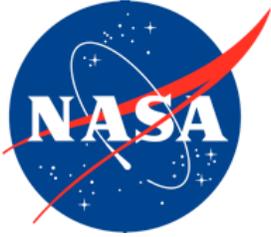Evaluating NextGen Closely Spaced Parallel Operations Concepts with Validated Human Performance Models: Flight Deck Guidelines

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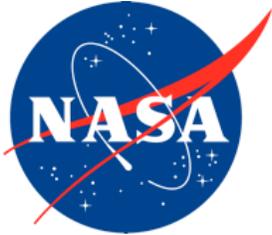
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Executive Summary

The objectives of the current research were to: Develop valid human performance models (HPMs) of approach and landing 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. These were accomplished in two phases. In Phase 1, CSPO scenarios were developed and validated. In Phase 2 (reported here) flight deck guidelines were developed.

<u>Phase 1 (Model Development and Validation).</u> Using NASA's Man-machine Integration Design and Analysis System v5 (MIDAS v5), a high-fidelity human performance model (HPM) of a two-pilot commercial crew flying current-day area navigation (RNAV) approach and landing operations was developed. The model contained over 970 individual pilot tasks, which were based on cognitive task analyses and cognitive walkthroughs conducted with commercial pilots and air traffic controllers. The model was validated by statistically comparing model results to existing Human-in-the-Loop (HITL) data. Workload output correlated with a comparable HITL study with r^2 values ranging from .55 to .94 depending on the specific type of workload. Visual percent dwell time correlated with three HITL studies (r^2 = .99). These validation results provide confidence that the model validly represented pilot performance. Next, the validated baseline RNAV model was extended to represent NextGen Closely Spaced Parallel Operations including the projection of new pilots tasks, flight deck automation, and displays for the depiction of blunder and wake threats in both nominal and off-nominal conditions. A comprehensive 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 (CSPO Evaluations).</u> The MIDAS CSPO model 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. Analyses of pilot performance measures, including time required to complete tasks, workload, scan patterns and responses to off-nominal events were used to draw conclusions regarding the flight deck requirements necessary to support NextGen CSPO concepts. This report summarizes the main findings, operational implications, and future research requirements for the following issues:

      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 (Primary Flight Display [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)

Full details including model assumptions, scenarios, and results can be found in the companion report:

1.   Introduction

Closely Spaced Parallel Operations (CSPO) are expected to enable paired approaches to minimum runway spacing in instrument meteorological conditions (IMC) while maintaining the required level of safety (Cox, 2010). To support these more precise and closely coordinated operations, it is anticipated that there may be substantially more data available to pilots on the flight deck (e.g., weather, wake, traffic trajectory projections, and data pertaining to paired aircraft broadcast via ADS-B). CSPO concepts are relatively early in the concept development phases. Examples include the Simplified Aircraft-based Paired Approach (SAPA; Swider, 2010; Johnson et al., 2010; Guerreiro, et al., 2010), MITRE's paired approach concept (Bone, 2000), 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), and Simultaneous Offset Instrument Approaches (SOIA), in use at several airports today. These NextGen technologies, procedures and operations, must be designed with consideration of the pilots' information requirements, capabilities and limitations. Failure to do so will leave the pilots, and thus the entire aviation system, vulnerable to error.

Human Performance Models (HPMs) can be used to evaluate new technologies and operational procedures, and determine the appropriate allocation of roles and responsibilities between the human operators and the automation (Gore, 2008; Foyle & Hooey, 2008). HPMs are software simulations of the flight deck environment, flight deck displays and related information and communication requirements between the flight crew and air traffic controllers (ATC) coupled with a simulation of pilots' workflow and cognitive processing. They allow for an analysis of existing and proposed pilot and ATC procedures, operations, and technology in evolving systems such as NextGen. HPMs have been shown to play a role in all phases of the technology design and development process (Gore, 2008; Foyle & Hooey, 2008). HPMs hold the most promise when they are used early in the system design process and when used iteratively with human-in-the-loop (HITL) simulation data (Elkind, Card, Hochberg, & Huey, 1989; Foyle & Hooey, 2008).

The objective of this two-phased research project was to develop guidelines and determine implications for NextGen closely spaced parallel operations (CSPO). In Phase 1, a baseline human performance model (HPM) of current-day RNAV approaches was developed and validated (see Gore et al., 2011) using the Man-machine Integration Design and Analysis System (MIDAS v5; described next). The model was extended to represent two CSPO operational concepts; and 'what-if' scenarios were exercised to evaluate human performance under four different off-nominal scenarios. This paper summarizes the results of Phase 2 of this research project, in which the validated model was extended to evaluate pilot human performance while varying the underlying assumptions associated with a range of automation and technologies for monitoring blunder and wake threats and managing spacing. Twenty-two scenarios were developed and analyzed to define CSPO guidelines for information presentation. The models are described in greater detail in Gore, Hooey, Mahlstedt, and Foyle (2013) while the operational findings and implications are reported here.

1.1   Background

The Man-machine Integration Design and Analysis System (MIDAS) is an established HPM that predicts human-system performance under nominal and off-nominal conditions (Gore, 2008). MIDAS symbolically represents many mechanisms that underlie and cause human behavior. It can be used to predict pilot workload, situation awareness, pilot scan metrics, and event detection times as a function of flight deck operations, procedures, and technologies.

The MIDAS model of RNAV approach and landing procedures developed in Phase 1 of this research project (Gore et al., 2011) included a high-fidelity representation of two-crew commercial transport operations. The model scenario initiated when the aircraft was on descent at 10,000 ft Above Ground Level (AGL) and continued to touchdown. The aircraft broke through the cloud ceiling at 800 ft AGL, with a decision height (DH) of 650 ft AGL (see Figure 1). The tasks of the pilot flying (PF) and pilot monitoring (PM) were modeled in high fidelity, while the tasks of air traffic control (ATC) were modeled in lower fidelity, but with sufficient detail to represent pilot-ATC interactions.
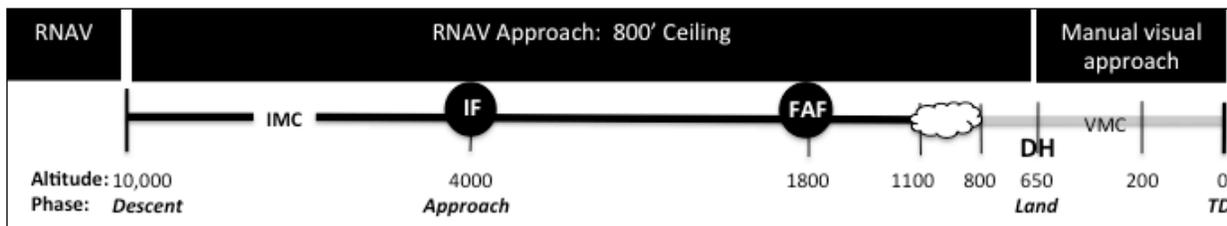

Figure 1. RNAV scenario.
Notes: DH = Decision Height; FAF = Final Approach Fix; IF = Initial Fix; IFR = Instrument Flight Rules; IMC = Instrument Meteorological Conditions; RNAV = Area Navigation; TD = touchdown; VMC = Visual Meteorological Conditions.

