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Review of Aircraft Self-Spacing Concepts: Implications for Controller Display Requirements

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July 2009

DOT/FAA/TC-TN-09/03

U.S. Department of Transportation
Federal Aviation Administration

William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

NOTICE

Technical Report Documentation Page

1. Report No.
DOT/FAA/TC-TN-09/03

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Review of Aircraft Self-Spacing Concepts: Implications for Controller Display Requirements

5. Report Date
July 2009

6. Performing Organization Code
AJP-6110

7. Author(s)
Carolina Zingale, Ph.D., Human Factors Team – Atlantic City, ATO-P
Ben Willems, Human Factors Team – Atlantic City, ATO-P

8. Performing Organization Report No.
DOT/FAA/TC-TN-09/03

9. Performing Organization Name and Address
Federal Aviation Administration
Human Factors Team – Atlantic City, ATO-P
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Federal Aviation Administration
Human Factors Research and Engineering Group
800 Independence Avenue, S.W.
Washington, DC 20591

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code
ATO-P

15. Supplementary Notes

16. Abstract

This report summarizes the concepts and the simulations conducted on pilot self-spacing and self-separation between 2005 and 2007 and focuses on the implications for air traffic control information needs and display enhancements. It follows a previous literature review on these concepts by McAnulty and Zingale (2005). In 2007, air traffic levels were predicted to double or triple by the year 2025. To manage this increase, the Federal Aviation Administration (FAA) has been planning to modernize the National Airspace System and to develop new concepts, procedures, and tools that will alter the roles and responsibilities of pilots and controllers. These concepts include the delegation of some responsibilities and procedures to the flight deck of appropriately equipped aircraft. It is anticipated that not all aircraft will be equipped to conduct these procedures at the same time. Therefore, some aircraft will be able to conduct such procedures as self-spacing and self-separation earlier than others, resulting in a mixed-equipage environment. Based on the level of traffic management required, controllers will need information to differentiate aircraft. The FAA must conduct extensive testing on these concepts and on the type of support provided to controllers to ensure that efficiency goals are realized while risks are minimized.

17. Key Words
Automatic Dependent Surveillance-Broadcast
Pilot Self-Spacing
Trajectory-Based Operations

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, Virginia, 22161. A copy is retained for reference at the William J. Hughes Technical Center Library.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

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Acknowledgments

The authors thank Anton Koros (Northrop Grumman Information Technology) for his role in conducting a major portion of the literature search.

Executive Summary

To manage expected increases in air traffic, the Federal Aviation Administration (FAA) is continuing to modernize the National Airspace System through new automation and the development of new concepts, procedures, and tools. The concepts include the delegation of some procedures to the flight deck that were once managed entirely by the controller. Given the extent to which pilot and controller roles will change with the new procedures, the FAA will need to thoroughly evaluate the concepts to determine whether they are meeting expected performance objectives while minimizing risks. This report summarizes the concepts and the simulations conducted on pilot self-spacing and self-separation between 2005 and 2007 and focuses on the implications for air traffic control information needs and display enhancements. It follows a previous literature review on these issues by McAnulty and Zingale (2005).

The results summarized in this report support those described earlier by McAnulty and Zingale (2005), which found that self-spacing aircraft maintained more precise spacing intervals than aircraft using existing procedures. However, new controller tools also improved spacing precision for aircraft that were not self-spacing. Other data indicated that self-spacing aircraft required less vectoring and fewer air-ground communications. However, the ability of aircraft to adhere to predictable route structures also produced similar benefits. Aircraft self-spacing procedures may therefore be only one means to improve efficiency.

The studies we summarize in this report also indicated that researchers were beginning to examine the effects of mixed-equipage environments, in which some aircraft are incapable of conducting the self-spacing procedure, and degraded conditions (e.g., an aircraft must abandon use of the procedure). Compared to current procedures, benefits were realized even when only some of the aircraft were self-spacing. However, the highest benefits were achieved when all of the aircraft were conducting the procedure. Controller workload levels were related to the number of aircraft managed by the controller rather than to the total number of aircraft in the airspace, suggesting that the procedure could allow for increased airspace capacity without negatively affecting the controller. However, the controllers reported that they needed to monitor unequipped aircraft more closely in a mixed-equipage environment than when using existing procedures. They were also concerned about forgetting to issue clearances to aircraft that were not conducting the procedure and about intervening effectively in problematic situations. The few simulations that included degraded conditions used structured settings in which the controllers knew in advance which situations to expect. More research is needed to understand (a) how readily controllers can determine that a problem has occurred and (b) how quickly it can be resolved. Additional work must also be conducted to examine the effects of weather when these procedures are in use.

Many of the more recent studies have included additional controller tools and display enhancements. Information needs are particularly high in mixed-equipage environments because controllers must distinguish the aircraft that are capable of performing procedures from the aircraft that are not capable of performing them. Controllers must also be able to identify which aircraft are currently using a procedure from those aircraft that are not. However, additional tools and display enhancements may produce display clutter and increase workload. Therefore, it will be necessary to reorganize information on the controller display when modifying the interface to minimize these effects.

1. INTRODUCTION

The Federal Aviation Administration (FAA) is modernizing the National Airspace System (NAS) to manage a projected doubling or tripling of air traffic levels by the year 2025. In 2006, estimates indicated that air traffic would increase by about 3.4 percent each year through 2017 and that traffic at the nation's busiest airports would be up by about 30 to 40 percent (FAA, 2006). The Next Generation Air Transportation System (NextGen) plan is being developed to manage increasing traffic volume and complexity (Joint Planning and Development Office, 2007). NextGen involves a transformation of the existing air traffic management system through the integration of new automation and surveillance capabilities and advanced information-sharing capabilities between air and ground and between aircraft. Full implementation of NextGen is planned for the year 2025. Other near- and mid-term solutions for managing increased traffic levels will also rely on some of the basic technologies that are currently available and beginning to be used in the NAS, though more advanced concepts will require additional capabilities.

Some of the procedures that have been examined to alleviate capacity constraints include the delegation of some responsibilities from the air traffic controller to the pilot. Given the extent to which pilot and controller roles will change with these procedures, the FAA needs to thoroughly evaluate the concepts to determine whether they meet the expected performance objectives while minimizing risks. This report follows a review of research conducted on the delegation of self-spacing and self-separation to the flight deck by McAnulty and Zingale (2005). In this literature review, we focus on the relevant simulations that have been conducted between 2005 and 2007 and concentrate on the implications for Air Traffic Control (ATC) information needs and display enhancements required to enable the procedures.

2. ENABLING TECHNOLOGIES

Several technologies are central to promoting enhanced flight-deck involvement in air traffic management. They include Automatic Dependent Surveillance – Broadcast (ADS-B) and the increased use of Area Navigation (RNAV) routes and Required Navigation Performance (RNP) capabilities. ADS-B can transmit Global Positioning System (GPS) information about aircraft to the ground and to the flight decks of appropriately equipped aircraft. ADS-B is also more accurate than radar data. Pilots with ADS-B In equipped aircraft can view data (e.g., position, speed) about nearby aircraft by using a Cockpit Display of Traffic Information (CDTI). Pilots would have precise information about aircraft locations, thus enhancing their situation awareness and potentially allowing them more responsibility in spacing and separating aircraft.

RNAV and RNP allow for more predictable and precise route navigation. Both are basic enablers of two NextGen concepts, Performance-based Navigation (PBN) and Trajectory-based Operations (TBO). PBN and TBO require aircraft adherence to defined routes and specific operational performance criteria; both improve traffic flow efficiency and predictability. RNAV eliminates the constraints of ground-based Navigational Aids (NAVAIDS), allowing aircraft to fly more direct, point-to-point routes. There are different levels of RNAV capability defined. RNAV-1, used for terminal airspace Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs), requires that an aircraft fly no more than 1 nm (1.9 km) from its designated route for 95% of its flight time. By 2010, the FAA expects that over 90% of the aircraft at the top 35 Operational Evolution Partnership (OEP) airports will be RNAV-1 capable (FAA, 2006).

