset to the TOGA response. The pilots' overall workload was differentially impacted depending on the pilot role (PF or PM), separation-responsibility concept, and alert type ($F(2,36)=3.2$, $p<.05$).

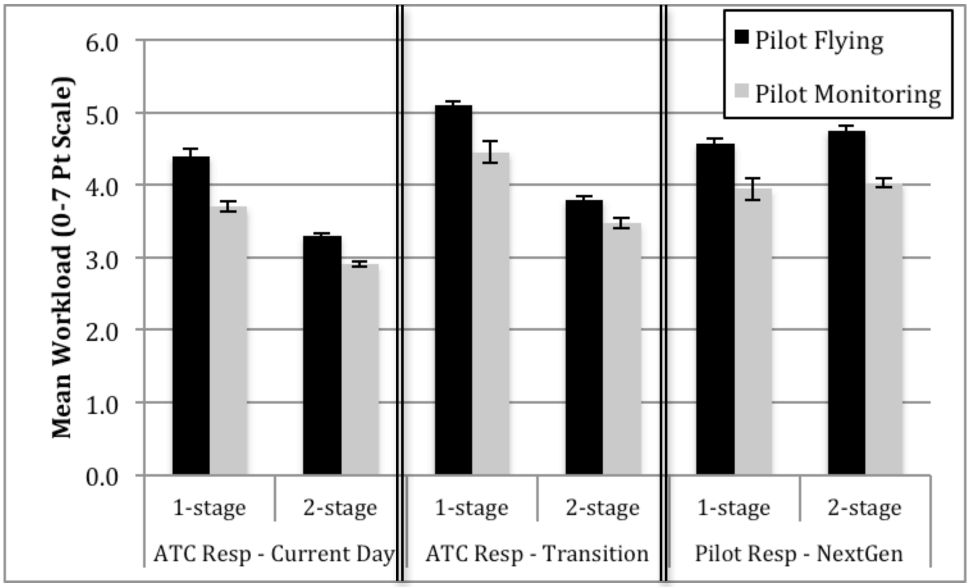

Figure 19. PF and PM mean workload ratings across the total alert phase by responsibility and display manipulations (+/- 1 SE).

In the one-stage alert condition, the PF's workload was significantly higher in the Transition condition than either the NextGen condition ($t(9)=15.2$, $p<.05$) or the Current-day condition ($t(9)=6.9$, $p<.05$). There was no difference between the NextGen condition and the Current-day condition ($t(9)=1.5$, $p>.05$). The same pattern was observed for the PM in the one-stage alert condition. The PM's workload was significantly higher in the Transition condition than either the NextGen condition ($t(9)=2.5$, $p<.05$) or the Current-day condition ($t(9)=4.8$, $p<.05$). There was no difference between the NextGen condition and the Current day condition ($t(9)=2.1$, $p>.05$). Workload is highest in the Transition because both flight deck crewmembers are responding to the blunder event and the ATC is communicating to the crew to resolve the transgression concurrently. In either the Current-day or NextGen conditions, the level of responsibility and requisite actions will be done primarily by the responsible crew, either the ATC in the Current-day or by the flight deck in the NextGen condition not both sets of crews. When there is a division of responsibility in this manner, workload is reduced. It is important to note that the high level of workload is for a very short period of time (8.7s).

With the two-stage alert, the PF overall workload in the NextGen condition was significantly higher than in the Current-day condition ($t(9)=29.7$, $p<.05$) and the Transition condition ($t(9)=30.2$, $p<.05$). Workload was significantly higher in the Transition condition than the Current-day condition ($t(9)=17.9$, $p<.05$). Again, the PM workload yielded the same pattern. In the two-stage alert condition, the PM's workload in the NextGen condition was significantly higher than in the Current-day condition ($t(9)=28.8$, $p<.05$) and the Transition condition ($t(9)=8.9$, $p<.05$). PM workload was significantly higher in the Transition condition than the Current-day condition ($t(9)=6.6$, $p<.05$). Workload is highest in the NextGen two-stage alert condition because the flight deck crew completes continuous decision cycles while they remain in the alert phase. This results in inter-cockpit crew coordination and increased crew monitoring to flight critical pieces of information. This period of high workload lasts for approximately 23s.

Both the PF, and the PM possessed increased workload with the addition of the separation responsibility task in NextGen operations. When the individual channels that make up the overall workload metric are evaluated (see Appendix C), it can be seen that the cognitive verbal and cognitive spatial workload channels are the aspects of workload that NextGen rules will impact most. The significance of this workload effect will need further analysis with HITL simulations.

3.2.2 Separation Responsibility Findings, Implications and Future Research

Model output revealed that shifting responsibility for wake and blunder detection to the pilots may result in reduced time to initiate an emergency escape maneuver (negligible), and this may be worse in a transition period during which flight decks are equipped with more information, but are not given the authority to act on it. In this transition environment, equipping the flight deck with wake depictions may result in slower initiation of the emergency escape maneuver, reduced pilot monitoring of PFD and OTW, and higher workload

Depending on flight deck display design, NextGen operations may also increase pilot workload and increase pilot scans toward the Nav Display at the expense of monitoring the PFD and OTW.

Finally, model output revealed that two-stage alerts for wake and blunder threats should be considered for NextGen CSPO concepts, because compared to one-stage alerts, two-stage alerts yielded faster initiation of the emergency escape maneuvers and only a small increase in PF workload.

3.2.3 Separation Responsibility Research Requirements

The following research requirements were identified:

- Wake displays must be designed to prevent excessive monitoring requirements. Designs may include status-at-a-glance display techniques, highlighting / cueing, and auditory notifications

- New task allocation and division of responsibilities within the cockpit may be required such that one pilot is dedicated to monitoring traffic and wake threats while on parallel approach, allowing the other pilot to prioritize primary flight performance

- Issues associated with pilot distraction and false alarm rates should also be considered

3.3 Evaluation of NextGen Information Requirements

The purpose of the third model was to identify requirements for presenting wake and spacing information on the flight deck during CSPO approaches. The third model modified the previously validated CSPO 200 scenario (described previously) and the off-nominal conditions generated in the validated model delivered (Gore et al., 2011) as outlined next. Two sources of information within the cockpit were manipulated: (1) the wake information and, (2) the speed management / spacing information. The off-nominal events of aircraft decoupling (at 1,000 ft and 700 ft), RNP loss (at 900 ft and 400 ft), and aircraft on the runway (at 150 ft) were used in this scenario. Parameter manipulations were made to the operator's attention weightings to reflect the impact that the availability of information had on the flight crew's performance (PDT, RNP-loss alert detection latency, workload).

3.3.1 Wake Information Requirements

The wake information requirements model evaluated the impact of wake information format (predicted versus real-time) and display location (PFD, Nav Display, or on both the PFD and the Nav Display). The ***predicted*** wake display format presented a static safe zone based on predicted data given lead aircraft and forecast wind conditions. The ***real-time*** wake display presented a dynamic wake display assumed to be updated in real-time based on factors including lead aircraft type and performance, and instantaneous wind data. The real-time display therefore had both higher expectancy (rate of change) and value (relevance) for the pilots. Six experimental conditions were run (2 formats X 3 display locations). Specific measures of interest in this model included the pilots' visual scan performance (percent dwell time, PDT), pilot detection of an alert that their aircraft became decoupled from the automation as indicated on the EICAS (at 700 ft altitude), pilot detection of an RNP alert indicating that the aircraft no longer had sufficient RNP to carry out the CSPO approach (presented at 900 ft and 400 ft), and time to detect an aircraft on the runway (when ownship was at 150 ft AGL).

3.3.1.1 Wake Information Requirements Results

Flight Deck Scanning Performance

The pilots' scan to the PFD, Nav Display, and OTW was analyzed to determine the impact that presenting the wake information in either a predicted or real-time format had on pilot's scan performance, and to determine the effect of display location on the pilots' scan. There was a significant interaction between whether information was presented in a predicted or real-time format, and display location ($F(2,36)=693.8$, $p<.01$). There was no significant difference between the PF and the PM's scan performance ($p>.05$). Figure 20 illustrates the PF's visual scan metric (percent dwell time) to the PFD, Nav Display, or OTW as a function of whether the wake information was presented in a predicted (left side of the figure) or real-time manner (right side of the figure) to a location on the PFD, Nav Display, or on both locations (LocPFD, LocNav, LocPFD+Nav). The PM's data yields the same result and can be found in Appendix D.

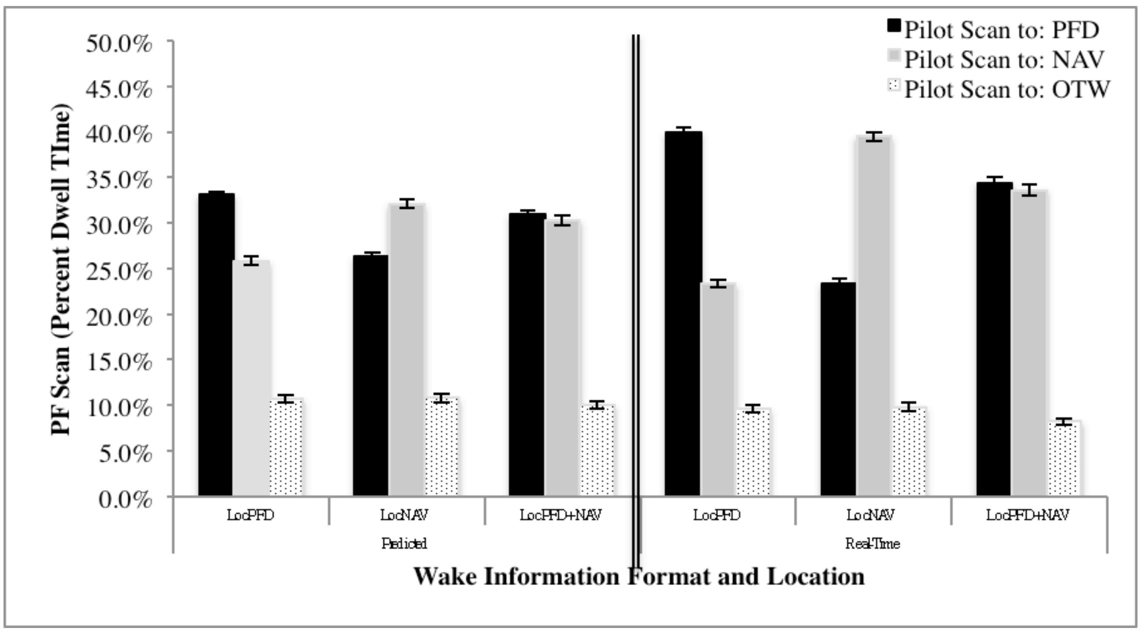

Figure 20. PF Scan pattern to the PFD, Nav Display, or to both as a function of information location (+/- 1 SE).

When the cockpit was modeled with a (static) predicted wake display (left side of Figure 20), it can be seen that the PF's scan to the PFD was significantly higher than either to the Nav Display or the OTW when the wake information was presented on the PFD ($t(9)=11.5$, $p<.05$; $t(9)=32.4$, $p<.05$). This is as expected because the pilots' priority should be to monitor the PFD when on approach. It is apparent that the PF viewed the Nav Display 25% of the time even when wake information was presented on the PFD. This is expected and is due to the cross-checks to the Nav Display to ensure that all systems are consistent, cross checks that are constantly engaged in by the pilot on approach. When wake information was presented on the Nav Display, the PF's scan to the Nav Display was significantly higher than either to the PFD or OTW ($t(9)=7.3$, $p<.05$; $t(9)=19.8$, $p<.05$). This is a possible area of concern as the model predicts that the attention is being drawn to the Nav and away from the PFD by 8% increasing the vulnerability that the pilots may miss critical information displayed on the PFD. When information was presented on both the Nav Display and the PFD, the pilot scanned these two displays equally ($p>.05$) and with less cost to the PFD than when information was presented on the Nav Display.