The RNAV model contained over 970 individual pilot tasks, which were based on cognitive task analyses and cognitive walkthroughs conducted during interviews with commercial pilots and air traffic controllers. The tasks, and the task sequences, were then validated using semi-structured, scenario-based, focus groups comprised of a total of eight commercial airline pilots. The scenario input parameters for workload and pilot scan patterns were validated using quantitative rating data collected from the eight focus group pilots (see Gore et al., 2011). Model outputs, including workload and pilot scan patterns, were statistically compared to existing HITL data. The workload model output correlated with a comparable HITL study with r^2 of .54 for overall workload. The individual workload dimensions also correlated positively with the HITL study with r^2 ranging from .55 to .94. Visual percent dwell time correlated with three HITL studies ($r^2 = .99$). These validation results provide confidence that the model validly represents pilot performance. Interested readers are directed to Gore et al. (2011), for further information on the validation process and results.

Next, the validated baseline RNAV model was extended to represent the Closely Spaced Parallel Operations (CSPO) concept being developed and evaluated at NASA Ames Research Center (VCSPA; Verma et al., 2008). Two operational implementations of the CSPO concept were evaluated (see Figure 2): 1) CSPO 800 ft, with an 800 ft ceiling and manual flight after a DH of 650 ft AGL, and 2) CSPO 200 ft with a 200 ft ceiling and autoland capability. The CSPO 200 implementation with a lower (200 ft) ceiling and autoland automation is most representative of NextGen CSPO goals. The model represented the pilots of the trailing aircraft of a CSPO pairing in

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high fidelity, while the task and procedures of the lead aircraft and ATC were modeled at a lower level of fidelity.
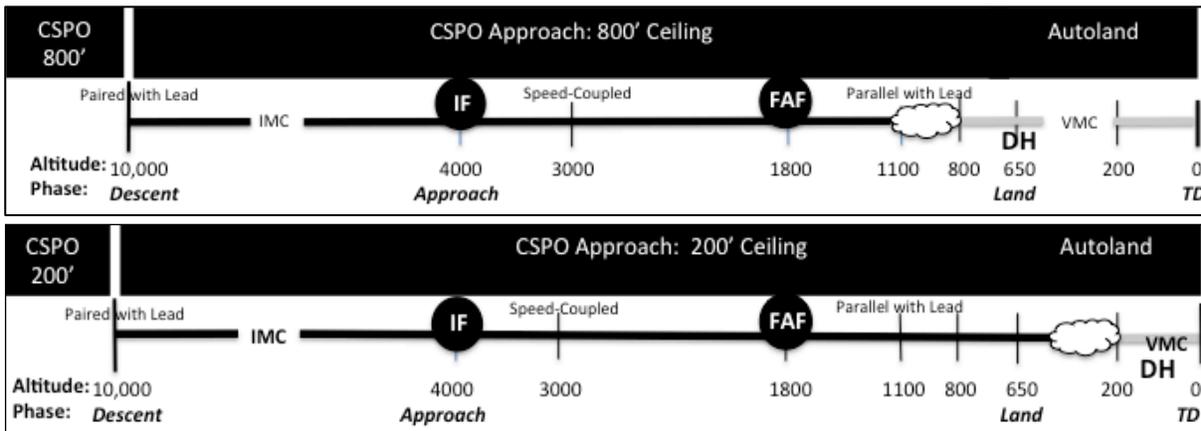

Figure 2. CSPO scenarios; CSPO 800 (Top panel) and CSPO 200 (Bottom panel).
Notes: IF = Initial Fix, FAF = Final Approach Fix, DH = Decision Height, IMC = Instrument Meteorological Conditions, VMC = Visual Meteorological Conditions, TD = Touchdown

The CSPO scenario inputs (task sequence and input parameters) were validated using the same scenario-based focus groups as for the RNAV model discussed above. The CSPO scenario outputs were compared to the RNAV scenario output to predict changes to pilot performance associated with CSPO procedures and compared to RNAV operations. 'What-if' scenarios were conducted to explore the impact of the NextGen CSPO concept on pilot performance during four *off-nominal* conditions: 1) High wind/turbulence; 2) Flight Mode Annunciator (FMA) Error; 3) Required Navigation Performance (RNP) alert; and, 4) Rogue aircraft present on the runway. These results are available in Gore et al., 2011.

In this second phase of the research project, the MIDAS scenarios of CSPO approach and landing were extended to assess the impact of various NextGen Flight Deck technologies for monitoring blunder and wake threats and managing spacing. This expanded model culminated in more than 1100 operator tasks. An overview of the important findings for each issue is provided below. Complete scenario details and additional data are available in the accompanying report (Gore, Hooey, Mahlstedt, & Foyle, 2013).

2. CSPO FLIGHT DECK REQUIREMENTS: FINDINGS AND IMPLICATIONS

The MIDAS CSPO scenarios were 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. The output for each scenario was generated from 10 Monte Carlo simulation runs. 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. Specifically, the validated CSPO models were augmented to evaluate the following issues:

> I. Operational Concept
> > a. Aircraft separation responsibility (ATC vs. Flight deck)
> II. Wake and Blunder Detection Avionics
> > 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)

2.1 OPERATIONAL CONCEPT

2.1.1 Aircraft separation responsibility (ATC vs Flight Deck)

In contrast to the current-day operational concept in which ATC is responsible for separation, NextGen concepts like NASA Ames' VCSPA concept (Verma et al., 2008) have considered shifting the responsibility for wake and blunder threat detection to the pilots. Such an operational concept would require advanced avionics capable of depicting conformance zones, wake, and enhanced traffic information on the flight deck. While providing a richer picture of the traffic environment, adding additional data on the flight deck must be balanced against the potential of increased workload and monitoring requirements that could then negatively impact overall pilot performance during this critical phase of flight. The following analysis assesses the tradeoffs between equipping the flight deck with blunder and alert warnings needed for pilot self-separation operations compared to maintaining the current-day ATC-separation responsibility.

Method

The CSPO scenario was modified to evaluate pilot performance in two conditions: 1) **Pilot-responsible separation**, with the flight deck equipped with enhanced wake and traffic displays; and, 2) **ATC-responsible separation**, with the flight deck equipped with current-day displays (without enhanced wake and traffic depictions).