RNAV-2 requires aircraft in en route airspace to fly no more than 2 nm (3.7 km) from the specified route for 95% of its flight time. Some RNAV routes are already being used, and parallel runway operations (based on RNAV and RNP) are planned for use by 2010.

RNP requires onboard aircraft performance monitoring that provides information to the flight deck about adherence to specified navigation performance criteria. Basic operations are RNP-2 for en route, RNP-1 for terminal, and RNP-0.3 for final approach (numbering indicates adherence criteria in nautical miles). Other RNP operations, such as Special Aircraft and Aircrew Authorization Required (SAAAR), are more specialized and require specific approvals for use. By 2017, predictions are that 80 to 90% of transport aircraft will be capable of basic RNP.

These more precise tracking and navigation capabilities have the potential to accommodate more aircraft in the airspace and have already been associated with reductions in the number of controller-pilot communications. For example, the use of SIDs and STARs in Atlanta (ZTL) and Dallas-Ft. Worth (DFW) reportedly reduced air-ground communications by up to 50% (FAA, 2006). Fewer clearances are needed when aircraft are adhering to defined routes. Also, less tactical maneuvering is required.

3. AIRCRAFT SELF-SPACING RESEARCH

In 2001, the FAA and EUROCONTROL collaborated on a description of procedures for the Airborne Separation Assurance System (ASAS) to address concepts allowing flight-deck involvement in spacing and separation (FAA, 2001). ASAS consists of four categories of applications. The first category enhances flight crew situation awareness without changing the current distribution of responsibilities between the flight deck and the controller. In the applications, the flight crew has additional information about surrounding aircraft on the CDTI, allowing enhanced capabilities for acquiring traffic out-the-window, conducting visual approaches, and executing “see and avoid” maneuvers.

The second category of applications gives the flight crew responsibility for achieving and maintaining designated spacing of their aircraft from another aircraft, but leaves separation assurance with the controller. In these applications, the controller could issue spacing instructions to suitably equipped aircraft. However, the controller would need information to designate which aircraft are capable of participating. The third and fourth applications are more advanced because they delegate some or all separation responsibility to the flight deck in which the controller may offer limited separation delegation to suitably equipped aircraft for a designated time or a specified distance. However, more procedural changes and more sophisticated tools are needed to enable these advanced concepts. The FAA/EUROCONTROL (2001) report emphasizes the need for a complete evaluation of concept feasibility that includes an assessment of the human factors issues involved. More advanced procedures would also require data communication to allow the timely exchange of information between systems.

In an earlier review of pilot self-spacing and separation research, McAnulty and Zingale (2005) found that the existing work focused primarily on the flight deck. Although many of the more advanced delegation concepts would substantially change ATC procedures, relatively little work had been conducted to investigate the concepts from the controllers’ perspective. The research that did focus on controllers was primarily conducted under optimal conditions: All aircraft were fully equipped to perform the required procedures, no equipment failures were introduced that would require aircraft to abandon the procedures, and weather was not a factor. The few reports that discussed these issues indicated that such circumstances were likely to be problematic.

From 2005 to 2007, a number of other studies – primarily conducted by researchers at the National Aeronautics and Space Administration (NASA), MITRE, and EUROCONTROL – have continued to address these concepts. Several of them have examined the effects of a mixed-equipage environment, the effects of degraded conditions (e.g., equipment outages), and the effects of the procedures on the controller. Some of the concepts are planned for earlier implementation and require less automation and fewer new tools than those planned for mid- to far-term implementation.

3.1 Merging and Spacing

MITRE has examined a merging and spacing (M&S) concept that consists of an en route component and another component that continues procedures through terminal airspace down to the runway (Bone & Marksteiner, 2007; Bone & Penhallegon, 2006; Bone et al., 2007; FAA, 2007). This M&S concept involves TBO, in which conflict-free flight paths are generated and then implemented through the Flight Management System (FMS) of the aircraft. In the United States, the FAA, United Parcel Service (UPS), MITRE, and NASA have investigated aspects of this concept, in which the Airline Operations Center (AOC) is responsible for initiating the procedure. The AOC determines the spacing interval but may coordinate with ATC to determine what interval is appropriate. The interval must be greater than current minimum separation standards and is based on winds, aircraft landing speeds, and other criteria. The AOC, not the controller, sends the relevant spacing data to the aircraft via the Aircraft Communications Addressing and Reporting System (ACARS). The near-term implementation of the concept would be used by a single carrier (i.e., UPS) to a single airport (Louisville International-Standiford Field [SDF]) and does not include the addition of any new controller tools or display modifications. Later implementation expands the concept to multiple carriers and airports.

The first component of M&S involves a ground-based, set-up phase termed Airline-Based En Route Sequencing and Spacing (ABESS). The participating aircraft are merged and sequenced to the final en route fix and use Continuous Descent Approaches (CDAs) to the runway, using flight deck-based merging (FAA, 2007). Different merge fixes are used for different sequences of flights. The AOC provides the speed advisories to the aircraft at or after the top of climb is reached and up to 30 min prior to the merge fix. Therefore, spacing intervals can be modified if flights need to speed up (to close gaps) or slow down (to avoid overtakes). The flight crew can accept or propose speed modifications, or reject the advisory temporarily or permanently. If the aircraft does not respond to a speed advisory within 5 min, the AOC may either uplink a new advisory or discontinue sending advisories to that flight. The flight deck notifies the controller about any changes. The controller maintains responsibility for separation and may intervene if needed. However, any instructions issued by the controller terminate ABESS for that flight.

Although early implementation of the concept does not include new controller tools, they are expected to be needed for later phases that involve more carriers and more airports. More coordination between ATC and AOCs will be required to develop comprehensive schedules to accommodate the mix of flights. The controller will need to have information to differentiate the aircraft that are capable of conducting the procedure from those that are incapable of conducting the procedure, and the controller will need to have information to indicate which aircraft are participating (Bone & Marksteiner, 2007).

NASA researchers (Prevôt et al., 2007) conducted a simulation to investigate an advanced implementation of ABESS termed Trajectory-Oriented Operations with Limited Delegation (TOOWiLD). This simulation included high-traffic levels with crossing traffic streams, multiple arrival flows and merge points, and a mixed-equipage environment in which 70% of the aircraft were capable of conducting the procedure. However, the evaluation still included only a single carrier that was equipped to perform the operation. The AOC uplinked data to aircraft, including the destination airport, scheduled runway, scheduled time at the runway, and speeds. The AOC also uplinked the traffic-to-follow (TTF), merge point, and spacing interval for aircraft conducting the procedure. The pilots informed the controller of their spacing status when checking in to the sector and when an aircraft terminated the procedure. The controller was responsible for issuing CDA clearances, managing the unequipped aircraft, and ensuring that separation was maintained for all aircraft.

The test scenarios included two flight deck conditions: one condition that involved pilot self-spacing and another condition that did not. Prevôt et al. (2007) tested these under three controller conditions. The first included only existing en route controller tools. The second controller condition included advanced scheduling and spacing tools (i.e., runway timeline display, speed advisories, conflict probe, trial planning capability, and spacing status information in the data block). The controller display provided scheduling and spacing information obtained from the AOC arrival management system and allowed the controller access to scheduled time of arrival (STA), TTF, and spacing interval for the self-spacing aircraft. The third controller condition included data link in addition to the advanced tools. Four en route and one terminal controller participated in the simulation.