When the cockpit was modeled with a (dynamic) real-time wake display (right side of Figure 20), it can be seen that the PF's scan to the PFD was significantly higher than either to the Nav Display or the OTW when the wake information was presented on the PFD ($t(9)=16.1$, $p<.05$; $t(9)=26.0$, $p<.05$). The PF still looked to the Nav Display 23% of the time when wake information was presented on the PFD, an important consideration for displaying redundant information. When real-time wake information was presented on the Nav Display, the PF's scan to the Nav Display was significantly higher than either to the PFD or OTW ($t(9)=19.1$, $p<.05$; $t(9)=19.3$, $p<.05$). In fact, the crewmembers reduced their scan on the PFD by approximately 17%, a large reduction on the information source that is the primary source of information. The acceptability of such a reduction needs to be evaluated in further research.

When real-time wake information was presented on both the Nav Display and the PFD, the pilot scanned the wake information equally on those displays with no significant difference between the scan percentages between PFD or Nav Display ($p>.05$).

Flight Deck Detection of Decoupling

The aircraft-decoupling event measured the time required for the flight deck to notice that the ownship was no longer coupled with the lead as indicated on the PFD. The flight deck detection time to notice the decoupling aircraft was the longest (and therefore responds slowest) when the wake information was presented in a real-time format on both the PFD and the Nav Display when the event occurred at 700 ft. The flight deck had the shortest time to detect the decoupling event (and therefore responded fastest) when the information was presented in a predicted format on either the PFD or the Nav Display. Presenting the wake information on both the PFD and Nav Display actually served to slow decoupling detection time (albeit the difference was not statistically significant), presumably because it introduced an additional information-monitoring requirement. These non-significant findings can be located in Appendix E.

RNP Alert Detection Latency

The RNP alert detection latency times were collected on 10 Monte Carlo simulation runs of the off-nominal events of RNP Alert at 900 ft and 400 ft for the PF and PM. None of the differences in RNP Alert Detection Latency were significant. See Appendix F for the data output.

Aircraft on the Runway

The modeled-pilots detection and response to an aircraft on the runway that they have been cleared to land on is presented in Figure 21. Model scenarios were run in a Monte Carlo fashion 10 times for each of the experimental conditions. The flight deck detection time of the aircraft on the runway was longer when the wake information was presented in a real-time format than the predicted format ($F(1,9)=10.4$, $p<.05$). The modeled-pilots took significantly longer to detect the aircraft on the runway when wake was presented as real-time information on the Nav Display ($t(9)=2.7$, $p<.05$) or when it was presented as *real-time* information on the PFD+Nav Display $t(9)=2.3, p<.05$) as compared to when it was presented in a *static* manner, using predicted wake data.

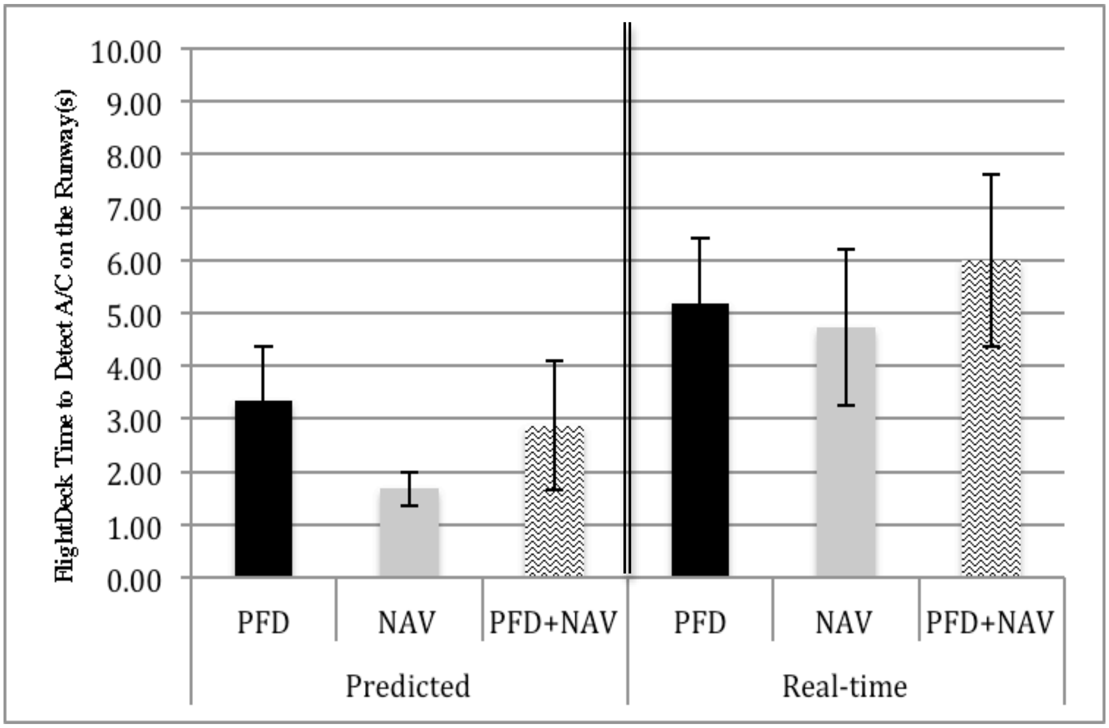

Figure 21. Flight deck time to detect aircraft on the runway by wake information manipulation.

Workload

The location and format of the wake information had very little effect on the operator's overall workload. This is expected, because the difficulty associated with detecting the wake information was not modeled in these scenarios. For completeness, all of the workload output can be found in Appendix G.

3.3.1.2 Wake Information Requirements Findings and Implications

Model output revealed that, compared to static wake depictions, dynamic real-time wake displays may result in:

- Increased time spent monitoring wake display elements
- Slower detection of flight performance status
- Slower detection of external objects such as aircraft on the runway

Further, presenting wake on both PFD and Nav Display may result in:

- Increased scans to wake-related display elements
- Slower response times to all off-nominal events

Unless the PFD and Nav Display afford inherently different presentations of the wake data (not tested here), there appears to be little or no support for presenting wake on BOTH displays.

3.3.1.3 Wake Information Requirements Future Research Requirements

The following future research requirements were identified:

- Identify minimal information requirements to enable cross-checking ATC commands that will not increase workload or delay response to blunder or wake threats

- Identify wake display formats, such as highlighting and cueing, which offer status-at-a-glance information without detracting attention from the PFD

- Investigate the use of filters to limit the data update rate of real-time wake displays

- Investigate alternative display formats, not direct visualization of wake, such as simple red/green light status indicators

- Determine if pilots require the precision afforded by real-time wake displays for CSPO

- Determine precise wake information requirements and identify formats and display best suited for presentation

- Wake displays may require new crew task allocations and division of responsibility

3.3.2 Speed Management / Spacing Information Requirements

The scenario consisted of a nominal approach, with no wake or blunder event. The scenario was repeated with two spacing automation styles: 1) Current-day, in which pilots managed spacing by controlling speed using the MCP; and, 2) NextGen, in which advanced automation controlled speed to maintain spacing. Because pilots were controlling speed in the current-day automation condition, both the expectancy (rate of change) and the relevance of the display was higher, in order to support the pilots closed-loop speed maintenance task. The information requirements (IR) model evaluated the impact of the speed-management automation (current-day automation, 4-D automation) and the placement of spacing management information (PFD, Nav Display, or both). Four scenarios were run using the CSPO 200 condition (outlined previously) and used the entire scenario from descent to land. Specific measures of interest in this model included the pilot scan performance (PDT), the time to detect the decoupling at 1,000 ft and 700 ft, and the time to detect the RNP alert (3,000 ft, 900 ft, and 400 ft). Model scenarios were run 10 times each.

3.3.2.1 Speed Management /Spacing Information Requirements Results

Flight Deck Scanning Performance

The pilots' scan to the PFD, Nav Display, and OTW was analyzed to compare the difference between current-day (MCP) spacing management and NextGen, automated spacing management. There was a significant three-way interaction among the automation style, the location of the information, and the AOI that the operator scanned given their crew role, $F(2,18=73.1, p<.05$.

Figure 22 presents the amount the PF scan percent dwell times (PDT) to the PFD, Nav Display, and OTW as a function of whether the spacing information was managed in a NextGen or current-day format and whether the spacing information was presented on the PFD, Nav, or on both PFD+Nav Display (LocPFD, LocNAV, LocPFD+NAV respectively).

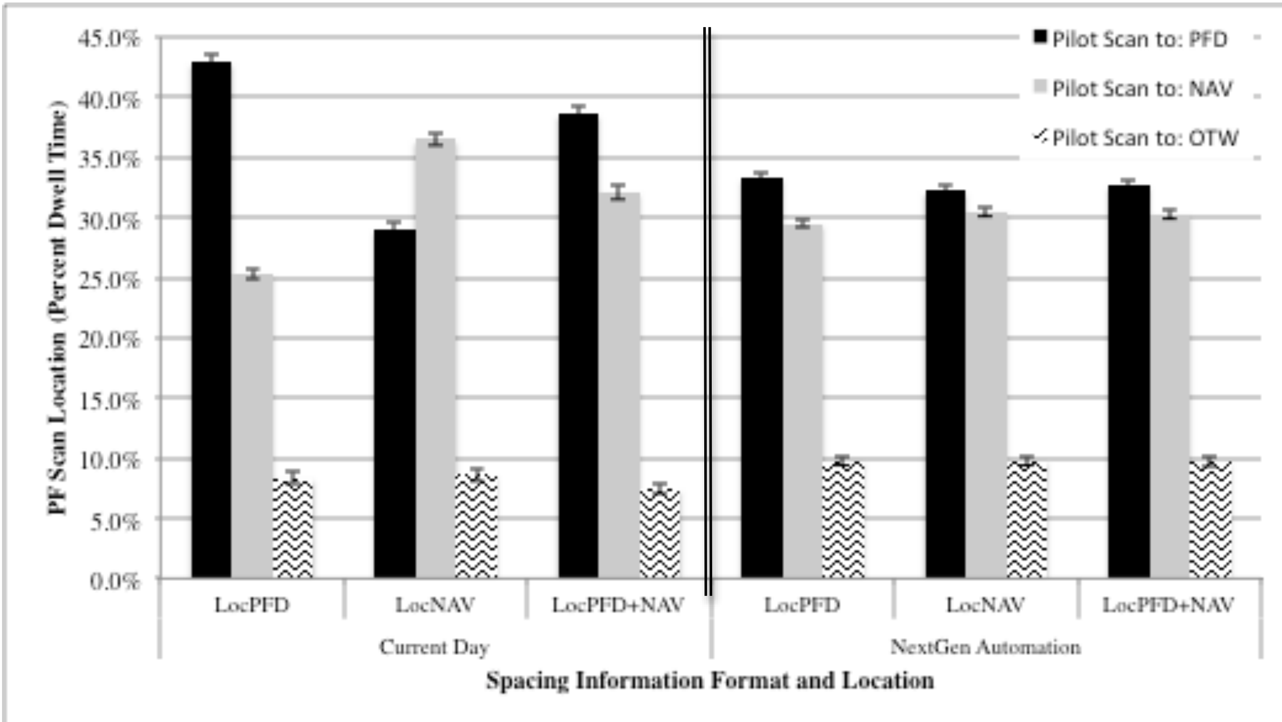

Figure 22. PF scan percentage as a function of spacing information and location.