In the scenario, as the aircraft was on final approach, a wake threat occurred in which the wake of the lead aircraft extended into the trailing aircraft's trajectory. This threat required a missed approach. In the pilot-responsible scenario, pilots of the trailing aircraft were equipped with wake avionics that issued an auditory and visual alert when an emergency escape maneuver was required. The dynamic breakout maneuver was shown on the Nav Display as in Verma et al.'s (2008) VCSPA concept. In the ATC-responsible scenario, ATC automation alerted the controller, who then issued a verbal Go-Around command to the aircraft, with a unique (non-procedural) missed approach path that accounted for metroplex traffic, terrain, and wind conditions.

Results

The impact of shifting separation responsibility from ATC to the flight deck on the pilots' time to initiate a Take-Off and Go-Around maneuver (TOGA), workload, and visual scan during the wake threat period was assessed. The data presented below are for the Pilot Flying (PF), as it is expected that the PF would be the most overloaded in this scenario, given PF responsibilities for monitoring aircraft performance and deciding if a missed approach is necessary in the event of a wake threat.

Time to Initiate TOGA Escape Maneuver. The model predicted that the time to initiate an emergency escape maneuver (by pressing the TOGA button) would be .3 sec faster in the NextGen pilot-separation scenario (2.9 s) than the ATC-separation scenario (3.2 s; Figure 3). This is expected because the pilot-separation concept eliminates the time required for ATC to detect the event and communicate to the fight deck. However, predicted time savings were actually quite small because,

in the pilot-separation scenario, the model also accounted for the additional time required to understand the wake threat and determine the appropriate maneuver required.
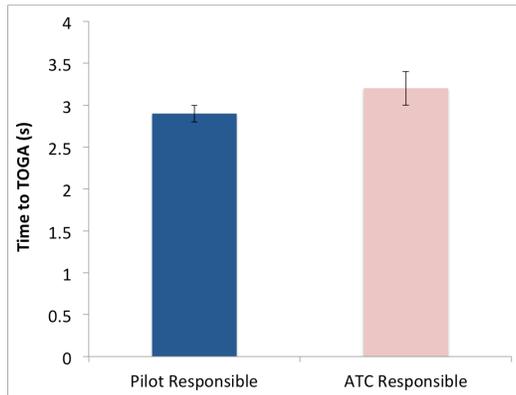

Figure 3. Predicted time to TOGA for the pilot-responsible and ATC-responsible scenarios (+/- 1 SE)

Workload. The small benefit of faster TOGA times (above) associated with the pilot-responsible scenario came at a cost of higher predicted visual, cognitive-spatial and cognitive-verbal workload (see Figure 4). This is because the model accounts for the demands of visually monitoring additional information, and continual decision-making processes required to assess the wake threat.

Pilot Scan. The model predicted that the PF in the pilot-responsible scenario would spend longer monitoring the Nav Display than in the ATC-responsible scenario at a cost of having less time to monitor the PFD and out the window (OTW). As can be seen in Figure 5, the ATC-responsible scenario yielded a more balanced scan pattern across the three main areas of interest (PFD, NAV, and OTW) during the alert phase.
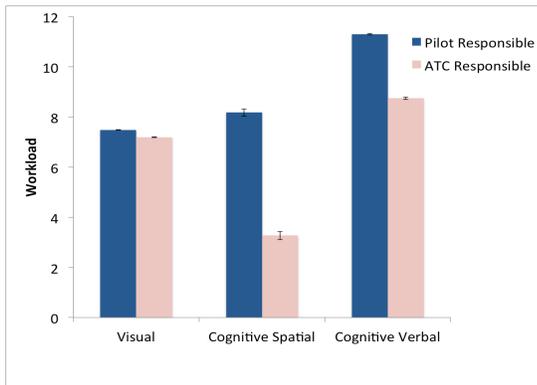

Figure 4. Predicted workload for PF for the pilot-responsible and ATC-responsible scenarios (+/- 1 SE)
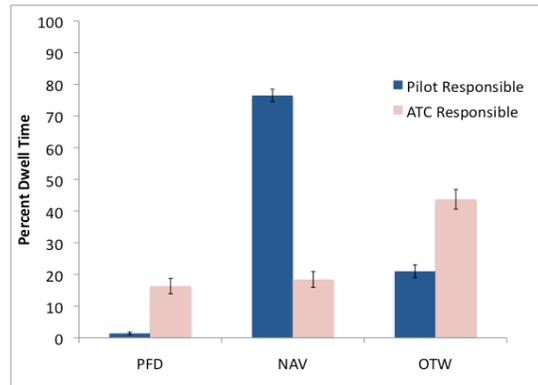

Figure 5. Predicted pilot (PF) scan pattern for the pilot-responsible and ATC-responsible scenarios (+/- 1 SE)

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Findings and Implications

Model output revealed that transitioning responsibility for wake and blunder detection to the pilots (with enhanced flight deck displays) may result in:
- Reduced time to initiate an emergency escape maneuver (negligible)

Depending on flight deck display design, this operational concept may also:
- Increase pilot workload
- Increase pilot scans toward the Nav Display at the expense of monitoring the PFD and OTW

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Research Requirements

- Wake displays must be designed to prevent excessive monitoring requirements.
  Consider status-at-a-glance displays and auditory notifications

- Providing access to wake threat information on PFD may help pilots monitor wake threats and flight status simultaneously

- 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

- Further evaluations of pilots' time to initiate emergency escape maneuver in high-fidelity simulation is required for more accurate (absolute) estimates

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2.2 WAKE AND BLUNDER DETECTION DISPLAYS

2.2.1 Wake and blunder avionics requirements

One potential concept that can be envisioned for CSPO is to enable closely spaced operations with a lower Minimum Descent Altitude (MDA), while maintaining ATC responsibility for directing breakouts as needed (either due to blunder or wake threat). Under these operations, it is expected that ATC would be equipped with enhanced technology to support wake threat monitoring, but it is unknown whether pilots will require enhanced avionics and displays to enable monitoring of the traffic and wake situation as well; and if so, how such displays may impact pilot flight deck performance.

Method

The CSPO scenario illustrated in Figure 2 was modified to evaluate pilot performance in two conditions: 1) **ATC-responsible for separation**, **flight decks not equipped with avionics** to display wake; and, 2) **ATC-responsible for separation**, **flight decks are equipped with avionics** to graphically depict real-time wake information on the Navigation Display. In the latter case, wake was depicted as a secondary display for situation awareness, but without on-board

alerts, and ATC maintained responsibility for detecting blunder/wake threats and issuing go-around commands.

In the scenario, as the aircraft pair were on final approach, a wake threat occurred in which the wake of the lead aircraft extended into the trailing aircraft's trajectory requiring ATC to instruct the trailing aircraft to execute an emergency escape maneuver.

Results
The predicted impact of the flight deck displays on the time to initiate the emergency escape maneuver (by pressing the TOGA button), and the pilot-monitoring's (PM) workload and scan pattern during the wake threat period was assessed. The data presented in Figures 7 and 8 are for the PM, as the PM is the pilot most likely to be monitoring the wake and traffic information during the approach.