Prevôt et al. (2007) found that controller workload ratings did not differ across test conditions. Relative increases and decreases corresponded to overall levels of traffic independent of the conditions and the tools available. The spacing intervals were more accurate and less variable when self-spacing was implemented, and the addition of the controller tools further improved these rates. The controller tools also helped improve the accuracy and reduced the variability of the spacing intervals for nonequipped aircraft. However, the researchers identified two unexplained issues that require further investigation: (a) the inclusion of data link did not result in additional benefits beyond those observed with the other tools and (b) the aircraft energy use was somewhat less efficient for self-spacing aircraft on CDAs.

The second component of M&S, Flight Deck-based Merging and Spacing (FDMS), has undergone more extensive investigation. Bone and Marksteiner (2007) described an evaluation of FDMS that included an assessment of normal procedures and degraded conditions (e.g., aircraft unable to comply). As in ABESS, the controller maintains responsibility for separation and intervenes if the designated spacing interval is not maintained (though controllers are expected to interfere as little as possible with the aircraft that are using the procedure). FDMS involves only the use of speed adjustments for spacing by the flight deck; it does not involve heading changes.

In the Bone and Marksteiner (2007) evaluation, pilots used a CDTI to achieve time-based spacing intervals behind a lead aircraft. These aircraft were on CDAs from the final en route fix to the Final Approach Fix (FAF).[1] Aircraft must maintain their position in the sequence and cannot pass the lead. Each aircraft is instructed to maintain a spacing interval from the aircraft directly ahead, rather than from a single lead in a string. As in ABESS, separation between aircraft is not reduced below current minima. The CDTI provides information to the pilot if the spacing interval cannot be maintained. Another existing FMS capability, the Required Time of Arrival (RTA) tool, is used to calculate the arrival time at the runway. The FMS system compares relative RTAs for the two aircraft to evaluate compliance with the spacing interval when the aircraft is within ADS-B range of the TTF.

Bone and Marksteiner (2007) discussed resolutions for situations in which aircraft are unable to maintain FDMS. If either the TTF or trail aircraft must abandon the procedure, the flight crew can manually disengage the FDMS function and follow controller-issued clearances. The AOC tools would also automatically detect a deviation and would discontinue sending speed commands. The crew would then fly using the last speed command provided. Current FDMS procedures also allow pilots to re-engage the procedure, but only between the original TTF, using the previously defined spacing interval.

Bone and Marksteiner (2007) also discussed procedures for managing some degraded conditions. Aircraft that have to terminate FDMS can remain in the flow but would be issued instructions from the controller to maintain appropriate spacing. If maintaining spacing were an issue, the controller could maneuver those aircraft to another route and to a different runway. More advanced implementation would provide slots for aircraft to transition into, if needed.

Bone et al. (2007) and Penhallegon and Bone (2007) summarized results from another FDMS simulation conducted with former en route controllers. This study included FDMS aircraft, non-equipped aircraft, and aircraft that crossed through the arrival streams to create potential conflicts and add complexity to the scenarios. There were five test conditions:

1. a baseline condition (using existing procedures for all aircraft),
2. an FDMS condition (in which all equipped aircraft in the scenario were using FDMS),
3. an FDMS overtake condition (in which one aircraft using the procedure began to increase speed relative to the TTF),
4. an FDMS suspension condition (in which two of the equipped aircraft in the scenario requested to stop using the procedure), and
5. an FDMS termination condition (in which all equipped aircraft started the scenario using the procedure but ended use at a designated point that was announced to the controller).

In this simulation, the researchers did not include new controller tools or display enhancements. However, some participants either added information to the data block (i.e., highlighting) or used the scratch pad to indicate which aircraft were using the procedure (R. Bone, personal communication, July 27, 2007).

[1] Although CDAs were used, they are not required for the procedure.

Bone et al. (2007) found efficiency benefits for FDMS. The participants issued fewer speed and heading instructions and spent less time on the frequency. They issued more transmissions and spent more time on the frequency in the baseline condition compared to each of the FDMS conditions, including those in which FDMS was suspended, terminated, or included an overtake. The participants made more transmissions in the condition in which aircraft suspended FDMS compared to the condition in which all aircraft used FDMS throughout and compared to the condition in which one FDMS aircraft began to overtake another aircraft. As expected, more intervention required more communication.

Overall, the participants reported that the procedure was acceptable, that it improved operational efficiency, and that it was "somewhat easier" to monitor the sequence of self-spacing aircraft compared to managing those aircraft individually. The participants also reported (a) that managing the traffic volume and complexity was "about the same to somewhat less" than controlling when using existing procedures and (b) that workload was lower when FDMS was in use. Bone et al. (2007) also reported that the participants were able to effectively manage situations in which all the aircraft terminated FDMS or when some aircraft suspended use of the procedure or began accelerating and overtaking the TTF. However, the participants raised some concerns. Their responses varied for several variables: (a) the extent to which pilot self-spacing was deemed acceptable, (b) the ease/difficulty of giving priority to FDMS aircraft, and (c) their certainty about knowing when to intervene in abnormal situations. One participant commented that he would need more information about aircraft speed changes, and another participant indicated that giving priority to the self-spacing aircraft requires a change in mindset from the current "first come, first served" way of thinking.

Bone and Penhallegon (2007) conducted a subsequent simulation in low-to-moderate density traffic (W. Penhallegon, personal communication, August 1, 2007). The simulation included a mixed-equipage environment, in which FDMS-capable aircraft (i.e., UPS) were on a separate arrival route to SDF than other aircraft that were not capable of performing the procedure. The majority of the FDMS-capable aircraft used the procedure. The researchers grouped them into sets of 2-4 aircraft, with each aircraft spaced behind the aircraft immediately ahead of it. En route and terminal controllers (most of whom were supervisors) participated in the simulation, but in separate trials. As in the other simulations, the researchers instructed the participants to minimize intervention with aircraft conducting FDMS but to take any actions necessary to ensure proper separation. The flight deck informed the controller of self-spacing on check-in and when the procedure had been re-engaged after an earlier termination. In this simulation, the participants used the call signs of the TTF in their transmissions and were allowed to query an aircraft to determine its FDMS status and TTF.[2]

Preliminary results indicated that en route participants found the procedure manageable and that workload appeared to be lower in the FDMS conditions (W. Penhallegon, personal communication, August 1, 2007). They found fewer differences between conditions for the terminal participants, but this may have been due in part to difficulties with CDA implementation. The researchers observed that both the en route and the terminal participants used data block highlighting or offsetting to differentiate aircraft using FDMS from nonparticipating aircraft.

[2] The specific phraseology for including the TTF in these communications is still being developed.

Some participants also varied the length of the leader line as an indicator. Although the scratch pad was available, the researchers observed that most participants used this for entering runway information. The participants reported that the use of the TTF call sign in their communications was helpful for ensuring that the appropriate aircraft were conducting the procedure, especially in degraded conditions (e.g., inappropriate spacing).

Researchers at the EUROCONTROL Experimental Centre (Grimaud, Hoffman, Rognin, & Zeghal, 2001, 2003a, 2003b, 2004) evaluated another pilot merging and spacing concept in the extended terminal (en route) and terminal environments in European airspace. In this concept the controller initiates the procedure and cancels it, if necessary. The pilot may also abandon self-spacing if there is an equipment problem that prevents the aircraft from continuing the procedure. The concept includes three steps. In the first step, the controller indicates the TTF to the flight deck, using the TTF transponder code rather than using the aircraft call sign. The flight deck selects the TTF via the CDTI and informs the controller when the target has been selected. In the second step, the controller issues the spacing clearance. In these earlier studies, headings and instructions to merge at a waypoint (e.g., heading 270, then merge at WPT 90 s behind target) could also be given prior to the spacing clearance. The flight deck responds (when turning to the waypoint) and adjusts the aircraft speed appropriately. In the third step, termination, the controller issues an instruction to “cancel spacing” and provides a speed clearance to the flight deck.