Considering only the Current-day spacing information (three sets of three bars on the left of Figure 22), when the Current-day spacing information was presented on the PFD, the PF scanned the PFD significantly more than the Nav Display (t9)=16.3, p<.05) or OTW (t9)=40.2, p<.05). This provides some support that the pilots maintain their attention and focus on the PFD when flying the approach, but that they do shift their attention to the Nav Display 25% of the time; likely due to the cross-checks that are necessary for the approach. The PF scans for spacing information were significantly greater on the Nav Display than the PFD when spacing information was located on the Nav Display (t(9)=7.2, p<.05). It is apparent that the PF will still look to the PFD 29% of the time when information is presented on the Nav Display. This is likely due to the cross-checks that are constantly engaged in by the pilot on approach. The PF scans for spacing information on the PFD to a greater extent than on the Nav Display when information was presented on both displays (t(9)=5.3, p<.05).

In terms of the NextGen automation spacing information style (three sets of three bars on the right of Figure 22), the PF's scan was more evenly distributed (less variable) than in the predicted condition. The PF scanned the PFD for spacing information significantly more than on the Nav Display (t(9)=6.8, p<.05) or OTW (t(9)=39.1, p<.05) when information was located on the PFD. When spacing information is located on the Nav Display, the pilot scanned significantly more to the PFD than either the Nav Display (t(9)=2.7, p<.05) or the OTW (t(9)=39.0, p<.05). When spacing information was presented in both locations, the PF scanned the PFD significantly more than either the Nav Display (t(9)=3.5, p<.05) or OTW (t(9)=37.3, p<.05). It is likely that the pilot scanned the PFD to a greater extent than the Nav Display because the pilot had greater priority to *aviate* tasks in this phase of flight and a lower priority on *navigate* tasks. There was no difference between the PF scans OTW (p>.05).

There was a significant interaction effect between Current-day and NextGen spacing automation format and the visual area of interest (F(2,18)=73, p<.05). As a relative comparison between the Current-day and NextGen spacing automation format impact on the pilots' scan, it is apparent that the PF looked at the PFD when spacing information as presented on the PFD significantly more (t(9)=21.6, p<.05), they looked at the Nav Display significantly more with current-day information than they did with NextGen automation spacing information (and in fact, they looked more at the PFD with current-day information, not the Nav Display) (t(9)=13.6, p<.05); and they looked significantly more to the PFD in the current day information style when information was in both locations (t(9)=13.1, p<.05). There is no statistical significant difference between the PF (presented above) and the PM. The PM data output is presented in Appendix H.

Flight Deck Detection of Decoupling

None of the differences in the time to detect aircraft decoupling within the 1,000 ft or within the 700 ft were statistically significant (p>.05). The data output from the model is presented in Appendix I.

RNP Alert Detection Latency

The RNP alert detection latency times when the RNP alert occurred at 3,000 ft, 900 ft and 400 ft were collected in 10 Monte Carlo simulation experimental runs. The RNP Alert detection latency time data when events occurred at 3,000 ft, 900 ft, and 400 ft are presented for the PF and PM in Appendix J None of the differences in RNP Alert Detection Latency were significant (p>.05).

Workload

All of the PF's and the PM's workload broken out by spacing information format and location of information can be found in Appendix K. As with the wake information, the location of the spacing information had little effect on the operators' workload. This was expected because the difficulty of accessing spacing information was not manipulated in this model.

3.3.2.2 Speed Management /Spacing Information Requirements Findings and Implications

Model output revealed that with Current-day spacing management automation, presenting spacing information on both PFD and Nav Display may result in more time monitoring the spacing task where as presenting spacing information only on the Nav Display may result in slower detection of an automation failure indicated on the PFD.

Model output suggests that Current-day speed-management automation may yield slower detection RNP-loss alert detection times than NextGen automation. However, NextGen speed-management automation may result in slower time for pilots to detect an automation failure (due to a complacency effect).

Future research should investigate initiatives to minimize pilot complacency with advanced automation.

4. Discussion and Conclusions

The MIDAS human performance model was used to evaluate proposed changes to flight deck technologies, pilot procedures, operations, and roles and responsibilities to support the development of the NextGen CSPO technologies and concepts. An iterative model development, validation, and extension process was adopted to generate a complex, valid NextGen operational scenario for CSPO that included the descent, approach, and land phases of flight.

Three model scenarios were generated in the current effort:

1) The **Crew Responsibilities scenario** manipulated the responsibilities of the PF and PM within the cockpit. The PF, PM roles were shifted from shared task allocation to divided task allocation required to manage NextGen technologies and displays.

2) The **Separation-Responsibility scenario** consisted of three conditions: Current-day scenario; Transition scenario; and, NextGen scenario. In the Current-day scenario, ATC was responsible for safe separation of aircraft and wake/blunder detection and flight decks with no changes to current-day flight deck equipage. In the Transition scenario, ATC maintained separation responsibility, but flight decks were also improved with enhanced wake and blunder depictions. In the NextGen scenario, pilots were responsible for self-separation and for detecting and initiating emergency escape maneuvers.

3) The **Information Requirements scenario** evaluated the impact of: Wake information type (predicted versus real-time); Level of speed-management automation (current automation vs. NextGen automation); and, Placement of both wake and the speed/spacing management information (PFD vs. Nav vs. Nav+PFD) on the flight performance in response to off-nominal conditions. Each will be discussed in turn.

The tasks and procedures were then encoded into a task network that contains a series of validated, reusable libraries of CSPO NextGen descent, approach, and land tasks. Analyses of pilot performance measures, including time required to complete tasks, pilot workload, pilot scan patterns and response times to off-nominal events were used to draw conclusions regarding the information requirements necessary to support NextGen CSPO concepts. The validated CSPO models were augmented to evaluate the following issues related to blunder detection, wake monitoring and spacing management on the flight deck. This extensive effort culminated in a set of NextGen operational procedures, a set of candidate procedural responses to likely off-nominal events, a network of more than 1100 tasks that can be re-used for other NextGen approach scenarios, and a series of seven guidelines derived from the quantitative output of this research effort. This research effort yielded the following products:

1. A validated model of current-day RNAV and Next-Gen CSPO approach and land procedures, including detailed task analyses of pilot and ATC tasks (see Gore, Hooey, Haan, Socash, Mahlstedt, & Foyle, 2013)

2. Implications and guidelines to support CSPO technology development and certification relating to the following topics (see Hooey, Gore, Mahlstedt, & Foyle, 2013):
   - I. Operational Concept
     - a. Aircraft separation responsibility (ATC vs. Flight Deck)
   - II. Wake and Blunder Detection Displays
     - a. Wake and blunder avionics requirements
     - b. Wake display format (predicted vs. real-time)
     - c. Wake display location (PFD, Nav Display, or Both)
     - d. Blunder alert styles (One-stage vs. two-stage alerts)
   - III. Spacing Management Automation
     - a. Spacing management automation (Current vs. NextGen)
     - b. Spacing management display locations (PFD, Nav Display, or Both)

3. Identification of a number of potential human-system vulnerabilities associated with NextGen implementation of NextGen CSPO technologies and concepts

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6. APPENDICES

A. NextGen Crew Roles and Responsibilities: Percent Dwell Time
B. NextGen Crew Roles and Responsibilities Workload
C. Separation-Responsibility Concepts: Workload
D. NextGen Information Requirements Predicted versus Real-Time Wake Information: Percent Dwell Time
E. NextGen Information Requirements Predicted versus Real-Time Wake Information: Detection of Aircraft Decoupling
F. NextGen Information Requirements Predicted versus Real-Time Wake Information: Detection of RNP-Loss Alert
G. NextGen Information Requirements Predicted versus Real-Time Wake Information: Workload
H. NextGen Information Requirements Speed Management and Spacing Information: Percent Dwell Time
I. NextGen Information Requirements Speed Management and Spacing Information: Detection of Aircraft Decoupling
J. NextGen Information Requirements Speed Management and Spacing Information: Detection of RNP-loss Alert at 3,000 ft, 900 ft, and 400 ft
K. NextGen Information Requirements Speed Management and Spacing Information: Workload

Appendix A – NextGen Crew Roles and Responsibilities: Percent Dwell Time

Figure 23 presents the scan performance by phase of flight for the PF (left) and for the PM (right) for both the shard and divided task allocation concepts during the descent phase of flight. The data presented illustrate that under the divided task allocation, the PF's scans were increased on the PFD, not changed on the Nav Display, and decreased OTW (p>.05). Figure 23 (right) reveals that in the descent phase of flight, the PM's scans were decreased on the PFD (t(9)=4.7, p<.05) with marginal increases on the Nav Display and OTW (p>.05). This means that the divided task allocation did allow the PF to allocate more attention to the primary flight instruments during flight while the PM increased attention to the Nav Display for monitoring wake and traffic. This suggests a potentially safer allocation of visual attention, maintaining both safe flight and safe separation under CSPO. There was also a marginal reduction in scans OTW for both the PF and PM when the roles were shifted to divided roles in the approach phase of flight. This is likely because both operators had better sources of information within the cockpit that OTW during this phase of flight.

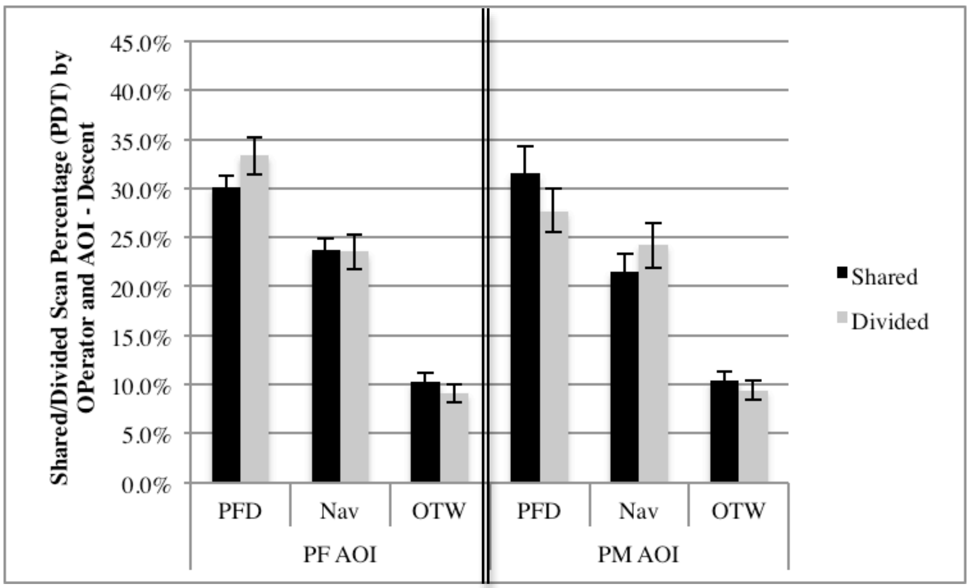

Figure 23. Shared and Divided CSPO 200 PF (left) and PM (right) Scan on the PFD, Nav Display, and OTW AOI in the Descent Phase of Flight (+/-1 SE).