Time to TOGA. The model predicted that the time to initiate the emergency escape maneuver (i.e., press the TOGA button) was slower when the flight deck was equipped with enhanced traffic and wake displays (9.8 sec) than without (5.7 sec; Figure 6). This is because pilots had more information to crosscheck (traffic, wake, weather) prior to complying with the ATC go-around command.
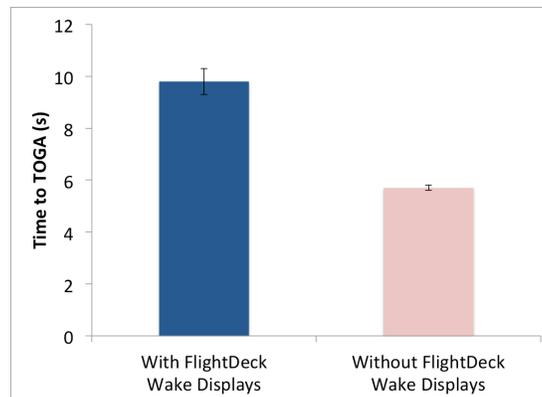

Figure 6. Predicted time to TOGA with and without advanced wake depictions on the Navigation Display (+/- 1 SE)

Workload. Figure 7 presents the predicted visual and cognitive workload of the PM. As can be seen, the model predicted that the flight deck wake displays would increase the PM's cognitive workload (both spatial and verbal). This is a function of the increased task demands associated with assessing the nature of the traffic/wake threat.

Pilot Scan. When provided with wake/blunder avionics, the model predicted that the PM will spend more time monitoring the Nav Display at a cost of monitoring both the Primary Flight Display (PFD) and out the window (OTW), see Figure 8. The preference to view the Nav Display over OTW might be expected given the enhanced situation awareness offered by the wake display relative to the OTW view, particularly in low-visibility. The implications of the reduction in time spent monitoring the PFD, though small, merits further investigation in future research efforts.
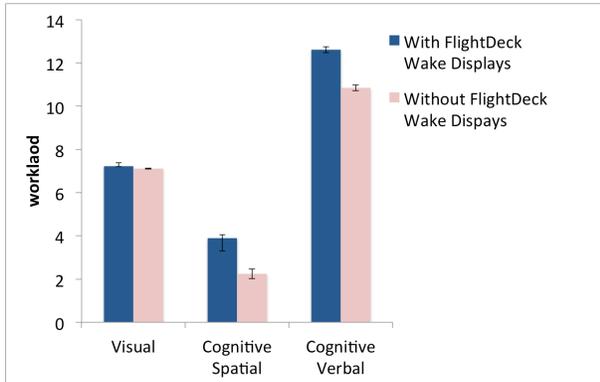
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Figure 7. Predicted PM visual and cognitive workload with and without advanced wake depictions on the Navigation Display (+/- 1 SE)
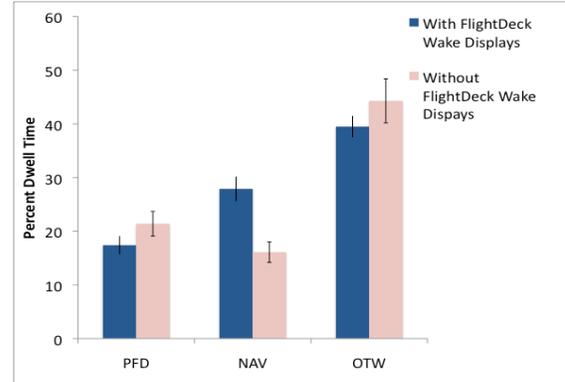

Figure 8. Predicted PM percent dwell time with and without advanced wake depictions on the Navigation Display (+/- 1 SE)

Findings and Implications

Model output revealed that, when ATC is responsible for aircraft separation in a CSPO 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
- Higher workload for the PM

Research Requirement

- Identify minimal information requirements to enable cross-checking ATC commands that will not increase pilot workload or delay pilot 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

2.2.2 Wake display format (predicted vs. real-time wake information)

The National Research Council (NRC) study on Wake Turbulence (2008) highlighted the need for a combination of modeling and measurement of wake vortices that would allow aircraft to continually adjust their spacing under visual flight rules (VFR) for optimization depending on the mix of aircraft approaching, the speed and direction of wind, and the rate of dissipation of vortices on approach to a given runway. The NRC report suggested that under instrument flight rules (IFR), the system would provide a safety backup assist to ensure avoidance of hazardous wake encounters. Further, the NRC noted that *dynamic spacing* of aircraft based on wake vortex motion will require prediction of wind behavior and that it is necessary for the pilot and/or controller to have information on the wake position in *real time* as a safety net to verify the predicted separation provided. The following analysis evaluates the effect of two different

formats for the visualization of wake information: *static* depictions of **predicted wake** and dynamic visualizations of **real-time** wake.

Method

Two nominal approach scenarios were evaluated: 1) A static wake display showing a safe zone based on predicted data given lead aircraft and forecast wind conditions. The size, shape, and relative location of the safe zone did not change throughout the approach and land scenario; and 2) A real-time wake display that visualized the wake updating dynamically in real time based on factors including lead aircraft performance, instantaneous wind data, and wake dissipation rates. For this analysis, the same wake information was presented on both the PFD and Nav Display (as in the VCSPA concept, Verma et al., 2008). In both scenarios, the pilots' time to detect off-nominal events was assessed as a measure of pilots' situation awareness of important aircraft parameters. The off-nominal events included: 1) An alert indicating a loss in Required Navigation Performance (RNP) located on the Engine Indication and Crew Alert System (EICAS) tested when the ownship was at 400 ft altitude); and, 2) an aircraft on the runway (when the ownship was at 150 ft altitude).