The researchers made some modifications to the controller displays that included colored symbols and markings to indicate TTF and the spacing instructions. This consisted of rings around the aircraft position symbols and lines that extended from one aircraft to another to designate the TTF (orange) or to indicate that self-spacing was in effect (green) (see Grimaud et al., 2004). All aircraft were equipped to self-space, so no additional display elements were added to indicate that capability.

Overall, Grimaud et al. (2001, 2003a, 2003b) found benefits, including improved throughput, better adherence to time-based spacing targets, and a reduction in air-ground communications. They found evidence that the participants sequenced aircraft further from the final approach fix as indicated by eye movement data and the location at which the participants issued clearances. The researchers also reported that the participants tended to treat self-spacing aircraft as a group and were reluctant to cancel self-spacing instructions. When they did cancel self-spacing, the participants typically used conventional control instructions thereafter rather than reinitiate the procedure. Although the researchers did not include degraded conditions in these simulations, the participants expressed concern about recovery from problems and the need to establish clear procedures for managing those events. They also reported that they monitored aircraft less frequently when self-spacing was used. However, eye movement data showed that the participants actually fixated more frequently on aircraft in the self-spacing condition.

Subsequently, Boursier et al. (2005) conducted another evaluation of the concept that supported their earlier results, but it also included the Arrival Manager (AMAN) tool to assist the controller with sequencing. AMAN is similar to the Traffic Management Advisor (TMA) in the NAS en route environment. Arrival aircraft are assigned times at which they are scheduled to cross designated fixes. The STAs are displayed to the controller along with the amount of time an aircraft needs to gain or lose to meet its STA. Boursier et al. also used the controller display elements used previously by Grimaud et al. (2004). Using recorded traffic, the study compared a condition in which current tools and procedures were used to one in which self-spacing instructions could also be issued to aircraft. The airspace was configured so that the equivalent of two en route sectors fed one terminal sector.

Boursier et al. (2005) found that the participants built aircraft sequences further from the airport – for example, 30 nm (55.6 km) from the FAF vs. 10 nm (18.5 km) – when aircraft were self-spacing and, once established, they vectored the aircraft less in terminal airspace. The participants were able to identify where and when other aircraft could be accommodated into the flow when the sequence was established early and displayed on AMAN. The researchers found that the majority of the aircraft (87%) were under spacing instructions at the merge point and that more consistent spacing between aircraft was achieved when the procedure was used. The participants issued fewer clearances, and workload levels remained manageable. On average, self-spacing also resulted in slightly better throughput.

3.2 Effects of Routes and Structured Airspace

The EUROCONTROL studies (e.g., Boursier et al., 2005) also identified some difficulties with the procedures when multiple routes were used in the terminal environment. Researchers subsequently made modifications to the airspace to enable self-spacing to be conducted more efficiently (see Grimaud et al., 2004). First, they implemented standard trajectories for each flow that merged at a single point upstream of the FAF. Then, they added extension legs to the trajectories to allow controllers to speed up or slow aircraft as well as a range of arrival routes that were separated from departure routes and overflights. The researchers determined that the use of the additional legs was problematic because the participants sometimes failed to issue an instruction (e.g., continue heading) for aircraft requiring the use of an extension. In these cases, the aircraft turned at the standard point on the route instead. This reduced the utility of the extension legs, and it increased workload.

Other researchers have looked specifically into the benefits of airspace modifications to enhance efficiency independent of aircraft self-spacing. For example, Becher, Barker, and Smith (2005) discussed merging and spacing procedures in high-traffic conditions for aircraft on RNAV routes that converge prior to final approach. The primary goal of the concept is to reduce the need to vector the aircraft to final and to space them appropriately to achieve more efficient throughput. Vectoring reduces the benefits of having flown an RNAV route earlier, and it increases workload for both the flight crew and the controller.

This concept uses currently available flight-deck and controller tools and existing procedures, but the researchers discuss some additional controller display enhancements. On the flight deck, the lateral offset capability of the FMS allows the flight deck to fly a designated distance – for example, 5 nm (9.3 km) – off an RNAV route. This tool has been available for many years. However, Herndon et al. (2003) reported that the function is not widely used largely due to unfamiliarity and lack of training. The controller tool – the Converging Runway Display Aid (CRDA), which is available on the Automated Radar Terminal System (ARTS) IIA, IIIA, and IIIE as well as on the Standard Terminal Automation Replacement System (STARS) – can identify a spacing problem so that a speed control or lateral offset can be initiated in time to keep aircraft better aligned for an approach. The flight deck would also use the RTA tool for time-based metering to manage speed control for aircraft that have been identified by CRDA as having spacing problems. Aircraft would be able to achieve appropriate spacing by the merge point when RTA-designated speed information is entered into the FMS. The controller can monitor the plan by using the CRDA, which presents "ghosted" aircraft on the display to indicate projected positions of aircraft along the merged route.[3] The authors indicated that the controller must be informed of the range of the RTAs that the aircraft are able to execute. This may require additional information on the display.

Becher et al. (2005) noted that aircraft are somewhat differently equipped in their ability to conduct the lateral offset procedure. The FMSs differ with respect to the distance to which they can offset from a route and the intercept angle used to initiate an offset and return to a route, though most FMSs use a 45-degree intercept angle (Herndon et al., 2003). At the time of the Becher et al. report, the Honeywell FMS, which is used on most Boeing aircraft, does not allow for offsets while on SIDs or STARs. However, most Boeing 737s use a Smiths FMS, which does allow that capability. As of 2005, most Airbus aircraft had a mix of the two. The authors noted that controllers would need information about the level of aircraft equipage to determine which aircraft could participate in the procedure. Presumably, as RNAV routes become more numerous, FMS manufacturers would expand their capabilities. Although simulations indicated that less vectoring was required to final approach when the procedure was used, the controllers found it problematic to use the lateral offset maneuver on one of the approach routes when aircraft speeds were high and there was little airspace available to offset. Airspace and route configuration would have to be structured effectively to optimize use of this procedure.

Boursier et al. (2006a) also reported on simulations that compared a baseline condition using current procedures to one in which RNAV routes were used (but there was no delegation of spacing to the flight deck). Using the RNAV routes, controllers were better able to sequence aircraft. They also reduced the number of clearances (primarily headings) issued and the time on the frequency. However, accuracy in adhering to the spacing interval was about the same in each condition. The controllers found the procedures to be no more difficult than current procedures. However, they did find them to be less flexible because the sequence order had to be established early. The researchers indicated that adherence to the spacing interval would likely improve further with self-spacing and would also enhance throughput; however, achieving the improved accuracy could also reduce flight efficiency because aircraft would need to make more speed adjustments and burn more fuel. The researchers further suggested that implementing self-spacing may result in even less flexibility because the specific ordering of the aircraft would have to be maintained.

In summary, these studies indicate that airspace configuration and route structures may provide some efficiency benefits, even though the researchers did not evaluate how the benefits compared to the benefits observed when aircraft self-spacing procedures were used. However, other studies have examined these issues with respect to more advanced aircraft self-separation procedures (see section 3.4; Pilot-Based Separation).

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[3] Smith and Becher (2005) identified problems with (and potential resolutions for) the algorithm used by CRDA. The tool does not always display ghost targets accurately for aircraft on multi-segmented routes (e.g., aircraft may appear to stall or go in reverse). These problems must be resolved before the tool can be used effectively for conducting this procedure.