Figure 24 (left) shows that in the approach phase of flight, the PF's scans toward the PFD increased (t(9)=8.4, p<.05), while scans decreased to both the NAV Display (t(9)=2.5, p<.05) and OTW (t(9)=7.0, p<.05). Figure 24 (right) shows that in the approach phase of flight, the PM's scanning significantly decreased on the PFD (t(9)=3.4, p<.05) and OTW (t(9)=2.3, p<.05), and increased significantly on the Nav Display (t(9)=7.4, p<.05). The PF spent significantly more of their scan percentage on the PFD when the roles were adjusted from shared to divided roles. The PM spent significantly less time on the PFD when operating under the divided responsibility over the shared responsibility. Both the PF's and the PM's scan on the Nav Display were significantly impacted by the change in roles, but in opposite directions. It was also apparent that the shift from shared to divided roles brought the PF's attention away from OTW information in the approach phase of flight. This was expected because when on approach, the aircraft was still in the clouds with no outside visibility until breakout at 200ft (which corresponds to the land phase of flight).

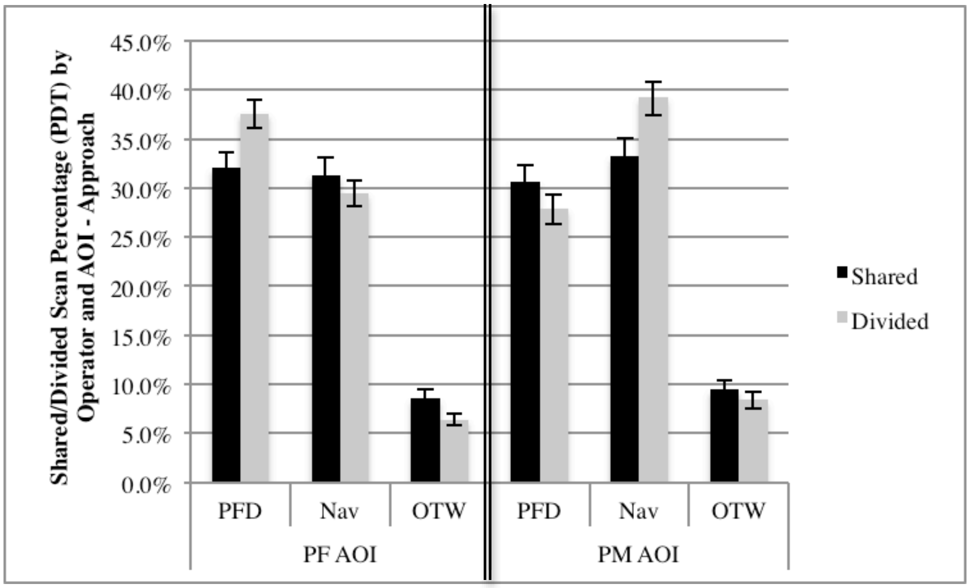

Figure 24. Shared and Divided CSPO 200 PF (left) and PM (right) Scan on the PFD, Nav, and OTW AOI in the Approach Phase of Flight (+/-1 SE).

Figure 25. presents the PF (left) and PM (right) PDT on three AOIs, the PFD, the Nav and the OTW for the land phase of flight operating under the shared and divided task allocation concepts. The PF's scan increased toward the PFD ($t(9)=7.4$, $p<.05$) and OTW OTW ($t(9)=4.4$, $p<.05$), yet decreased on the Nav Display ($p>.05$),when the task allocation was shifted from shared to divided in the land phase of flight. The PM's scan significantly decreased on the PFD ($t(9)=4.3$, $p<.05$), however significantly increased on the Nav Display ($t(9)=7.4$, $p<.05$), and OTW ($t(9)=2.4$, $p<.05$) when the roles were shifted from shared to divided in the land phase of flight.

When the shared task allocation condition is considered, it was apparent that the PF and the PM have very similar scan patterns. However, in the divided task allocation condition, it was apparent that the visual scan was no longer consistent between the two operators. For instance, in the divided-task allocation the PF spent more time monitoring the PFD and the PM spent more time monitoring the Nav Display.

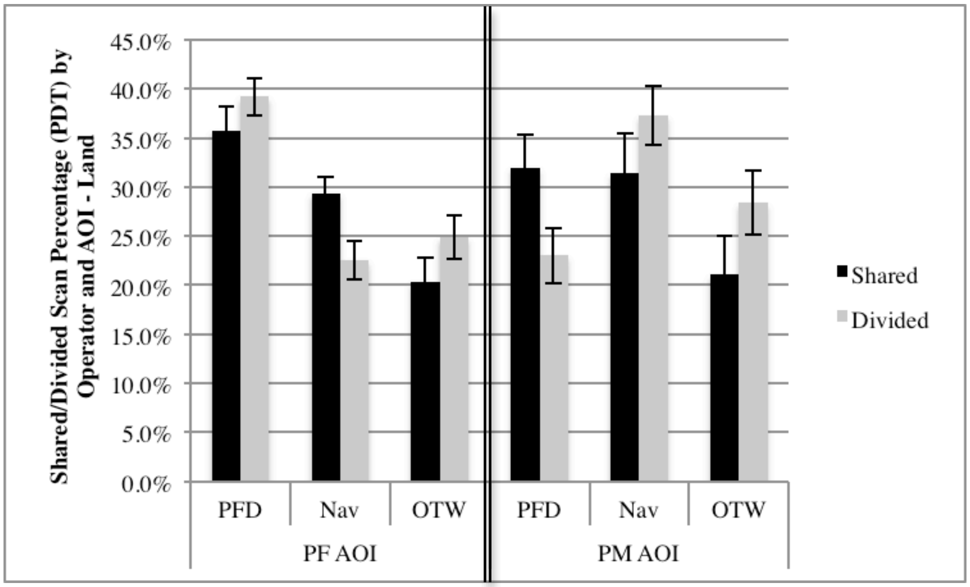

Figure 25. PF (left) and PM (right) Scan Performance on the PFD, Nav Display, and OTW AOI in the land phase of flight with shared and divided task allocation (+/- 1 SE).

Appendix B - NextGen Crew Roles and Responsibilities Workload

Figure 26 through Figure 28 (Descent, Approach, and Land respectively) presents the workload by channel by phase of flight for the PF and for the PM given the shared and divided task allocation concepts. The workload output illustrates a pattern of high but constant load across the three phases of flight on the visual, cognitive-spatial (CS), and cognitive-verbal (CV) workload channels. Modifying the roles from shared to divided task allocation impacted the workload predictions only *negligibly* (at the 10^{th} of a decimal place).

It can be seen that visual workload was higher for both PF and PM on descent, and lowered in the approach phase with no significant difference between the validated and the adjusted models ($p>.05$). The PF and the PM visual workload increased in the land phase of flight as compared to the approach phase of flight with no significant difference between the validated and the adjusted models ($p>.05$). The visual workload was highest for both the PF and PM in the land phase of flight and is attributed to the fact that the aircraft broke out of the clouds at 200 ft so up until that point, all of the pilot scans were internal or into the cloud cover. The CS load followed a similar pattern to the visual pattern; higher in the descent phase, lower in the approach, and highest in the land with no significant difference between the validated and the adjusted model ($p>.05$). The CS data pattern is attributed to the fact that the aircraft did not break through the clouds until 200 ft so all of the scanning that was completed by the flight deck occurred on the internal displays and did not require any external speed and distance estimates to be completed, thereby reducing the visual, and CS workload. The CV load highest in the descent, lowest in the approach and with a higher CV load in the approach than the land phases of flight for the PF and PM with no significant difference between the validated and the adjusted models ($p>.05$). The adjustment to the validated model had the largest impact on the CV channel in the land phase of flight but none of the workload channels were significantly impacted by the adjustment.

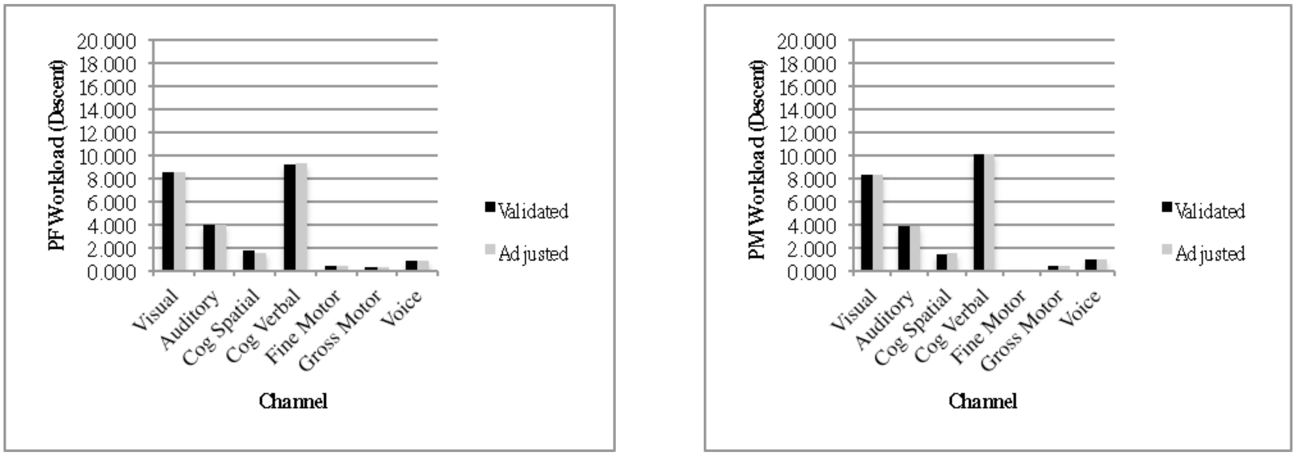

Figure 26. Workload by Channel for the PF (left) and PM (right) in the Descent Phase of Flight with Shared and Divided Task Allocation.

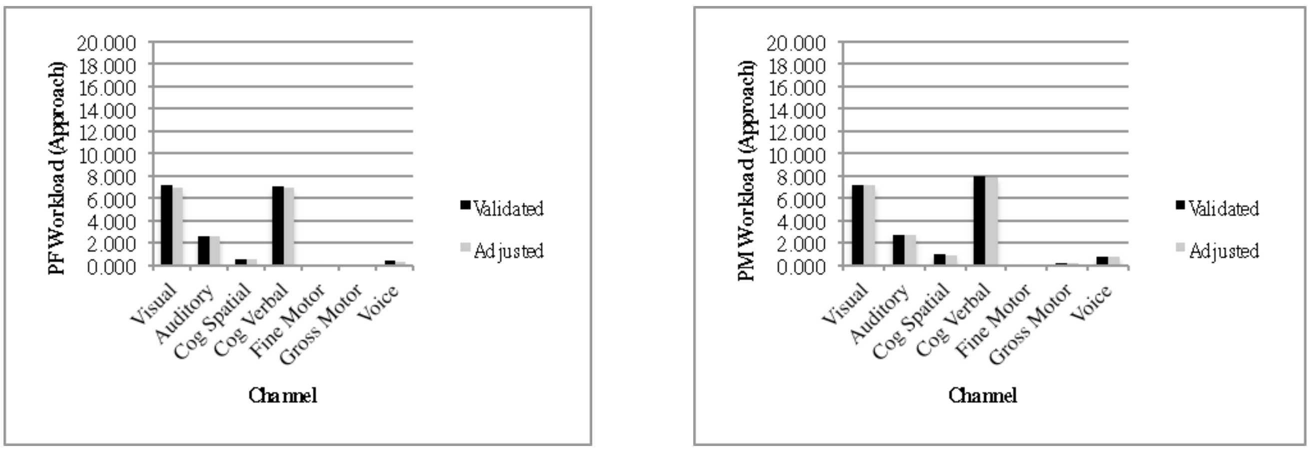

Figure 27. Workload by Channel for the PF (left) and PM (right) in the Approach Phase of Flight with Shared and Divided Task Allocation.