Results

Pilot Scan. The model predicted that the pilot will spend more time looking at the wake display elements with the real-time wake format (29.6% of time) than the static wake format (13.6% of time; Figure 9). Increased scans to the wake information on the PFD and Nav Display are likely to be a reasonable monitoring strategy, given the richness and clarity of the data available on the display relative to that obtained out-the-window (OTW) during a low-visibility approach.
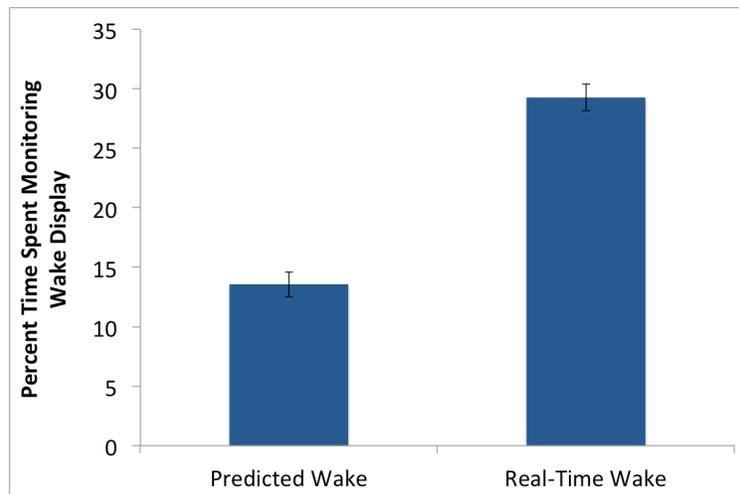

Figure 9. Predicted percent time (PF) spent monitoring wake display with static and real-time wake displays (+/- 1 SE)

Off-nominal Event Response Time. A consequence of the increased time spent monitoring the PFD and Nav Display, described previously, was that there was a corresponding predicted delay in the time for pilots to detect and respond to both the RNP alerts on the EICAS (Figure 10) and an aircraft on the runway (Figure 11).
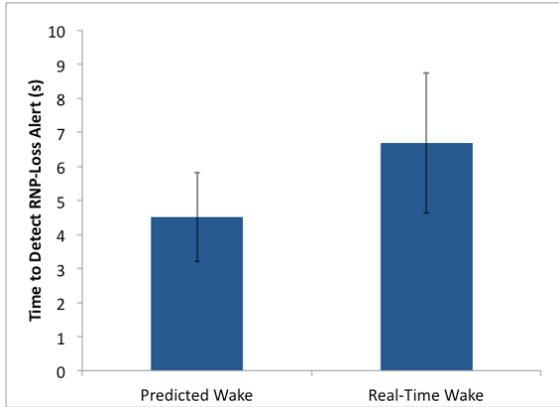
Figure 10. Predicted PF response times to RNP-loss alerts with static versus real-time wake displays (+/- 1 SE)
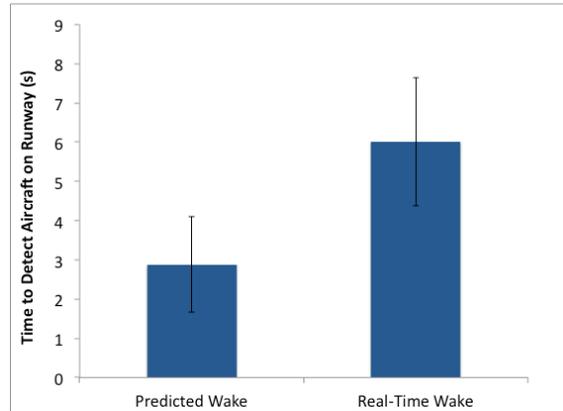
Figure 11. Predicted PF response times to detect an aircraft on runway with static versus real-time wake displays (+/- 1 SE)

Findings and Implications

Model output on the pilot performance 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

Research Requirement

- Real-time wake displays may require filters to limit the data update rate on the flight deck

- Real-time wake prediction tools may require alternative display formats, not direct visualization of wake, consider simple red/green light status indicator as suggested in NRC (2008)

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

2.2.3 Wake display location

Lozito (2011) reported that "there appears to be no consensus regarding where on the flight deck [spacing and wake] data should be presented to the flight crew" and called for "further research to determine where the data necessary for [Closely Spaced Parallel Approach] operations should reside on the flight deck". The analysis presented here assesses the impact on pilot performance when wake data is presented on the PFD, Nav Display, or in both locations at the same time.

Method

The nominal CSPO scenario was modified to manipulate the location of the wake information. It was presented either on the PFD, Nav Display, or in both locations. Both the predicted and real-time display formats (described previously) were evaluated in each of the three display locations, however, as the pattern of results did not differ between the display formats, only data for the real-time display are presented here (see Gore, Hooey, Mahlstedt, & Foyle, 2013) for additional data). All other aspects of content and format of the wake display were held constant for these evaluations in order to isolate the effect of the display location. Pilots' response time to three kinds of alerts were tested: 1) RNP failure alert located on the EICAS when the ownship was at 900 ft altitude; 2) Automation decoupling alert on the PFD when the ownship was at 700 ft altitude; and, 3) Aircraft on the runway when the ownship was at 150 ft altitude.

Results

Pilot Scan. When wake information was presented on both the Nav Display and PFD, the model predicted that the pilots will look at the wake display elements the most (29.6% of the time), compared to when presented on the PFD only (17.3%), or the Nav Display only (16.9%; See Figure 12).
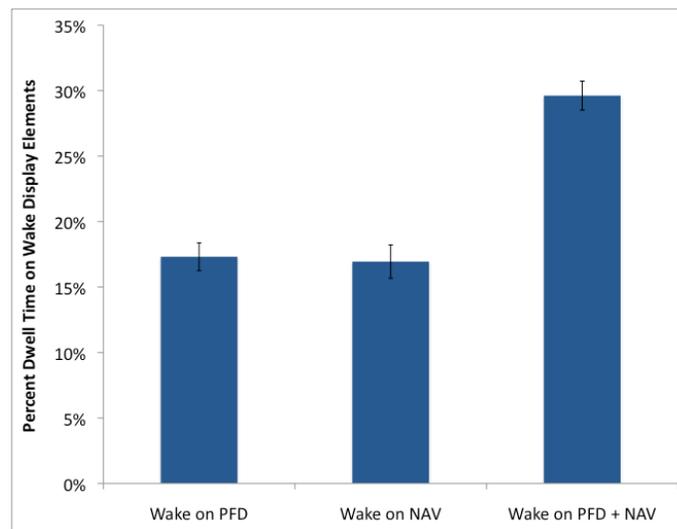

Figure 12. Predicted Percent Dwell Time (PF) on wake display elements during approach as a function of wake display location (+/- 1 SE)

