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Pilot-Based Spacing and Separation on Approach to Landing: The Effect on Air Traffic Controller Workload and Performance

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16. Abstract

This document summarizes the existing literature on workload and performance issues related to pilot-based spacing and separation, methods under investigation for managing increases in traffic. Multiple concepts are under development, all of which involve pilot use of a Cockpit Display of Traffic Information (CDTI) that presents data about nearby traffic (e.g., location, altitude). More advanced CDTIs include functions that alert the pilot to potential conflicts or provide guidance about flight paths or speeds. This document focuses on concepts proposed for use during sequencing and merging and on final approach. Some concepts are considered more basic in that they would involve little change to current procedures and require only basic CDTI functionality. The literature indicates that pilot use of a basic CDTI to assist in visually acquiring traffic and following a lead aircraft is beneficial, and that pilot workload is generally acceptable. Controller reaction to pilot use of the CDTI for these purposes has also been generally positive. More advanced concepts that involve the use of more sophisticated CDTI functions require modifications to current procedures and additional controller workstation tools. The results from most studies indicate that the advanced concepts require further development before they become operationally feasible.

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Table of Contents

Page

Executive Summary v
1. Introduction 1
   1.1 Background 1
2. Overview of Pilot Self-Spacing Concepts 4
3. Feasibility of Pilot Self-Spacing 9
   3.1 Pilot Self-Spacing Research 9
   3.2 Effects of Pilot Self-Spacing on Air Traffic Control 15
      3.2.1 Operational Evaluations 15
      3.2.2 Eurocontrol Simulations 19
      3.2.3 U.S. Simulations 22
4. Status of Pilot Self-Spacing 24
   4.1 Feasibility of Pilot Self-Spacing 24
   4.2 Status of Pilot Self-Spacing Effects on Air Traffic Control 25
   4.3 Status of the Pilot Self-Spacing Concepts 27
5. Summary and Recommendations 34
References 37
Acronyms 43

List of Illustrations

Table Page

Table 1. Summary of Controller Critical Incident Ratings (from OECG, 2001) 17
Table 2. Summary of Controller Questionnaire Ratings 18
Table 3. Comparison of Pilot Self-spacing Concepts 28

Executive Summary

This document summarizes the existing literature on issues related to pilot-based spacing and separation on the workload and performance of pilots and Air Traffic Control Specialists (ATCSs). Pilot self-spacing is one of the methods under investigation by the U.S. Federal Aviation Administration (FAA) and other air traffic organizations around the world for managing expected increases in traffic volume. Pilot self-spacing shifts the responsibility for spacing between aircraft from the controller (who is monitoring multiple aircraft) to the pilot, who can focus on the lead aircraft and use highly accurate information on a Cockpit Display of Traffic Information (CDTI) display to achieve precise spacing. The CDTI displays information about nearby air traffic (e.g., location, altitude, direction of flight) to the pilot relative to ownship. More advanced CDTIs may also include functions that alert the pilot to potential conflicts or provide guidance about optimum flight paths or speed. Multiple variations of pilot self-spacing are under development for application in the en route, terminal, and airport surface environment.

The focus of this document is on those concepts planned for earliest implementation and proposed for use during sequencing and merging and on final approach. These concepts include: CDTI Assisted Visual Separation (CAVS), Enhanced Visual Approach (EVApp), Visual Separation on Approach (VSA), Approach Spacing for Instrument Approaches (ASIA), Independent Closely Spaced Parallel Approaches (ICSPA), National Aeronautics and Space Administration (NASA) Distributed Air-Ground Traffic Management (DAG TM) Concept Element 11 (CE11), and Sequencing and Merging (S&M).

Of these, CAVS, EVApp, and VSA are considered more ready for near-term implementation in that they involve little or no change to current procedures, and would require only basic CDTI functionality on the flight deck side. The literature indicates that pilot use of a basic CDTI to assist in visually acquiring traffic and following a lead aircraft is beneficial, and that pilot workload is generally acceptable. Controller reaction to pilot use of the CDTI for these purposes has also been generally positive.

The more advanced concepts (ASIA, ICSPA, NASA DAG TM CE11, and S&M) would require modifications to current procedures and more sophisticated CDTI capabilities for the pilot, and additional controller workstation tools. The results from most flight deck and air traffic control studies indicate that the advanced concepts are not mature and require further development before they become operationally feasible.

1. Introduction

The U.S. Federal Aviation Administration (FAA) and other air traffic organizations around the world are investigating methods for managing expected increases in traffic volume. One method under consideration would allow pilots to space their aircraft from others under several specified operational conditions. The transfer of spacing responsibility to the flight deck is hypothesized to improve the accuracy of inter-aircraft spacing and possibly to reduce controller workload. A substantial body of research has been conducted to evaluate whether pilot self-spacing is feasible and produces anticipated system efficiencies while maintaining the safety of flight.