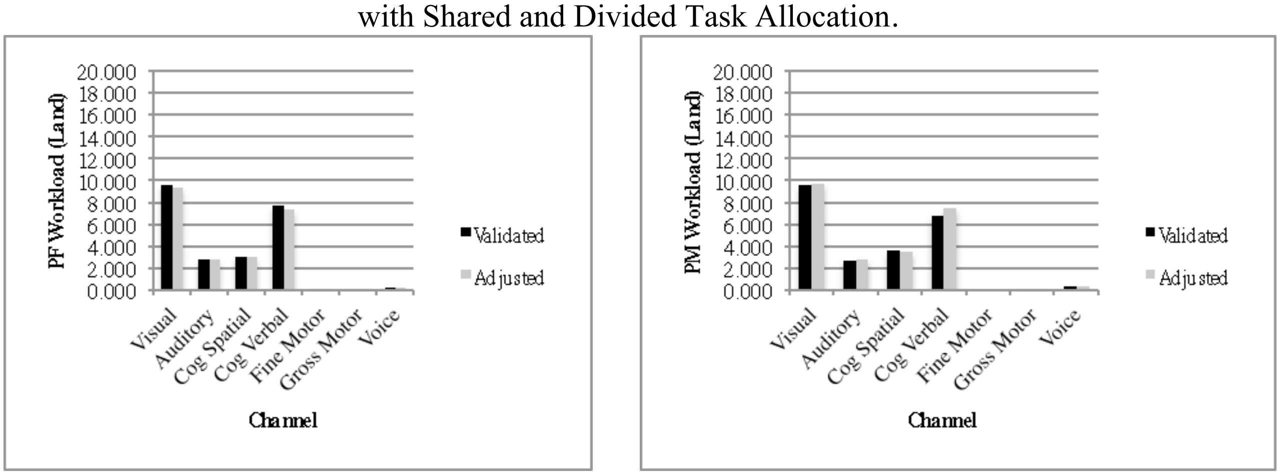

Figure 28. Workload by Channel for the PF (left) and PM (right) in the Land Phase of Flight with Shared and Divided Task Allocation.

Appendix C – Separation-Responsibility Concepts: Workload

Figure 29 presents the workload by channel for the PF across the three separation-responsibility concepts and the two alert styles. The channel-specific workload is comprised of individual channels that comprise the mean workload measure. The workload by channel output highlights that specific aspects of the operator are being taxed to a greater or lesser extent than other aspects of their workload profile. The channels that are impacted most by the use of NextGen CSPO technologies (automation) are visual, cognitive-spatial (CS) and cognitive-verbal (CV) workload channels. As a result, the visual, CS and CV channel effects of transition to NextGen will be highlighted next. There was a significant four–way interaction of concept, by type of alert, by workload channel, by operator ($F(12,216)=2.2$, $p<.05$) indicating that the flight crew's workload by channel was differentially impacted depending on whether the PF or PM operated under Current-day, Transition or NextGen rules in response to a one or two-stage alert.

PF – One-stage alert Condition. The PF's visual workload in the one-stage alert NextGen condition was significantly lower than in the Current-day condition ($t(9)=5.7$, $p<.05$). The PF's visual workload was significantly higher in the one-stage alert Transition condition as compared to the NextGen condition ($t(9)=9.4$, $p<.05$). There was no significant difference in PF's visual workload between the Transition condition as compared to the Current-day condition ($t(9)=.17$, $p>.05$).

The PF's CS workload in the one-stage alert, NextGen condition was significantly higher than in the Current-day condition ($t(9)=12.8$, $p<.05$) and the Transition condition ($t(9)=9.4$, $p<.05$). CS workload in the Transition condition was higher than Current-day condition ($t(9)=5.2$, $p<.05$).

The PF's CV workload in the one-stage alert NextGen condition was significantly lower than Current-day condition ($t(9)=6.9$, $p<.05$) and the Transition condition ($t(9)=27.5$, $p<.05$). The PF CV workload was significantly higher in the one-stage alert Transition condition than the Current-day condition ($t(9)=9.2$, $p<.05$).

PF – Two-stage alert Condition. The PF's visual workload in the two-stage alert NextGen condition was significantly higher than in the Current-day condition ($t(9)=19.3$, $p<.05$) and the Transition condition ($t(9)=16.1$, $p<.05$). The PF's visual workload was significantly higher in the two-stage alert Transition condition than the Current-day condition ($t(9)=5.7$, $p<.05$).

The PF's CS workload in the two-stage alert NextGen condition was significantly higher than the Current-day condition ($t(9)=20.1$, $p<.05$) and the Transition condition ($t(9)=20.6$, $p<.05$). The PF's CS workload was significantly higher in the Transition condition than the Current-day condition ($t(9)=10.2$, $p<.05$).

The PF's CV workload in the two-stage alert NextGen condition was significantly higher than the Current-day condition ($t(9)=47.5$, $p<.05$) and the Transition condition ($t(9)=23.2$, $p<.05$). The PF's CV workload was significantly higher in the one-stage alert Transition condition than the Current-day condition ($t(9)=19.4$, $p<.05$).

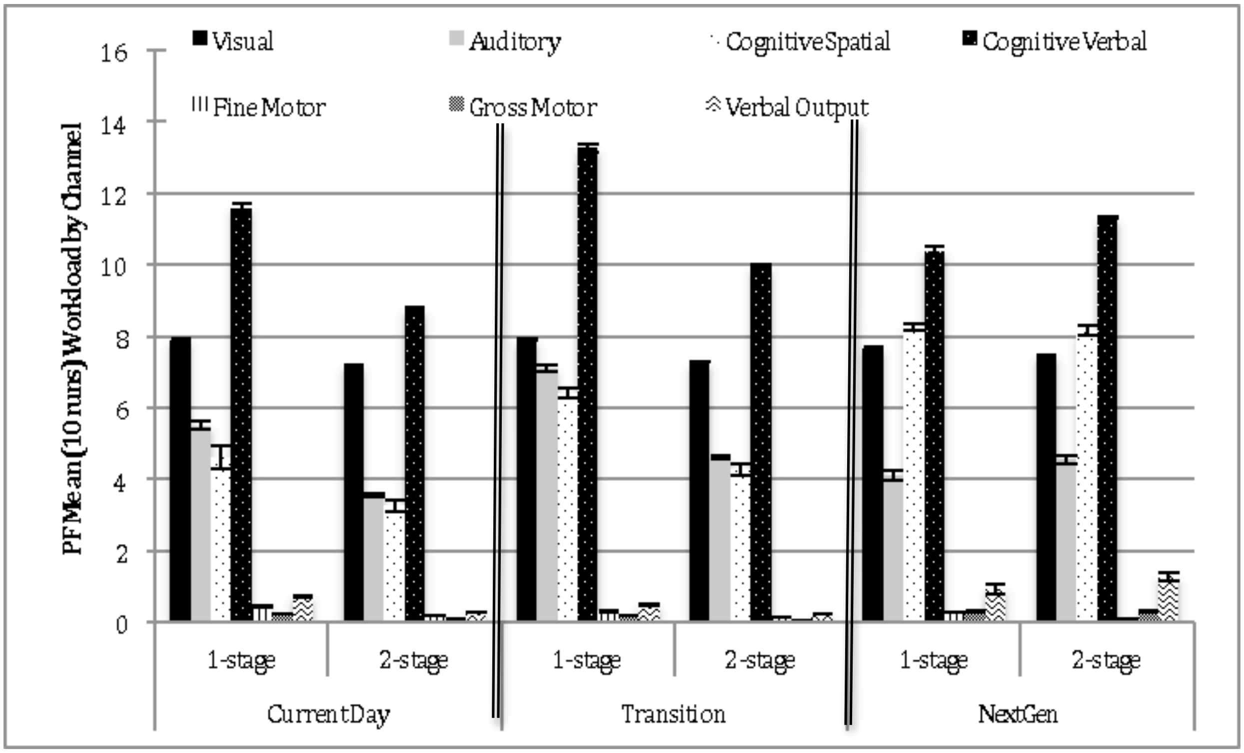

Figure 29. PF Workload by Channel Ratings Across the Total Alert Phase by Separation-Responsibility Concept and Display Manipulations (+/- 1 SE).

Figure 30 presents the workload by channel output for the PM across the experimental manipulations.

PM – One-stage Alert Condition. The PM's visual workload in the one-stage alert NextGen condition was significantly higher than the Current-day condition ($t(9)=2.2$, $p<.01$). The PM's visual workload was significantly higher in the one-stage alert Transition condition as compared to the NextGen condition ($t(9)=3.1$, $p<.05$). The PM's visual workload was significantly higher in the one-stage alert Transition condition as compared to the Current-day condition ($t(9)=2.6$, $p<.05$).

The PM's CS workload in the one-stage alert NextGen condition was significantly higher than the Current-day condition ($t(9)=5.2$, $p<.05$). There was no significant difference between the PF's CS workload in the one-stage alert NextGen condition as compared to the Transition condition ($t(9)=1.5$, $p>.05$). The PM's CS workload was significantly higher in the Transition condition than the Current-day condition ($t(9)=2.3$, $p<.05$).

The PM's CV workload in the one-stage alert NextGen condition was significantly lower than in the Current-day condition ($t(9)=6.1$, $p<.05$). The PM's CV workload was significantly lower in the one-stage alert NextGen condition as compared to the Transition condition ($t(9)=13.2$, $p<.05$). The PF's CV workload was significantly higher in the one-stage alert Transition condition as compared to the Current-day condition ($t(9)=8.3$, $p<.05$).

PM – Two-stage Alert Condition. The PM's visual workload in the two-stage alert NextGen condition was significantly higher than in the Current-day condition ($t(9)=9.9$, $p<.05$) and the Transition condition ($t(9)=3.4$, $p<.05$). The PF's visual workload was significantly higher in the Transition condition than the Current-day condition ($t(9)=3.6$, $p<.05$).

The PM's CS workload in the two-stage alert NextGen condition was significantly higher than the Current-day condition (t(9)=13.5, p<.05) and the Transition condition (t(9)=7.6, p<.05). The PM's CS workload was significantly higher in the Transition condition as compared to the Current-day condition (t(9)=4.0, p<.05).

The PM's CV workload in the two-stage alert NextGen condition was significantly higher than the Current-day condition (t(9)=31.2, p<.05) and the Transition condition (t(9)=8.3, p<.05). The PM CV workload was significantly higher in the two-stage alert Transition condition as compared to the Current-day condition (t(9)=7.4, p<.05).