Off-nominal Event Response Time. When the wake information was presented on both the PFD and Nav Display, the model predicted that pilots would take longer to detect cockpit alerts and events in the environment compared to when the wake information was located on either just the PFD or just the Nav Display alone (See Figure 13). This was the case for each of the three different alerts: RNP-loss, automation decoupling, and an aircraft on the runway.
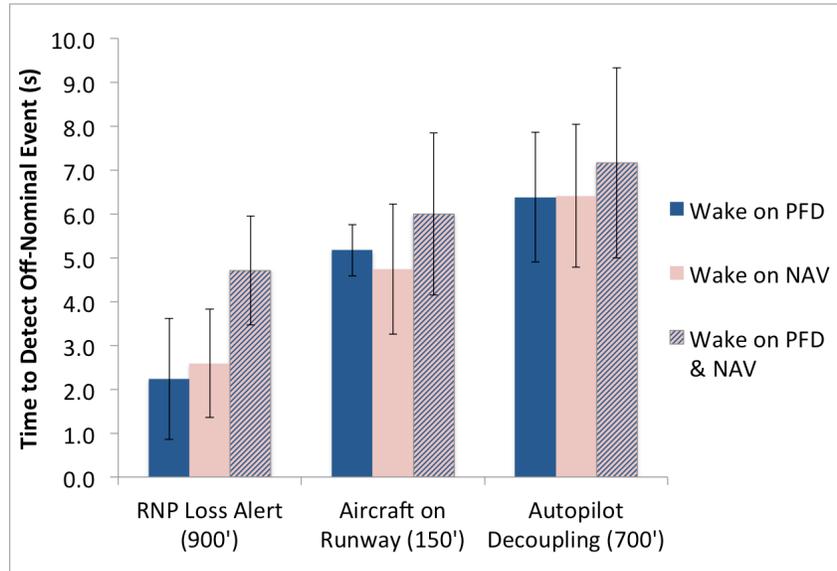
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Figure 13. Predicted PF detection time for three off-nominal events as a function of the location of the real-time wake display (+/- 1 SE)

Findings and Implications

- Model output suggests that presenting wake information on both PFD and Nav 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.

Research Requirement

- 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

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2.2.4 Blunder alert styles (one-stage vs. two-stage alerts)

It is assumed in most CSPO concepts (e.g., VCSPA; Verma et al., 2008) that flight deck alerts would be issued in the event of a wake threat or blundering aircraft. What is less clear, however, is the format that the alert would take. For example, it is unclear whether the alert would be a

one-stage or two-stage alert. A one-stage alert format is defined by the system being in either a nominal no-alert state, or being in the alert state that would require an action by the pilot (i.e., to initiate a missed approach). A two-stage alert, as proposed by the Ames VCSPA concept (Verma et al., 2008), is similar to a TCAS alert. A *traffic (or wake) advisory* would be issued if either wake or paired traffic was approaching the ownship's safe zone, thus directing the pilots' attention to a possible future conflict. This would provide pilots with critical time to gather situation awareness and prepare for the missed approach. A *resolution advisory* would be triggered when the wake or lead aircraft actually does encroach on the trailing aircraft's safety zone. In this case, the pilots would be provided aural and visual commands to resolve the conflict. Pilots are expected to make no inputs until they receive the second-stage resolution advisory. The following evaluation will compare the effects of one-stage and two-stage alerts in CSPO.

Method
A scenario was created to represent NextGen CSPO conditions in which the pilots were responsible for self-separation and for detecting and initiating emergency escape maneuvers. Two conditions were tested. In the one-stage alert condition, pilots experienced simultaneous auditory and visual alerts when an emergency escape maneuver was required due to a wake threat (wake blown into the trailing aircraft's trajectory). In the second condition, pilots were provided with a two-stage alert. Initially, the source of the threat (blunder or wake) was highlighted in yellow to indicate a potential threat, but no action was required. When an emergency escape maneuver was required, the source of the threat turned red, and was accompanied by an aural alert.

Results
Predicted time to TOGA and workload of the PF were compared as a function of the alert style: One-stage or two-stage.

Time to TOGA. The model predicted substantially faster times to initiate the emergency escape maneuver for the two-stage alert format (2.9 sec) than the one-stage alert format (9.8 sec; Figure 14). This shows the intended benefit of the two-stage alert -- it allows the pilots to develop awareness of the traffic situation and prepare to act before the alert requiring the response is issued.

Workload. The two-stage alert format predicted only negligible increases in cognitive workload as compared to the one-stage format (See Figure 15). The small increase may be because the pilot is engaged in tasks aimed at assessing the threat level and planning the escape maneuver during the traffic/wake advisory phase.
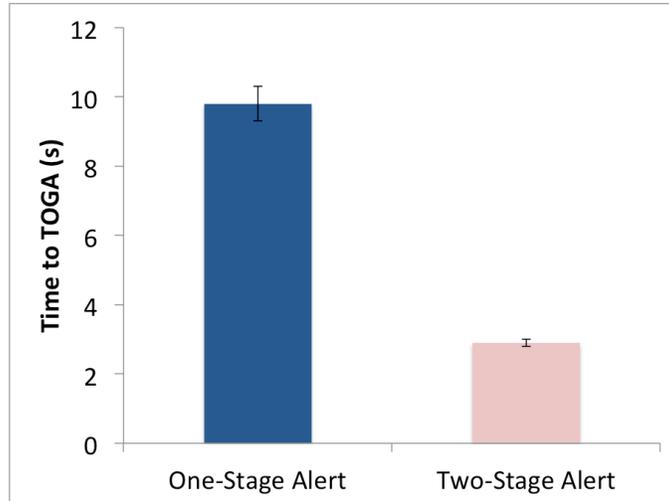
Figure 14. Predicted time to TOGA with one-stage and two-stage wake threat alerts (+/- 1 SE)
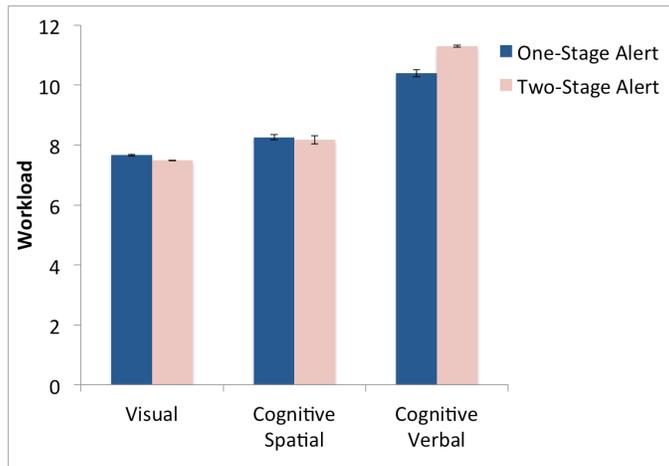

Figure 15. Predicted PF workload with one-stage and two-stage wake threat alerts (+/- 1 SE)

Findings and Implications

Model output revealed that, compared to one-stage alerts, two-stage alerts for wake and blunder threats yielded:
- Faster initiation of emergency escape maneuvers
- A small increase in PF workload

- Two-stage alerts for wake and blunder threats should be considered for NextGen CSPO concepts.

Research Requirements

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

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2.3 SPACING MANAGEMENT

2.3.1 Spacing management automation
Johnson et al. (2010) considered four methods for speed management in the Simplified Aircraft-based Paired Approach (SAPA) concept and concluded that a technique termed 'Station Keeping' had the greatest merit. According to their definition, in the station-keeping technique, "the fast aircraft, once properly positioned, would then remain in a fixed, relative position by matching the ground speed of its leading aircraft. Once it reached a speed equal to its planned final approach speed (PFAS), which would naturally occur due to its leader decelerating, it would then maintain that speed until landing." They reported that this technique allows the spacing aircraft to make minor spacing adjustments to compensate for wind prediction or other similar errors until it reaches its planned final approach speed while still achieving a smooth deceleration to that speed.