3.3 Mixed-Equipage Environments and Degraded Conditions

Other researchers began to examine aircraft self-spacing procedures in mixed-equipage environments and in degraded conditions. Boursier et al. (2006a) conducted a series of small, low-fidelity studies that included aircraft of mixed-equipage, go-arounds, and improper implementation of spacing instructions by the flight deck (see also Boursier, Hoffman, Rognin, Vergne, & Zeghal, 2006). The focus of these efforts was on controller comments and feedback about the feasibility of the procedures rather than on the data collection, so the results are limited. Additionally, very few controllers participated in each evaluation, and the researchers did not collect measurements to determine whether the controllers were able to detect the problems.

Boursier et al. (2006a) and Boursier et al. (2006) described a simulation in which aircraft on different routes went to different initial approach fixes and then merged at a point downstream. In the mixed-equipage environment, all aircraft were ADS-B equipped (pilots could broadcast their position information) and 50% were equipped with ASAS to allow them to self-space. To enable controllers to differentiate the aircraft, the researchers presented the data blocks of the non-ASAS equipped aircraft in yellow. The controllers integrated the unequipped aircraft into the flows by sending them direct to the merge fix to fill the available slots. The researchers deemed heading instructions unfeasible for managing the unequipped aircraft; therefore, the controllers did not issue them in this procedure.[4]

The researchers found greater benefits (i.e., fewer clearances issued, better spacing accuracy) when 50% of the aircraft were self-spacing than when none of the aircraft were using the procedure, but less than when all of the aircraft were self-spacing. However, the researchers reported only relative results, not the specific number of clearances and the spacing intervals. They also did not report the results of any statistical tests. The researchers noted that the controllers reported having to monitor the unequipped aircraft more than the equipped aircraft and more than aircraft flying under current conditions. In addition, the controllers indicated that they were concerned that they could forget to issue a clearance (e.g., speed) to the unequipped aircraft in a sequence. The controllers appeared to have individual preferences for how to manage the mixed-equipage environment. One controller preferred to keep the equipped and unequipped aircraft in different clusters, but another controller preferred to alternate equipped and unequipped aircraft.

Boursier et al. (2006a) and Boursier et al. (2006) also asked controllers to evaluate some other events, including holding, go-arounds, and the inability of an aircraft to maintain spacing. All aircraft in these instances were able to self-space. However, the researchers did not collect aircraft performance data, so it was not possible to compare the extent to which throughput was affected in these conditions. The procedure proposed for holding called for the controller to cancel self-spacing for aircraft going into a hold and then to reintegrate them into the flow when slots were available. The procedure for managing go-arounds was similar. In an overtake, the

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[4] EUROCONTROL (2005) identified the use of headings as problematic in hazard assessments, so their use was discontinued in the self-spacing procedure. That report determined that controllers did not have full control over situations in which the “heading-then-merge” and “heading-then-follow” procedures were used. Controllers reported concerns about (a) aircraft merging without the appropriate heading or (b) aircraft merging at the wrong merge point when these instructions were issued.

procedure called for the controller to cancel the spacing instruction, reduce the aircraft speed, and then have the aircraft re-establish spacing with the TTF or begin as the lead aircraft in another stream. The controllers commented that the procedures would be no more difficult than those used today. However, this work did not include a comprehensive evaluation of the procedures nor did it evaluate the effects of a mixed-equipage environment with these situations or the effects of weather.

Callantine, Lee, Mercer, Prevôt, and Palmer (2005) conducted an investigation on the delegation of merging and spacing to the flight deck in terminal airspace in a mixed-equipage environment. In their study, terminal controllers used STARS displays and a timeline that presented a landing sequence with the STAs and estimated times of arrival (ETAs) of aircraft much like TMA in en route airspace. Callantine et al. (2005) also implemented other display modifications including route displays and indicated airspeeds (shown below the position symbol). Callantine et al. displayed a green "/S" to the right of the aircraft call sign to indicate that an aircraft was capable of self-spacing and displayed the call sign of the TTF and spacing information on the third line of the data block.

When the controller issued a spacing instruction, he could manually change the symbol to white as an indication that the aircraft was now self-spacing. The controllers could modify the symbol, the spacing interval, and the TTF via a separate shortcut panel. The panel also allowed the controller to determine the distances between aircraft and to perform other functions such as handoffs. When the controller dwelled on the position symbol, a "history circle" surrounded it indicating the aircraft's position relative to the lead. If the aircraft was spacing at the assigned interval, the display presented the aircraft centered within the circle. If the aircraft was not spacing precisely, the symbol appeared slightly ahead of or behind the circle.

Callantine et al. (2005) incorporated flows of traffic that came to a merge fix after having been previously spaced by the en route sector (coordinated) or without having been previously spaced (uncoordinated) and included 25% of aircraft that were not equipped for self-spacing. In the procedure, the controllers used the lead aircraft call sign to designate the TTF to aircraft. The controller initiated the spacing instruction by designating the TTF. The pilots did not have to confirm selection of the lead aircraft first, as in the EUROCONTROL procedure. The controller could only initiate self-spacing instructions after issuing a required heading or a direct-to clearance. The controller could only cancel self-spacing if the procedure became problematic (or to issue an approach clearance). Callantine et al. did not use airspace specifically configured to support merging and spacing, but the existing route structure enabled aircraft to be separated by altitude at the merge fix.

Callantine et al. (2005) evaluated four test conditions. One test condition included no flight-deck tools (i.e., no aircraft self-spacing capability) and no controller tools to support self-spacing. A second test condition included flight-deck tools, but no controller tools. A third test condition included controller tools, but no flight-deck tools. The fourth test condition included both flight-deck and controller tools. The results indicated that flight-deck tools resulted in more accurate spacing intervals at the fix, regardless of whether the controller tools were available. However, controller tools did improve spacing above that observed when no tools were available. Throughput did not differ across conditions, but the authors speculated that the inclusion of degraded conditions (e.g., bad weather) into the evaluation would likely make these differences apparent.

Callantine et al. also reported that whenever self-spacing was used, spacing accuracy improved even in situations in which the traffic on the merging routes was not coordinated. However, coordinated traffic flows resulted in the highest spacing accuracy. The controllers issued a greater number of clearances when flows were uncoordinated and proportionately more spacing clearances when the flows were coordinated. Similar to other research (e.g., Grimaud et al., 2004), this study found that controllers set up flows earlier when pilot self-spacing was implemented. Callantine et al. also found that use of the TTF call sign in the clearances was not a problem.

Although overall on-line workload ratings (measured every 5 min during scenarios) remained within an acceptable range in all conditions, Callantine et al. (2005) found some differences across conditions. The controllers handling the feeder position reported the lowest workload levels in the conditions in which no tools were used and reported the highest workload levels in the conditions in which only the controller tools were used. The controller handling the final position reported the lowest workload level when only flight-deck tools were used and reported the highest workload levels when only controller tools were used. The on-line workload ratings differed markedly from the workload ratings obtained at the conclusion of the scenarios. These measures of overall workload indicated that controllers rated the ground tools condition as having the lowest workload and the flight-deck tools condition as having the highest workload. The controllers also rated the condition in which ground tools were used as highest in safety. Callantine et al. speculated that some of these evaluations may reflect the controllers' perceived need for information, rather than how much effort was involved to work traffic.

Battiste et al. (2005) focused on the flight-deck side of a merging and spacing procedure in a mixed-equipage environment using simulated airspace in DFW Terminal Radar Approach Control (TRACON). In their simulation, all aircraft were ADS-B equipped, and 75% were equipped to conduct merging and spacing, using a three-dimensional CDTI and additional interactive display tools that allowed pilots to select the TTF and the spacing interval, and to evaluate their spacing from the lead. The controller tools included information provided in the data block that indicated the call sign of the TTF, the current and targeted spacing interval, and a tool that displayed estimated time of arrival for the aircraft (see Granada, Dao, Wong, Johnson, & Battiste, 2005).