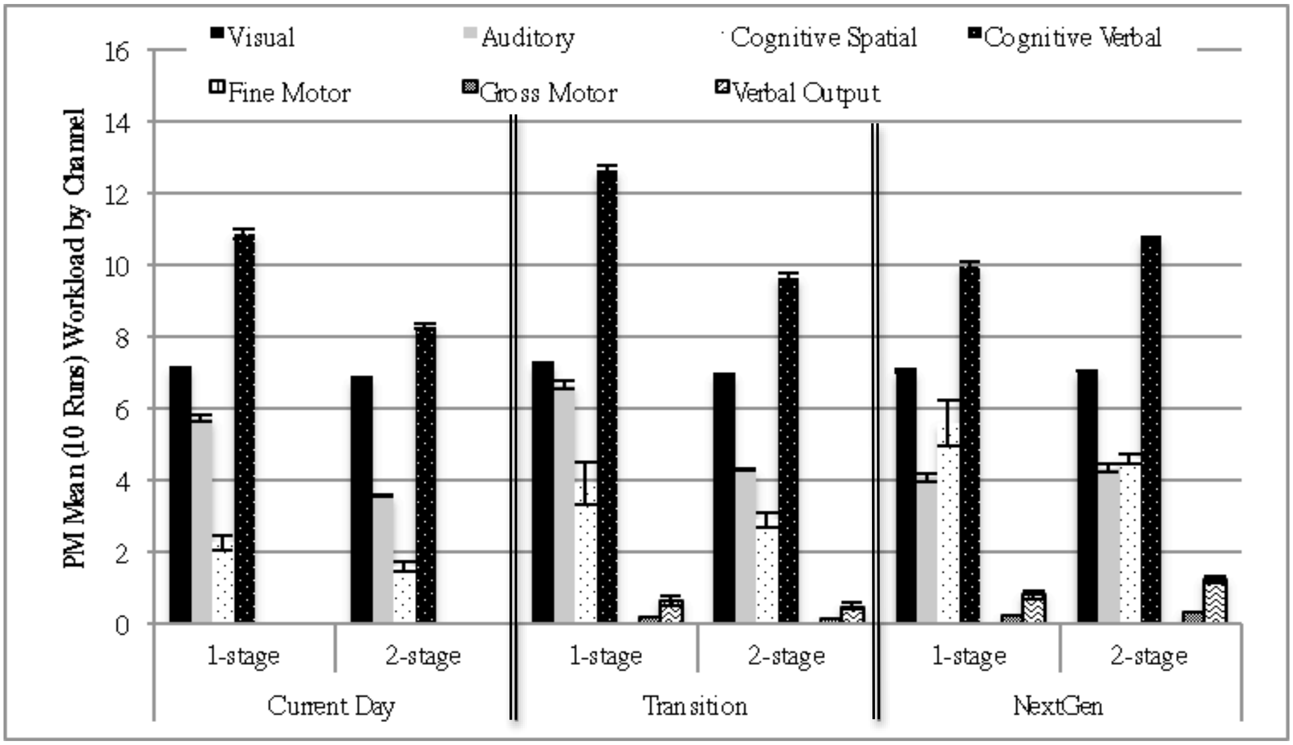

Figure 30. PM Workload by Channel Ratings Across the Total Alert Phase by Separation-Responsibility Concept and Display Manipulations (+/- 1 SE).

Appendix D – NextGen Information Requirements Predicted versus Real-Time Wake Information: Percent Dwell Time

Figure 31 presents the PM's percent dwell time to the PFD, Nav or OTW as a function of whether the wake information was presented in a predicted or real-time format on the PFD, Nav Display, or on both locations (LocPFD, LocNav, LocPFD+Nav).

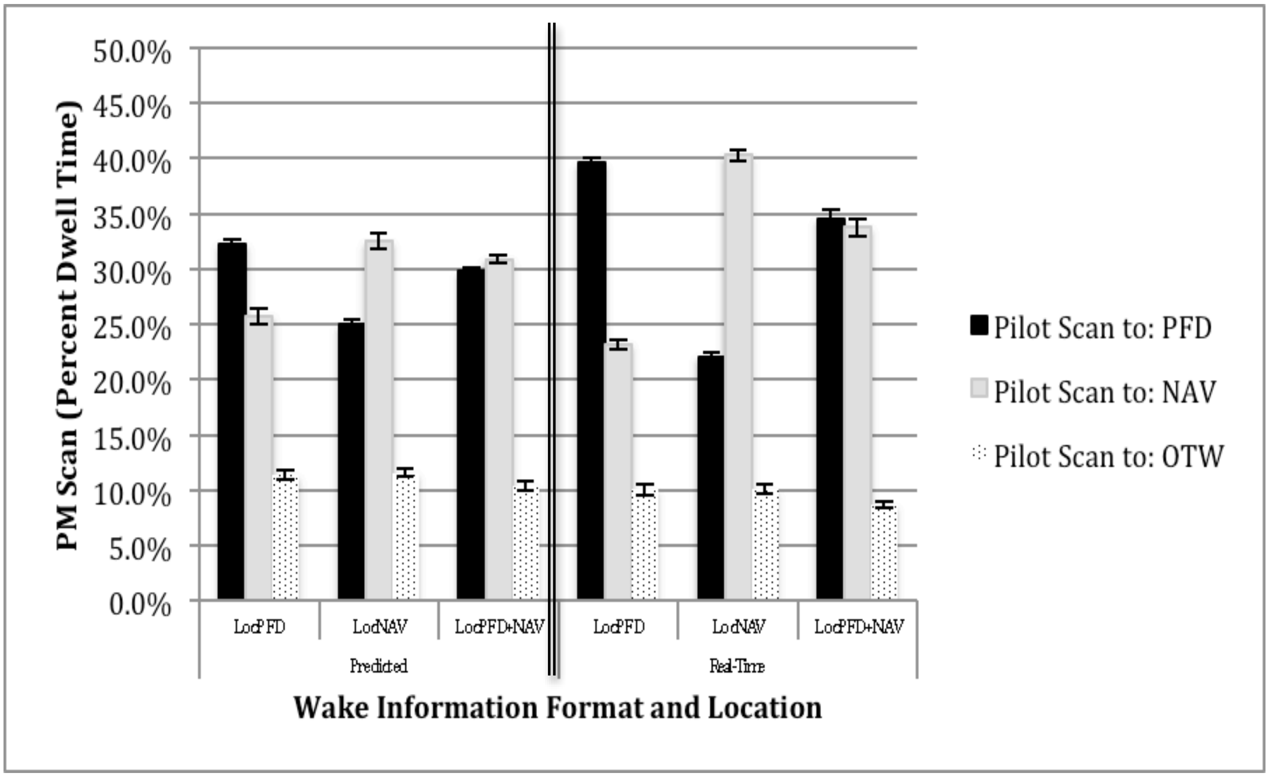

Figure 31. PM Scan Pattern to the PFD, Nav, or to Both as a Function of Information Location (+/-1 SE).

Predicted Wake Format. In terms of the predicted format (left side of Figure 31), it can be seen that the PM's scan to the PFD was significantly higher than either to the Nav Display or the OTW when the wake information was presented on the PFD ($t(9)=6.4$, $p<.05$; $t(9)=34.6$, $p<.05$). It is apparent that the PM still looked to the Nav Display on 23% of the time when information was presented on the PFD. This is likely due to the cross checks that are constantly engaged in by the pilot on approach.

When wake information is presented on the Nav Display, the PM's scan to the Nav Display is significantly higher than either to the PFD or OTW ($t(9)=7.0$, $p<.05$; $t(9)=19.5$, $p<.05$). It is apparent that the PM will still looked to the PFD 22% of the time when information is presented on the Nav Display due to the crosschecks that are constantly engaged in by the PM on approach. When information was presented on both the Nav Display and the PFD, the PM scans for the wake information equally on those displays with no significant difference between the scan percentages between PFD or Nav Display ($p>.05$).

Real-time Wake Format. In terms of the real-time wake information format (right side of Figure 31), there was a significant difference on the pilot's scan performance (the amount that the PM looks at a given area of interest) ($F(1,18)=161.8$, $p<.05$). It can be seen that the PM's scan to the PFD was significantly higher than either to the Nav Display or the OTW when the wake information was presented on the PFD ($t(9)=16.1$, $p<.05$; $t(9)=26.0$, $p<.05$). The PF still looked to the Nav Display 23% of the time when information was presented on the PFD, an important consideration for displaying redundant information. When the overall pattern of data is examined on the graph, it can be seen that there was a greater spread in the scan data between the PTD on the PFD and Nav Display.

When real-time wake information was presented on the Nav Display, the PM's scan to the Nav Display was significantly higher than either to the PFD or OTW ($t(9)=19.1$, $p<.05$; $t(9)=19.3$, $p<.05$). It is apparent that the PF still crosschecked information on the PFD 23% of the time when information was presented on the Nav Display.

When real-time wake information was presented on both the Nav Display and the PFD, the pilot scanned for the wake information equally on those displays with no significant difference between the scan percentages between PFD or Nav Display ($p>.05$).

Appendix E – NextGen Information Requirements Predicted versus Real-Time Wake Information: Detection of Aircraft Decoupling

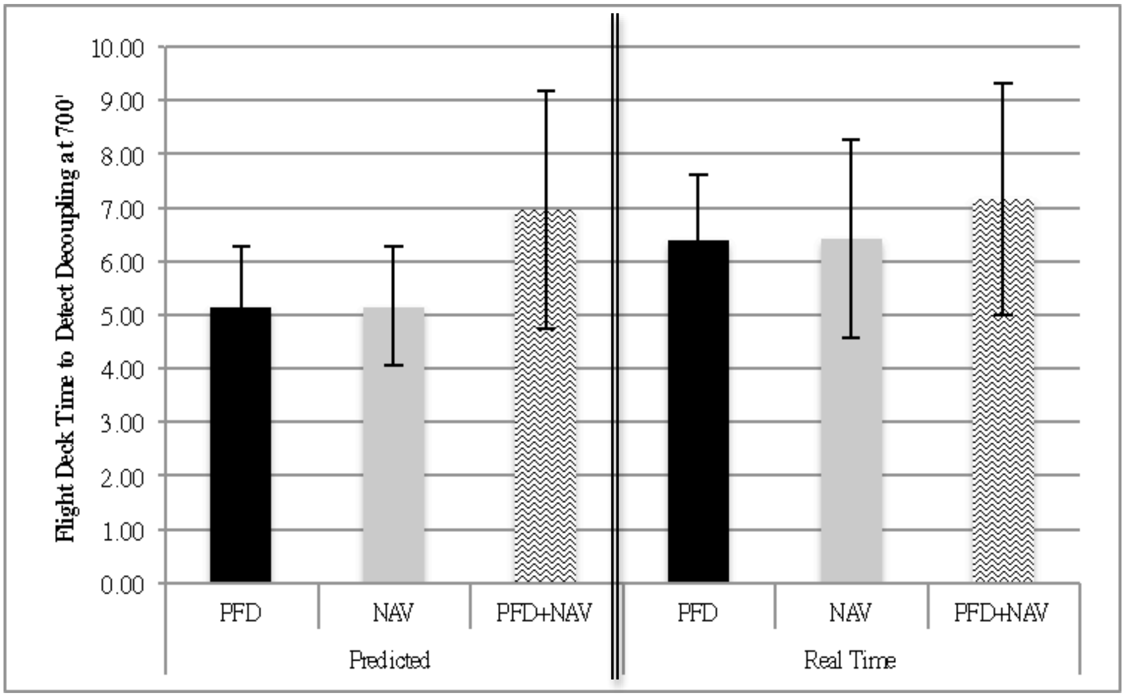

Figure 32. Flight Deck Detection of the Aircraft Decoupling Event on the PFD when wake information was presented either on the PFD, Nav Display, or Both (+/-1 SE).