Verma et al. (2011) reported a HITL study that compared pilot performance in a CSPO environment with an auto-speed control flight deck automation tool versus current-day flight deck speed automation (using FMS input or MCP input). The NextGen auto-speed control tool was developed to assist the crew in the task of maintaining the required spacing behind the lead aircraft and was a modification of the Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm developed at NASA Langley Research Center for merging and spacing operations (Murdoch, Barmore, Baxley, Abbott, & Capron, 2009). Their study found that workload was low for both the current-day automation and the advanced automation styles and there were no significant differences in workload between the two automation styles. Also, no differences in pilot situation awareness were observed, though current-day automation was rated as more demanding than NextGen auto-spacing.

This analysis extends these HITL studies by assessing the impact of two speed-management modes (current-day automation or NextGen automation) on pilot scan patterns and off-nominal event detection.

Method
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. In both cases, spacing information was located on both the PFD and Nav Display (as in Verma et al., 2011). All other model parameters were held constant. The scenario included two off-nominal events: 1) RNP-failure alert located on the EICAS when the ownship was at 3,000 ft altitude; and, 2) Automation mode error located on the PFD at 1,000 ft.

Results
Pilot Scan. During the descent phase of flight (10,000 ft to 4,000 ft), when spacing management is most critical, the model predicted that pilots will have a higher percent dwell time (i.e., percentage of time that the pilot is looking at the display) for spacing-related display elements

with current-day automation (37.6%) than with NextGen automation (22.4%), see Figure 16. This reflects both a locus of control effect (in the current-day automation scenario, the pilot was responsible for spacing, whereas in the NextGen automation scenario, the avionics system was managing spacing) and the need to make and verify more frequent speed adjustments with current-day automation.

Off-nominal event detection. A consequence of increased monitoring of the speed-related display components is a predicted delay in the time to detect events elsewhere in the cockpit. At 3,000 ft altitude, a visual alert on the EICAS indicated an RNP failure. In the model, pilots were slower to detect this alert with current-day speed automation than with NextGen speed automation (see Figure 17). On the other hand, the increased visual scanning demands of the current-day spacing condition, caused pilots in the model to view the PFD more frequently. As a result, the pilots were faster to detect an automation failure alert on the PFD (See Figure 18). This suggests a possible complacency effect when NextGen automation is responsible for managing aircraft speed.
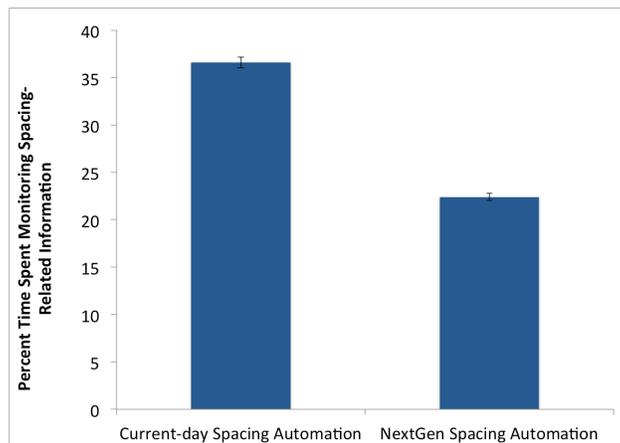

Figure 16. Predicted PF percent dwell time on spacing-related
display elements during approach as a function of automation style (+/- 1 SE)
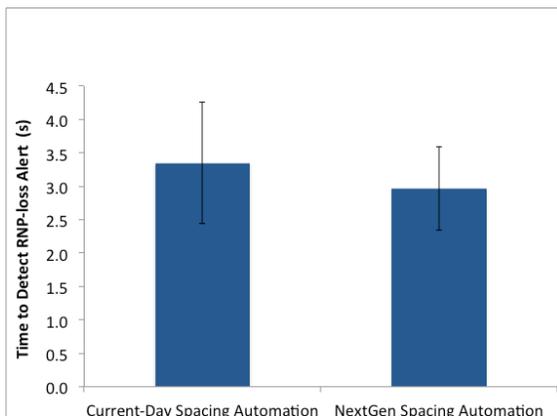

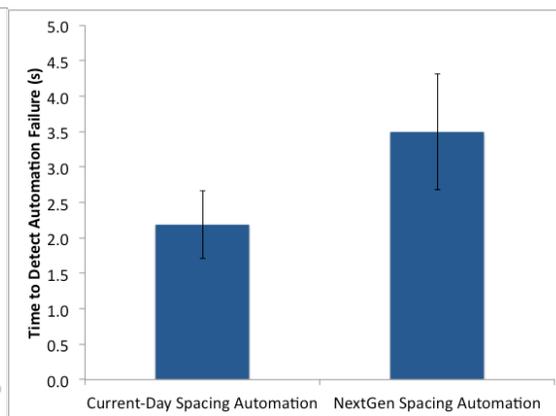Figure 17. Predicted response time (PF) to RNP-loss alert (+/- 1 SE)

Figure 18. Predicted response time (PF) to an automation failure (+/- 1 SE)

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<table>
<tr><td align="center">Findings and Implications</td></tr>
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Model output suggests that current-day speed-management automation may:
- Increase time required to monitor spacing-related displays
- Enable pilots to detect RNP-loss faster

NextGen speed-management automation may:
- Result in slower time for pilots to detect an automation failure (due to a complacency effect)

<table>
<tr><td align="center">Research Requirement</td></tr>
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- Initiatives to minimize pilot complacency with advanced automation

2.3.2 Spacing management display location

As with wake information, analyses are required to determine the appropriate location within the cockpit for the CSPO spacing information. Verma et al.'s (2011) paper included components on both the PFD and Nav Display. Specifically, they included "conformance bars that indicated the spacing window behind the leader on the Nav Display and markers for the spacing on the PFD to help the crews manage conformance." Verma et al. concluded that "scan patterns and heads-down time were concerns expressed by the pilots. They suggested key information should be redundantly presented on their focal displays (PFD, Nav) and should be filtered to indicate when they need to act." The analysis presented here builds on Verma et al.'s findings by assessing the impact on pilots' scan patterns and off-nominal event detection when spacing data is placed on the PFD, the Nav Display, or both of these displays.

Method

The scenario consisted of a nominal approach, with no wake or blunder event. Pilots flew the CSPO approach with current-day automation, in which they managed spacing by controlling speed using the Mode Control Panel (MCP). Spacing information was located on the PFD, Nav Display, or both displays. All other model parameters were held constant. Two off-nominal events were included in the scenario: 1) RNP-failure alert located on the EICAS (when ownship was at 3,000 ft altitude); and, 2) Automation decoupling event when the ownship was at 1,000 ft altitude.