The test conditions included current operations and three merging and spacing conditions: one condition that used only flight-deck tools, a second condition that used only controller tools, and a third condition that included both flight-deck and controller tools. In the merging and spacing procedure, a feeder controller issued clearances to aircraft to merge and follow (or follow only) a lead aircraft on each of two arrival routes. The final controller then merged the traffic from these routes into a single stream. In the merging and spacing conditions, the pilots informed the controller if spacing requirements could not be met. The controller remained responsible for ensuring separation and could cancel the procedure at any time.

Battiste et al. (2005) did not find any significant differences in adherence to the spacing interval across the three merging and spacing conditions. They found that the use of the flight-deck, the controller, and both flight-deck and controller tools resulted in about the same spacing intervals by the time the aircraft reached the FAF. Battiste et al. also found that the earlier the controller issued the clearance to initiate the procedure, the better the spacing performance. The pilots rated their workload lower when conducting the procedure compared to when conducting the current operations. However, the controllers indicated that they preferred conducting the operation when ground tools were used and that it was difficult to manage traffic in a mixed-equipage environment. As in other studies, Battiste et al. did not find any errors attributable to the use of TTF call signs in the transmissions.

3.4 Pilot-Based Separation

Additional studies investigated more advanced concepts involving the allocation of separation responsibility to the flight deck. Much of the research began as part of NASA's Distributed Air-Ground Traffic Management (DAG-TM) program. Lee, Prevôt, Mercer, Smith, and Palmer (2005) conducted a human-in-the-loop simulation of the self-separation concept to evaluate pilot and controller tools designed to enable the procedure. The flight-deck and controller tools were fully integrated with data link. The pilots of the self-separating aircraft were responsible for maintaining separation from all other aircraft, and they were required to resolve potential conflicts at least 2 min prior to a loss of separation (LOS). The controllers were notified of potential conflicts between self-separating and controller-managed aircraft if the pilot had not resolved the conflict at least 3 min prior to the LOS.

The researchers used simulated en route airspace in the study and existing en route separation standards. This airspace consisted of a high-altitude sector in Albuquerque Center (ZAB), two high-altitude sectors in Dallas-Ft. Worth Center (ZFW), and a low-altitude sector in ZFW. Two arrival streams traversed the high-altitude sectors and merged at a meter fix in the low-altitude sector before entering DFW TRACON. A ghost controller staffed the TRACON.

Lee et al. (2005) evaluated four test conditions using high-traffic level scenarios that reflected existing Monitor Alert Parameter (MAP) values or higher and that included arrivals, departures, and overflights. The first condition consisted entirely of controller-managed aircraft. The second condition consisted of a mixed fleet of aircraft (75% equipped). The third and fourth conditions included the same number of unequipped aircraft as the second condition, but with incremental increases in the number of self-separating aircraft, all of which were overflights.

The simulation included controller display tools and enhancements that were based on the results and feedback from participants in an earlier simulation (Lee et al., 2003). These display modifications included the use of limited data blocks (i.e., call sign, data link status, and current altitude) for the self-separating aircraft to minimize their salience and different color data blocks for the arrivals, departures, and overflights. They also included speed advisories in the fourth line of the data block. The controllers had trial planning capabilities and TMA and could issue clearances or modify flight plans to delay or speed up aircraft to meet the STA. Controllers could evaluate proposed flight plans by accessing the trial planning tool via an icon (i.e., arrow) displayed adjacent to the aircraft call sign. They also saw a time value (in min) indicating time until a LOS next to this icon, unless two self-separating aircraft were involved. Selecting the LOS time value highlighted the aircraft involved by displaying filled J-rings around their position symbols and by displaying the respective flight paths of the aircraft and their predicted conflict location. If a self-separating aircraft went into conflict with a controller-managed aircraft, its limited data block expanded to a full data block. The researchers also maintained the existing conflict alert function. The sooner the expected LOS, the higher the aircraft appeared in the conflict list. Color also indicated proximity to the projected LOS. Data displayed in red indicated that the LOS would occur in less than 2 min, data displayed in yellow indicated that the

LOS would occur in 2 to 5 min, and data displayed in white indicated that the LOS would occur in more than 5 min. Although the controllers were not responsible for separating the self-separating aircraft from the controller-managed aircraft, they were able to see these conflicts displayed (so that they could intervene if necessary).

The results indicated that aircraft met their STAs within 15 s, regardless of whether they were self-separating or were managed by the controller. Controller workload ratings corresponded to the number of controller-managed aircraft in the sector rather than to the overall number of aircraft. However, the participants rated the safety of the procedure somewhat negatively. They were concerned that the flight-deck automation may not detect a conflict and that the window of time allowed for pilots to resolve a conflict was too short. The participants were also concerned about having less awareness of the self-separating aircraft, particularly if conditions were degraded.

The participants found that the limited data blocks were effective for suppressing the salience of the self-separating aircraft, but that they also reduced the amount of information needed to intervene in problematic situations. The participants were also concerned that increasing traffic density would create unsafe conditions because it left less room to maneuver aircraft in the event of problems. Even when the participants knew the intent of the self-separating aircraft, they were not sure that the actions taken by the flight deck were appropriate.

The participants also commented on the support tools and display enhancements. They reported that data link, the speed advisory and trial-planning tool, and color coding were *highly useful* (mean ratings 4.5 or higher on a scale of 1 to 5). Data link allowed the participants to work high levels of traffic even in the condition in which all aircraft were controller-managed. The participants reported that it allowed them more time to manage other situations and to work with other tools. The participants commented more negatively on the display of conflict alerts. Display clutter was a problem when conflict alerts occurred between self-separating and controller-managed aircraft because when this occurred, the limited data blocks of the self-separating aircraft expanded. The participants also reported that the conflict list (and lists in general) produced too much clutter and that they ignored the lists when they were busy. The participants preferred to obtain information from the data block when it was available. Other comments indicated that it was more difficult to monitor and maintain separation in the mixed-equipage environment and that operations were less safe compared to current operations. Therefore, although the concept was observed to increase the number of aircraft that could be accommodated in a sector, a number of serious concerns remained.

The NASA Co-Operative Air Traffic Management (CO-ATM) concept extends the work that had begun with DAG-TM, but it places the emphasis on TBO to enable greater airspace capacity. In this respect, it is similar to the concepts evaluated by Becher et al. (2005) and Boursier et al. (2006b) but includes the delegation of self-separation to the flight deck as a further enhancement. Prevôt et al. (2005) provided a description of the concept that includes the same flight-deck and controller tools described by Lee et al. (2005) and full data link capabilities between air and ground. CO-ATM assumes a mixed-equipage environment, initially, that transitions to one in which most aircraft are capable of performing the procedures. Aircraft with more advanced FMS and data link capabilities would be managed differently than aircraft with limited capabilities.

In CO-ATM, the airlines would work with Traffic Flow Management (TFM) to develop trajectory-based schedules designed to deliver aircraft to a metering fix within 5 to 10 s of their targeted arrival time. Subsequently, the flight deck would assume responsibility for maintaining that spacing interval and would be assigned the task to self-separate. The CO-ATM would include a new area controller position. The area controller would manage airspace that spans multiple sectors and includes aircraft equipped for self-spacing and separation. The area controller would monitor, evaluate, and coordinate with the aircraft using data link should any flight path modifications be necessary. The sector controller would continue to manage other aircraft using voice communications. Unlike the DAG-TM concept, the area controller could also provide assistance to the self-separating aircraft to resolve a conflict or other issues, if requested. If a problem occurs, the area controller may resolve it by communicating with the aircraft by voice, handing off the aircraft to the sector controller, or issuing revised spacing instructions to the flight deck.