Appendix F – NextGen Information Requirements Predicted versus Real-Time Wake Information: Detection of RNP-Loss Alert

The RNP alert detection latency times were collected on 10 Monte Carlo simulation runs of the off-nominal events of RNP-Loss alert at 900ft and 400ft for the PF and PM (Figure 33 and Figure 34). While none of the difference in RNP-loss alert detection times for either the PF (Figure 33) or PM (Figure 34) was statistically significant, the output is reported as it provides insight into the sensitivity of the model for use in wake information display manipulations.

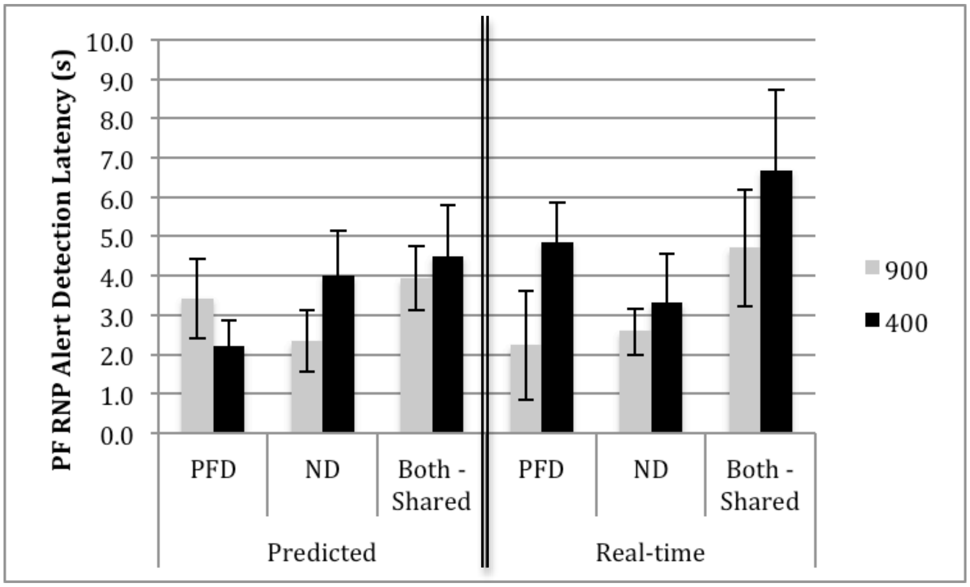

Figure 33. PF RNP-Loss Alert Detection Latency (in seconds) when alert was issued at either 900 ft and 400 ft altitude (plotted with +/-1 SE).

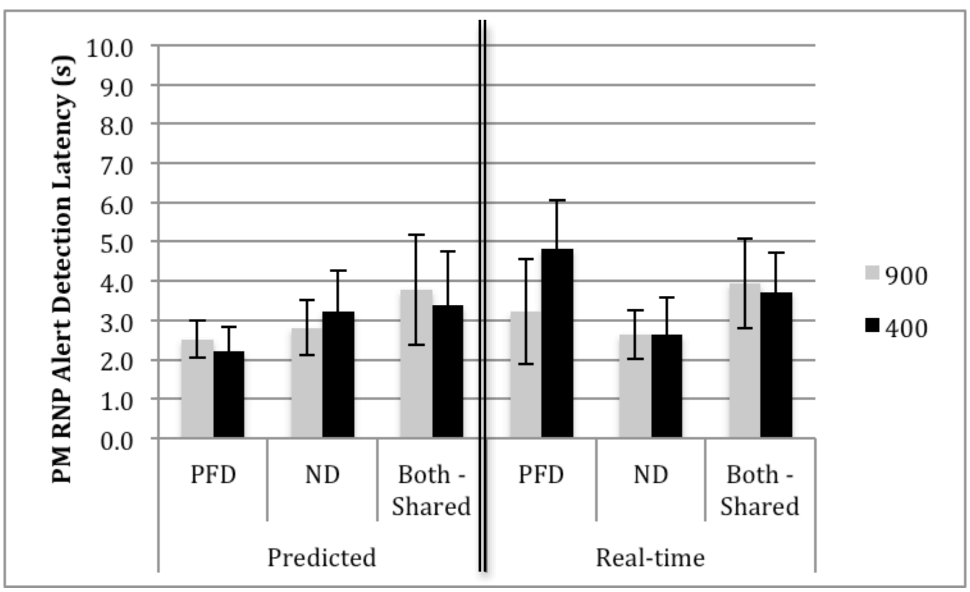

Figure 34. PM RNP Alert Detection Latency (s) wake information requirements manipulation by 900 ft and 400 ft event probe.

Appendix G – NextGen Information Requirements Predicted versus Real-Time Wake Information: Workload

The location and format of the wake information had very little effect on the PF's overall workload (see Figure 35). This is consistent with expectations because the location of wake information was manipulated in the model, which was not expected to impact the operator workload.

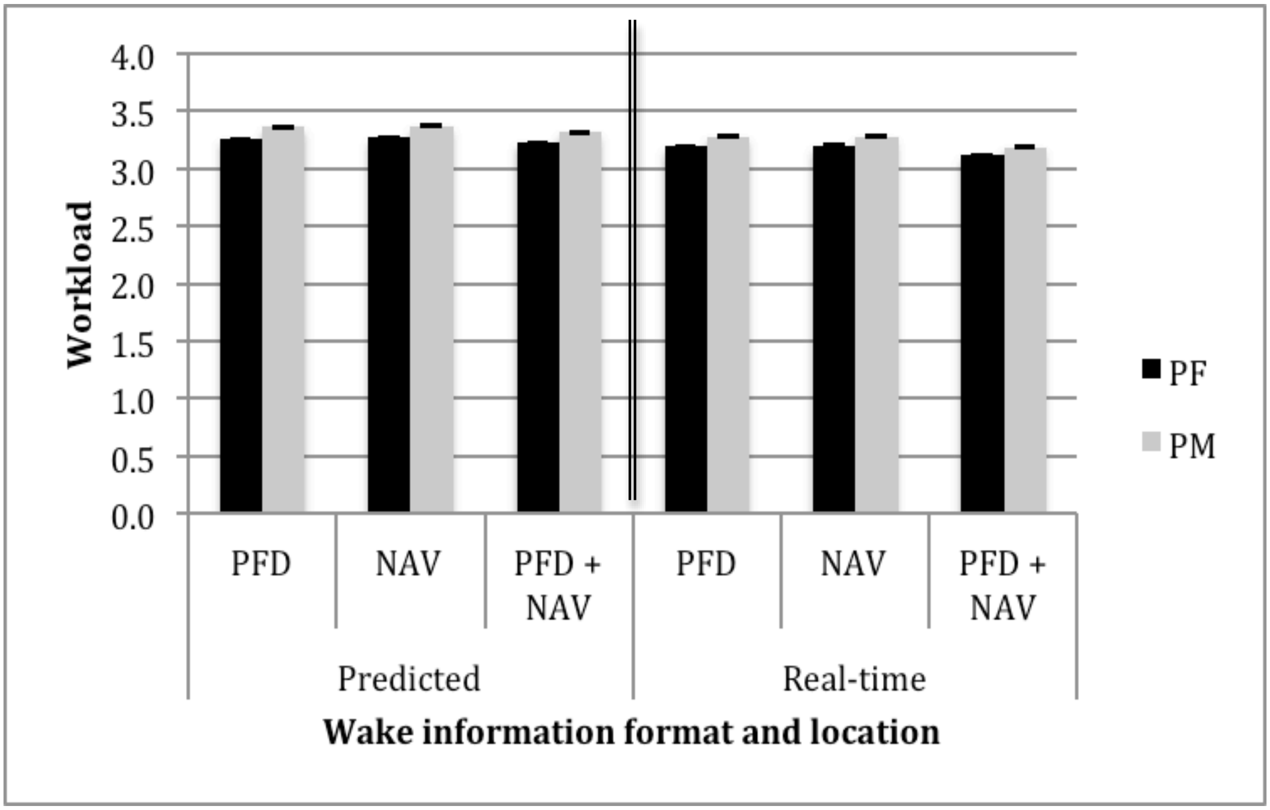

Figure 35. Mean PF workload given wake information format and location.

Appendix H – NextGen Information Requirements Speed Management and Spacing Information: Percent Dwell Time

Figure 36 presents the PM's scan percentage to the PFD, Nav, and OTW for spacing information, given the location and format of the spacing information. While there is no statistical significant difference between the PF (presented earlier) and the PM, the output of the PM is presented for completeness sake.

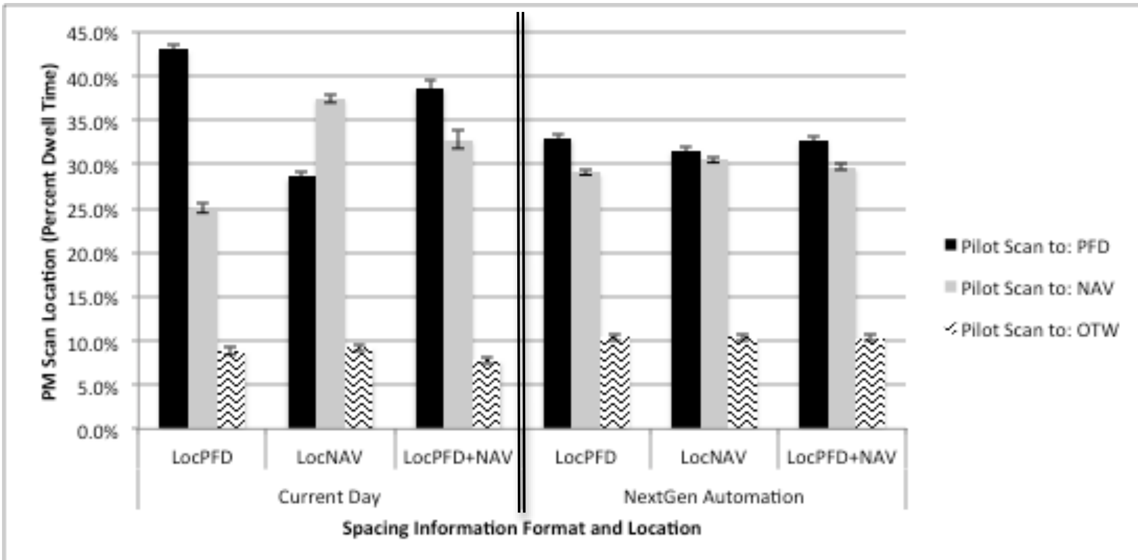

Figure 36. PM scan percentage given spacing information style and location.

Current-day Spacing Automation. In terms of the current-day spacing information style (three sets of three bars on the right of Figure 36), it can be seen that the PM's scan was more evenly distributed than in the NextGen automated condition. The PF scanned for spacing information on the PFD more than on the Nav Display ($t(9)=8.3$, $p<.05$) or OTW ($t(9)=38.7$, $p<.05$) when spacing information was located on the PFD. When spacing information was located on the Nav Display, the PM scanned significantly more to the PFD than either the Nav Display ($t(9)=1.7$, $p<.05$) or OTW ($t(9)=32.4$, $p<.05$). When spacing information was presented in both locations, the PM scanned the PFD significantly more than either the Nav Display ($t(9)=5.4$, $p<.05$) or OTW ($t(9)=33.3$, $p<.05$). There was no difference between the PM scans OTW ($p>.05$).