Results

Pilot Scan. With advanced NextGen automation for spacing management, the amount of time that pilots spent monitoring spacing-related display elements was not predicted to differ as a function of display location (22% in each of the three display locations). Using current-day automation to manage spacing, the modeled pilot monitored spacing-related information more when it was presented on BOTH displays (37.6% of the time), than on the PFD (32.4%) or Nav (28.9%) alone (see Figure 19).
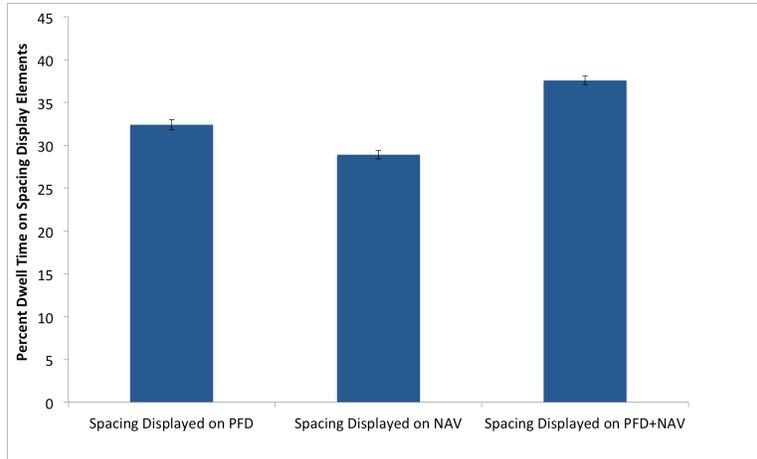
Figure 19. Predicted percent dwell time (PF) on spacing display elements using
current-day spacing automation during descent as a function of display location (+/- 1 SE)

Off-nominal event detection. The detection of RNP-loss alert, located on the EICAS, was not predicted to be affected by location of spacing information (see Figure 20, left). Pilots were equally likely to make a scan to the EICAS from either the PFD or Nav Display.

However, when spacing-management information was presented on the Nav Display, the model predicted that the time to detect an automation-decoupling event on the PFD would be delayed (See Figure 20). This is because the pilots spent more time monitoring wake on the NAV Display and consequently less time monitoring the PFD where the automation-decoupling event was indicated. This raises a concern about the pilots' ability to monitor important aircraft status parameters simultaneously with wake status.
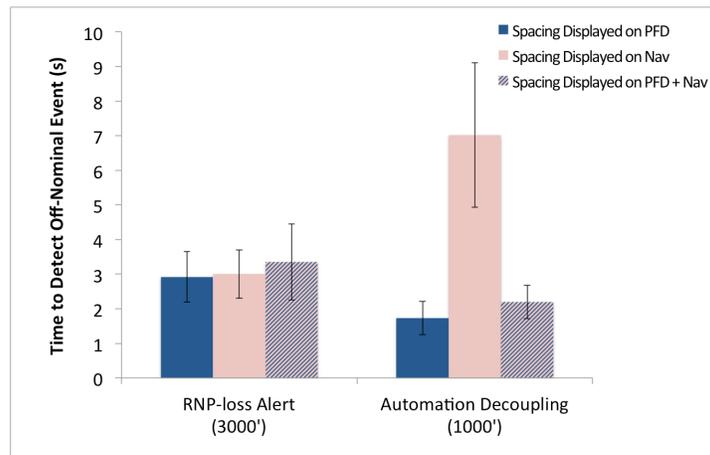

Figure 20. Predicted PF response time to detect RNP-loss alert and
automation decoupling as a function of spacing information location (+/- 1 SE)

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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
  - Presenting spacing information only on the Nav Display may result in slower Detection of an automation failure indicated on the PFD

</div>

3.   CONCLUSION

The current research efforts have resulted in a stable validated human performance model of Closely Spaced Parallel Operations. This model has proven useful for addressing the following research issues:

- Avionics (displays and alerts) design and integration
- Procedures, tasks definition, and training requirements
- Roles and responsibilities and function allocation
- ConOps development

The present research assessed the implications of several CSPO flight deck technology implementations regarding pilot monitoring and management of blunders, wake, and spacing using analyses based on the output of a validated CSPO human performance model using MIDAS v5.

3.1 PROPOSED FUTURE RESEARCH DIRECTIONS

These MIDAS v5 CSPO scenarios can be extended further to address the following CSPO research gaps identified by Lozito (2011; Closely Spaced Parallel Approach Flight Deck Human Factors Summary). In future work, specific research gaps to be addressed would be developed and refined in collaboration with FAA sponsors.

Proposed future research candidates include determining implications and guidelines regarding:
- Transition of separation responsibility from pilot to ATC during or after emergency escape maneuvers
- Effect of routine interruptions and distractions on flight crew's ability to monitor CSPO approaches
- Effect on the trailing aircraft crew of the lead aircraft's blunder as a function of slowing down (i.e., because it is harder to detect and determine the maneuver)
- Effect of customized, non-procedure, escape maneuvers
- Level of conformance and alert data monitoring that can be performed continually
- Amount of data entry that is acceptable for flight crews on approach
- Flight crew threshold levels for Alerts and Warnings (for CSPO and ADS-B, in general)
- Tradeoffs between information availability and display clutter
- Formats and flight deck locations of spacing/interval non-conformance displays
- Wake 'protected zones'
- Escape-maneuvers on the flight deck

- Crew procedures
- Development of new pilot task allocation and division of responsibilities

The current research addressed the effect of various CSPO technologies on pilot performance. The MIDAS v5 CSPO scenarios are easily modified to evaluate different technologies within any phase of flight (i.e., en-route, departures, or taxi). The current focus has been on modeling pilot performance, but high-fidelity models of ATC operations can also be generated with the same research approach. MIDAS v5 is well suited to address research questions related to the many facets of current-day and NextGen environments: ConOps development; flight deck and ATC tasks and procedures; pilot and ATC roles and responsibilities; information requirements; and technology integration.

3.2   SUMMARY

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

2. Implications and guidelines to support CSPO technology development and certification relating to the following topics:
   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
       d.   Blunder alert styles (One-stage vs. two-stage alerts)
   III. Spacing Management
       a.   Spacing management automation
       b.   Spacing management display locations (PFD, Nav Display, or Both)
3. Identification of remaining research gaps critical for successful fielding of NextGen CSPO technologies and concepts

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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 presents guidelines and implications for flight deck display designs and candidate roles and responsibilities. A companion document (Gore, Hooey, Mahlstedt, & Foyle, 2013) provides complete scenario descriptions and results including predictions of pilot workload, visual attention and time to detect off–nominal events.

15. SUBJECT TERMS

human performance models, closely spaced parallel operations (CSPO), NextGen, Man-machine Integration Design and Analysis System (MIDAS) v5

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