Other aircraft-based separation concepts for conducting aircraft crossing, merging and sequencing, and grouping maneuvers have been discussed by Morgenstern (2006). Morgenstern's concept assumes RNAV and RNP capabilities, though few details about what the procedures would involve were provided and no simulations have been conducted. A crossing procedure would be used in cases in which a potential conflict has been identified. The controller would designate a point at which one of the aircraft would be instructed to pass behind another. Using advanced flight-deck tools, the pilot would determine the direction and route of the change, and each flight crew would monitor the location and intent data of the other via the CDTI. Morgenstern proposes that the concept could be expanded to allow pilots to monitor and identify potential conflicts and take the necessary actions to avoid them.

The merging and sequencing concept and the grouping concept that Morgenstern (2006) describes are closely related. In merging and sequencing, the controller assigns a point to which several aircraft are instructed to merge into a common flow while maintaining separation from the other aircraft. A stream of "grouped" aircraft could be used to move traffic through constrained airspace (e.g., due to weather). In this case, the controller would assign one aircraft as the lead and require others to sequence and merge behind it at a designated point.

Morgenstern (2006) describes the need to develop procedures for handling situations in which aircraft merge mid-stream, cross a stream, and abandon a stream (e.g., because of an onboard equipment failure) but does not describe specific procedures for managing these situations. Shifting part of a stream could be done by designating one aircraft in the original stream as the new lead on a different path and assigning others to follow that lead. Parallel streams were also proposed but would require systems to detect blunders and provide solutions for how to resolve them. Morgenstern proposes reserving lower altitude airspace for aircraft to maneuver into if they encounter a problem. However, this solution may negate the airspace capacity benefits that such procedures are intended to produce.

4. CONCLUSION

This report focuses on the implications of aircraft self-spacing and self-separation concepts on the controller and on the additional tools and display requirements needed to support concept use. The results support those of previous studies, which found that self-spacing aircraft maintained more precise spacing intervals than aircraft that used current procedures. However, the addition of new controller tools also improved spacing precision for aircraft that were not self-spacing (Prevôt et al., 2007). Other data indicated that self-spacing aircraft required less vectoring and fewer air-ground communications, though researchers found that the ability of aircraft to adhere to predictable route structures (e.g., RNAV routes) also produced similar benefits (Boursier et al., 2006). Therefore, aircraft self-spacing procedures may be only one means by which efficiency gains can be achieved. It will be important to understand which procedures result in greater benefits and whether further benefits are realized if the procedures are used together.

The more recent research also began to consider the effects of mixed-equipage environments and degraded conditions in concept evaluations. Most of the earlier simulations did not address these effects, though controllers had identified them as potentially problematic. The studies conducted with aircraft in mixed-equipage environments found that workload was associated with the number of aircraft managed by the controller rather than the total number of aircraft in the airspace (Lee et al., 2005; Prevôt et al., 2005). This suggests that the procedure could allow for increased airspace capacity without negatively affecting controller workload. In addition, the aircraft adhered better to spacing intervals and the controllers issued fewer clearances in mixed-equipage environments (e.g., 50% equipage) compared to conditions in which no self-spacing was implemented, though the researchers found the greatest benefits when all aircraft were using the procedure (Boursier et al., 2006b, 2006). However, in mixed-equipage conditions, controllers reported that they needed to monitor the unequipped aircraft more closely than when using existing procedures. The controllers were also concerned about forgetting to issue clearances to aircraft that were not conducting the procedure and intervening effectively in problematic situations, especially when more advanced, self-separation procedures were used (Boursier et al., 2006a; 2006; Lee et al.).

A few of the more recent simulations included degraded conditions, such as aircraft that could not continue using a procedure. However, the researchers presented these conditions in a structured manner. The controllers knew in advance which situations to expect and were not tasked with identifying problems or managing the traffic, but rather with evaluating the proposed methods for handling the issue (e.g., Boursier et al., 2006a, 2006). More research is needed to understand how readily controllers can determine that a problem has occurred and how quickly it can be resolved.

Additional work is also needed to examine the effects of weather when these procedures are in use. The participants cited weather as a major concern, particularly with respect to more advanced concepts (e.g., Lee et al., 2005). To fully assess concept feasibility and usefulness, it will be necessary to determine how quickly procedures can be modified or abandoned under poor weather conditions and to determine what the results of those actions are on risk, workload, and efficiency.

Recent studies have also included additional controller tools and display enhancements. Controller information requirements increase with concept complexity. For more advanced concepts, capabilities such as data link that allow the efficient and timely exchange of information between the air and ground systems will be necessary. Information needs are particularly high in mixed-equipage environments because controllers must distinguish aircraft that are capable of performing procedures from those that are not. They must also be able to identify which aircraft are using a procedure. Feedback from recent simulation participants indicated that the availability of this information is especially important when conditions are degraded (Bone et al., 2007; Lee et al., 2005).

However, as additional tools and enhancements are provided, display clutter and increased workload may result. For example, Lee et al. (2005) identified that display clutter was an issue when the limited data blocks of self-separating aircraft expanded to full data blocks when the aircraft were involved in conflicts with controller-managed aircraft. Other studies found that workload was higher when controllers used additional tools in aircraft self-spacing conditions compared to conditions in which only the flight-deck tools were used (Callantine et al., 2005). In this study, controllers were responsible for manually entering data to indicate when an aircraft was utilizing self-spacing, thereby adding tasks that could have influenced these ratings. Despite these workload responses, controllers reported (a) that they preferred to manage traffic with the additional tools and (b) that they believed that safety was higher when they used the tools. These results suggest that controllers want to be informed (though it could come at a cost, unless the interfaces are carefully structured).

In summary, the self-spacing and self-separation procedures will change the roles of the pilot and the controller. Both pilots and controllers will need additional tools to support their use of such concepts if the concepts are ultimately determined to be feasible, beneficial, and viable in all conditions. Controllers will need information to determine aircraft equipage and whether an aircraft is using (or no longer able to use) a procedure. However, simply adding individual display elements to each aircraft data block on the controller workstation can contribute to clutter and increase workload. The FAA must develop a more effective approach. The interface should be structured so that commonalities across aircraft are emphasized and shared attributes and capabilities are apparent. The emphasis on shared attributes will better support the controller in determining how different aircraft need to be managed. This is especially important in mixed-equipage environments because aircraft that are flying RNAV routes or conducting self-spacing procedures are likely to require less controller intervention than aircraft that are using existing procedures. By providing information on the display to help differentiate these aircraft types, the controller can more efficiently allocate attention across the airspace and manage the traffic more effectively.

References

Battiste, V., Palmer, E., Johnson, W., Smith, N., Prevôt, T., Mercer, J., et al. (2005). Human centered decision support tools for arrival merging and spacing. *Proceedings of the 13th International Symposium on Aviation Psychology,* Oklahoma City, OK.

Becher, T. A., Barker, D. R., & Smith, A. P. (2005). *Near-term solution for efficient merging of aircraft on uncoordinated terminal RNAV routes.* McLean, VA: The MITRE Corporation.

Bone, R. S., & Marksteiner, J. (2007). *Flight deck-based merging and spacing (FDMS) application description* (Version 1.5). Federal Aviation Administration: MITRE.

Bone, R. S., & Penhallegon, W. J. (2006). *Flight deck-based merging and spacing (M&S) MITRE human-in-the-loop simulation 2 quick look report, August 21–September 5, 2006: Flightdeck focus.* McLean, VA: The MITRE Corporation.

Bone, R. S., & Penhallegon, W. J. (2007). *Flight deck-based merging and spacing 4: En route controller simulation plan, May 21–June 15, 2007.* McLean, VA: The MITRE Corporation.