NextGen Spacing Automation. Considering only the NextGen automated spacing information (three sets of three bars on the left of Figure 36), when the NextGen automated spacing information was presented on the PFD, the PM scan to the PFD was significantly greater than to the Nav Display ($t(9)=17.2$, $p<.05$) or OTW ($t(9)=47.1$, $p<.05$). As in the wake information manipulation, this provides some support that the pilot will maintain their attention and focus on the PFD when flying the approach, but that they do shift their attention to the Nav Display 25% of the time; likely due to the cross-checks that are necessary for the approach. The PM monitored the Nav Display more than the PFD when spacing information was located on the Nav Display ($t(9)=10.5$, $p<.05$). It is apparent that the PM still looked to the PFD 29% of the time when information was presented on the Nav Display; likely because they were conducting cross-checks during the approach phase. The PM scanned for spacing information on the PFD to a greater extent than on the Nav Display when information was presented on both displays ($t(9)=3.8$, $p<.05$).

Appendix I – NextGen Information Requirements Speed Management and Spacing Information: Detection of Aircraft Decoupling

NextGen Spacing Automation. In the NextGen Automation condition (right side of Figure 37) when the decoupling event occurred at 1000 ft, the detection of the aircraft decoupling was fastest when the information was presented on both the PFD and the Nav Display. In the NextGen Automation condition when the decoupling event occurred at 700 ft the detection of the aircraft decoupling was fastest when the information was presented on either the PFD or the Nav Display but not both. In summary, the model predicted that the fastest time to detect the decoupling event when decoupling occurred at 1000ft or at 700 ft was when the spacing information was located on the PFD in a Current Day format. When presented in a NextGen Automation format, the pilot's eyes appear to be drawn away from the RNAV/LNAV notation on the PFD due to the other dynamic information on the flight deck, and probably due to a complacency effect because the pilot is not actively controlling speed or separation.

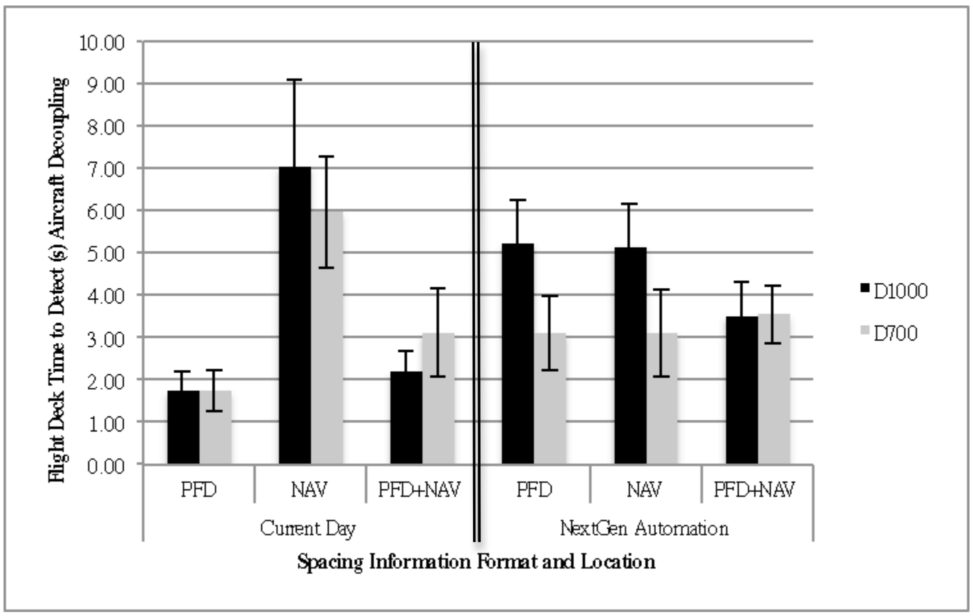

Figure 37. Flight deck time to notice aircraft decoupling (in seconds) at 1000 ft and 700 ft in predicted or real-time information style.

Appendix J – NextGen Information Requirements Speed Management and Spacing Information: Detection of RNP-loss Alert at 3,000 ft, 900 ft, and 400 ft

The RNP-loss alert detection latency times when the RNP alert occurred at 3,000 ft, 900 ft and 400 ft were collected in 10 Monte Carlo simulation experimental runs. The RNP Alert detection latency time data when events occurred at 3,000 ft, 900 ft, and 400 ft are presented for the PF and PM in Figure 38 and Figure 39 respectively. While none of the differences in RNP detection time were statistically significant in the 3,000 ft, the 900 ft, or the 400 ft condition, they are being reported as the results provide insight into the sensitivity of the model to the manipulations that were made (p>.05).

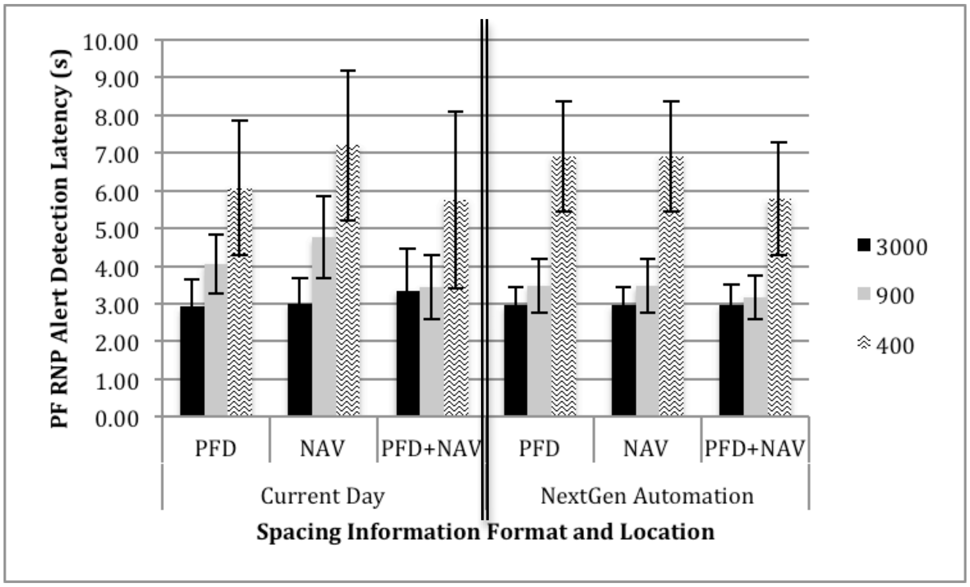

Figure 38. PF RNP-loss alert detection latency (in seconds) at 3,000 ft, 900 ft, and 400 ft in the spacing information requirements model.

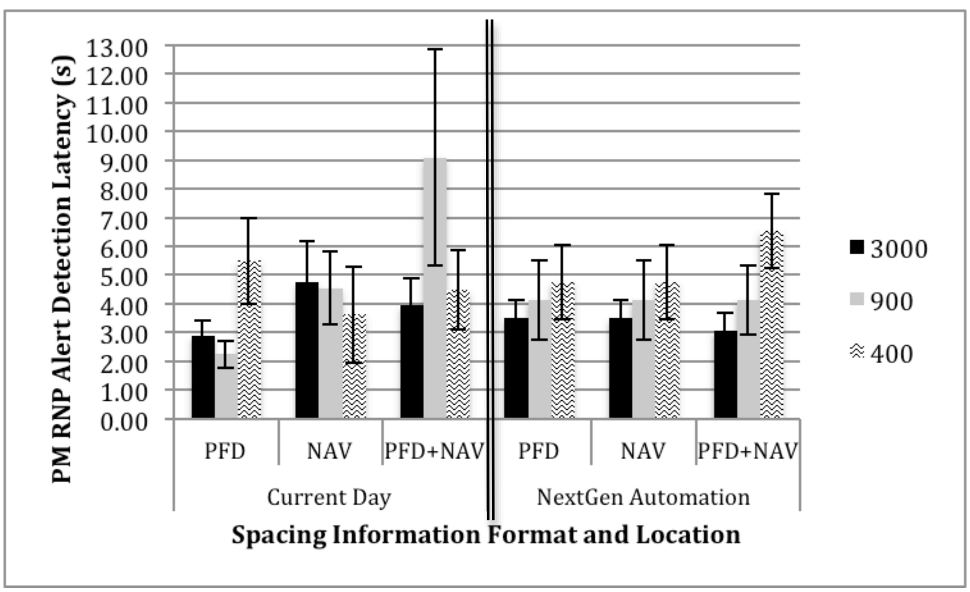

Figure 39. PM RNP-loss alert detection latency (in seconds) at 3,000ft, 900ft, and 400ft in the spacing information requirements model.

Appendix K – NextGen Information Requirements Speed Management and Spacing Information: Workload

Figure 40 presents all of the PF's and the PM's workload broken out by spacing information format and location of information. As evident in the figure, the workload was predicted to be at a mid-level on the TAWL zero to seven-point scale. As with the wake information, the location of the spacing information had little effect on the operators' workload. This happened because the rate that the information was updated was manipulated and not the difficulty to detect the spacing information.

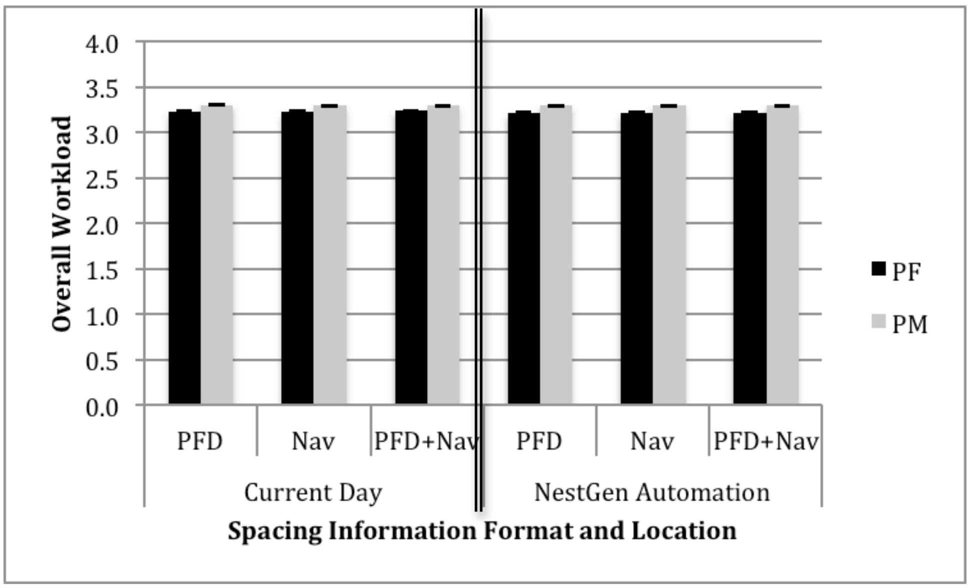

Figure 40. Mean PF and PM workload as a function of spacing information format and location.

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14. ABSTRACT
The objectives of the current research were to develop valid human performance models (HPMs) of approach and land operations; use these models to evaluate the impact of NextGen Closely Spaced Parallel Operations (CSPO) on pilot performance; and draw conclusions regarding flight deck display design and pilot-ATC roles and responsibilities for NextGen CSPO concepts. This document describes the model scenarios and results including predictions of pilot workload, visual attention, and time to detect off-nominal events. A companion document (Hooey, Gore, Mahlstedt, & Foyle, 2013) presents design guidelines and implications.

15. SUBJECT TERMS human performance models, NextGen, Closely Spaced Parallel Operations (CSPO), Man-machine Integration Design and Analysis System (MIDAS) v5

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