Bone, R. S., Penhallegon, W. J., Stassen, H. P., Simons, E., DeSenti, C., & McGarry, K. (2007). *Flight deck-based merging and spacing on en route Air Traffic Control operations: FDMS 1 Simulation, May–June, 2006*. McLean, VA: The MITRE Corporation.

Boursier, L., Favennec, B., Hoffman, E., Rognin, L., Trzmiel, A., Vergne, F., et al. (2006a). *Airborne spacing in the terminal area: Controller experiments on mixed equipage, abnormal situations, and transition*. EEC Note No. 24/06, Brétigny-sur-Orge, France.

Boursier, L., Favennec, B., Hoffman, E., Rognin, L., Trzmiel, A., Vergne, F., et al. (2006b). Integrating aircraft flows in the terminal area with no radar vectoring. *Sixth AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, September 2006, Wichita, KS.

Boursier, L., Favennec, B., Hoffman, E., Rognin, L., Vergne, F., & Zeghal, K. (2005). Combining sequencing tool and spacing instructions to enhance the management of arrival flows of aircraft. *Fifth AIAA Aviation Technology, Integration and Operations Conference*, September 2005, Arlington, VA.

Boursier, L., Hoffman, E., Rognin, L., Vergne, F., & Zeghal, K. (2006). Airborne Spacing in the Terminal Area: A study of non-nominal situations. *Sixth AIAA Aviation Technology, Integration and Operations Conference,* September 2006, Wichita, KS.

Callantine, T. J., Lee, P. U., Mercer, J., Prevôt, T., & Palmer, E. (2005). Terminal-area traffic management with airborne spacing. *Fifth AIAA Aviation Technology, Integration and Operations Conference*, September 2005, Arlington, VA.

EUROCONTROL. (2005). *Mediterranean free flight programme: Working area 7 (MFF730 TR019) D733-MFF intermediate safety case*. Retrieved July 20, 2007, from http://www.medff.it/ public/archive/public_deliverables/documents/wa7/730TR019-1.0-P-D733-MFF%20Intermediate%20Safety%20Case.pdf

Federal Aviation Administration. (2006). *Airline-based en route sequencing and spacing concept of operations description* [Draft version 1.6]. FAA Safe Flight 21 Ground-based Merging and Spacing Development Subgroup, Washington, DC.

Federal Aviation Administration. (2007). *Operational Evolution Plan 2007–2025* (Version 1.0). Retrieved July 20, 2007, from http://www.faa.gov/about/office_org/headquarters_offices/ ato/publications/oep/version1/overview/overview.pdf

Federal Aviation Administration/EUROCONTROL Cooperative Research and Development. (2001). *Principles of operation for the use of airborne separation assurance systems* (Version 7.1). Retrieved May 15, 2007, from http://adsb.tc.faa.gov/RFG/po-asas71.pdf

Granada, S., Dao A. Q., Wong, D., Johnson, W., & Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit situation display for distributed air-ground operations, *2005 International Symposium on Aviation Psychology,* Oklahoma City, OK.

Grimaud, I., Hoffman, E., Rognin, L., & Zeghal, K. (2001). Delegating upstream: Mapping where it happens. *Fourth International Air Traffic Management R&D Seminar,* Santa Fe, NM.

Grimaud, I., Hoffman, E., Rognin, L., & Zeghal, K. (2003a). Spacing instructions in approach: Assessing usability from the air traffic controller perspective. *American Institute of Aeronautics and Astronautics Guidance, Navigation and Control Conference*, Austin, TX.

Grimaud, I., Hoffman, E., Rognin, L., & Zeghal, K. (2003b). Towards the use of spacing instructions for sequencing arrival flows. *Paper presented at the Operational Datalink Panel (OPLINKP) Meeting of Working Group A*, Annapolis, MD. Retrieved August 18, 2004, from http://www.fr/projects/cospace/Publications.htm

Grimaud, I., Hoffman, E., Rognin, L., & Zeghal, K. (2004). Spacing instructions in approach: Benefits and limits from an air traffic controller perspective. *American Institute of Aeronautics and Astronautics Guidance, Navigation and Control Conference,* Providence, RI.

Herndon, A. A., Williams, J. T., Vaughn, W., DeArmon, J. S., Duquette, M. A., Formosa, J. J., et al. (2003). Utilizing RNAV avionics: Testing lateral offset procedures. *Proceedings of the 22nd Digital Avionics Systems Conference (DASC)*. Piscataway, NJ: IEEE.

Joint Planning and Development Office. (2007). *Concept of operations for the Next Generation Air Transportation System* (Version 2.0). Retrieved July 17, 2007, from http://www.jpdo. gov/library/NextGen_v2.0.pdf

Lee, P., Mercer, J., Prevôt, N., Smith, N., Battiste, V., Johnson W., et al. (2003). Free maneuvering trajectory negotiation and self-spacing concepts in distributed air-ground traffic management. *Proceedings of the 5th EUROCONTROL/FAA Air Traffic Management Research and Development Conference*, Budapest, Hungary.

Lee, P., Prevôt, T., Mercer, J., Smith, N., & Palmer, E. (2005). Ground-side perspective on mixed-operations with self-separating and controller-managed aircraft. *Sixth USA/Europe Air Traffic Management R&D Seminar*, Baltimore, MD.

McAnulty, D. M., & Zingale, C. (2005). *Pilot-based spacing and separation on approach to landing: The effect on air traffic controller workload and performance* (DOT/FAA/CT-05/14). Atlantic City International Airport, NJ: Federal Aviation Administration, William J. Hughes Technical Center.

Morgenstern, R. (2006). *Communications, navigation, surveillance, and avionics within a 2020 future vision.* McLean, VA: The MITRE Corporation.

Penhallegon, W. J., & Bone, R . S. (2007). Evaluation of a flight deck-based merging and spacing concept on en route Air Traffic Control operations. *Seventh USA/Europe Air Traffic Management R&D Seminar*, July 2007, Barcelona, Spain.

Prevôt, T., Callantine, T., Homola, J., Lee, P., Mercer, J., Palmer, E., et al. (2007). Air/ground simulation of trajectory-oriented operations with limited delegation. *Seventh USA/Europe Air Traffic Management R&D Seminar*, July 2007, Barcelona, Spain.

Prevôt, T., Callantine, T., Lee, P., Mercer, J., Battiste, V., Johnson W., et al. (2005). Co-operative air traffic management: A technology enabled concept for the Next Generation Air Transportation system. *Sixth USA/Europe Air Traffic Management R&D Seminar,* Baltimore, MD.

Acronyms

ABESS	Airline-Based En Route Sequencing and Spacing
ADS-B	Automatic Dependent Surveillance – Broadcast
AMAN	Arrival Manager
AOC	Airline Operations Center
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
CDA	Continuous Descent Approach
CDTI	Cockpit Display of Traffic Information
CO-ATM	Co-Operative Air Traffic Management
CRDA	Converging Runway Display Aid
DAG-TM	Distributed Air-Ground Traffic Management
DFW	Dallas-Ft. Worth
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FDMS	Flight Deck-Based Merging and Spacing
FMS	Flight Management System
LOS	Loss of Separation
M&S	Merging and Spacing
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAIDS	Navigational Aids
NextGen	Next Generation Air Transportation System
PBN	Performance-Based Navigation
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
SDF	Standiford Field
SID	Standard Instrument Departure
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
STARS	Standard Terminal Automation Replacement System

TBO	Trajectory-Based Operations
TMA	Traffic Management Advisor
TRACON	Terminal Radar Approach Control
TTF	Traffic-to-Follow
UPS	United Parcel Service
ZFW	Dallas-Ft. Worth Air Traffic Control Center