This document summarizes the existing literature on issues related to pilot self-spacing on the workload and performance of pilots and Air Traffic Control Specialists (ATCSs). The primary focus will be on issues related to the operational conditions proposed for earliest implementation: pilot self-spacing during sequencing and merging and on final approach.

These findings will guide the development of additional requirements for evaluating terminal ATCS workload and performance under various self-spacing conditions. The results of the proposed evaluations will identify areas that should be addressed before pilot self-spacing can be successfully implemented and will provide input useful for designing or modifying tools for ATCS workstations.

1.1 Background

The FAA operates the busiest and most complex National Airspace System (NAS) in the world while maintaining the highest level of safety (FAA, 2004). The NAS includes hundreds of facilities, including Flight Service Stations, airport towers, Terminal Radar Approach Controls (TRACONs), Air Route Traffic Control Centers (ARTCCs), and the Air Traffic Control System Command Center (ATCSCC); thousands of pieces of equipment to support the surveillance, navigation, and communication functions; and thousands of ATCSs, technical operations support staff, and other related personnel. Flight Service Stations provide weather briefings to pilots, accept and file flight plans, provide en route advisories and flight following, and initiate search and rescue operations if needed. Airport tower personnel provide initial route clearances, coordinate ground taxi operations, and control airborne arrival and departure traffic within five miles of the airport, primarily through visual sighting of the aircraft.

TRACON ATCSs use radar surveillance to control aircraft arriving from high altitude, en route airspace to the airport area, those departing the tower area to en route airspace, and aircraft transitioning the airspace. The TRACON area of responsibility typically extends about 40 miles from the primary airport (the area may also include secondary airports), and from 3000 feet above the airport to approximately 10,000 feet above mean sea level (MSL), although some TRACONS control a larger volume of airspace. ARTCC ATCSs use radar surveillance to control aircraft operating above the TRACON airspace. All aircraft flying above 18,000 feet MSL are on Instrument Flight Rules (IFR), and ATCSs provide positive control for separation. Aircraft below that flight level may either be on an IFR flight plan or can fly under Visual Flight Rules (VFR), depending on aircraft capabilities and intent, and on weather conditions. VFR pilots are responsible for maintaining visual separation from other aircraft, but may receive traffic and other advisories from ATCSs if requested and time is available. Finally, the

ATCSCC takes a system-wide view of the NAS, monitoring traffic flows and weather conditions, and coordinating with the airlines, the military, and the Air Traffic Control (ATC) facilities to maintain an optimum flow of traffic across the nation. At any point in time, more than 5,000 aircraft may be operating in the NAS.

Historically, pilots have flown routes dictated by ground-based navigation aids, such as Very High Frequency (VHF) Omnidirectional Range (VOR) systems, which transmit signals that the pilot can use as a guide to fly from point to point. The navigation system enables pilots to fly in instrument meteorological conditions (i.e., when they cannot see the ground for visual pilotage) and provides a highly structured route system that ATCSs can monitor. Controllers maintain safe separation between aircraft by issuing clearances for altitudes, headings, speeds, etc. In the en route environment, controllers must maintain minimum separation distances between aircraft of 5 nm horizontally and 1000-2000 ft vertically, depending on altitude. In terminal airspace, IFR aircraft are separated horizontally by 2.5 - 6 nm, depending on aircraft type, weather, turbulence, airport facilities, etc.; and by 1000 ft vertically.

However, this system was not highly efficient (e.g., pilots usually could not fly direct routes from end to end but rather had to zig zag from one VOR to the next) and produced periods of congestion, especially when weather limited the number of available routes. The inefficiencies in the NAS became increasingly apparent as the annual number of commercial travelers increased from under 200 million in 1970 to nearly 700 million in 2000. As the demand on the NAS increased, so did the number and duration of flight delays, and the number of operational errors. Following the terrorist attacks with commercial airliners on September 11, 2001, the volume of air travel initially decreased, but in 2004 traffic was above 2000 levels at some airports and increasing to near that level at others. The long term trend is for a steadily increasing volume of air passengers, which will put increasing demands on the system. Version 5.0 of the FAA Operational Evolution Plan (FAA, 2004) is designed to increase capacity by 27% by 2013.

The FAA has been pursuing multiple solutions to increase the efficiency of the NAS while maintaining the safety of flight and the health of the environment (FAA, 2004, 2005). The solutions include building new runways at overburdened airports (which requires many years to design and construct, and is very expensive) and redesigning the airspace to be more efficient (e.g., adding more direct routes, modifying approach and departure routes, and reducing the minimum vertical separation criteria at high altitudes). The solutions also include providing controllers with improved equipment and new tools (e.g., the User Request Evaluation Tool [URET], the Traffic Management Advisor [TMA], the Integrated Terminal Weather System) and providing pilots with new tools (e.g., the Traffic Alert and Collision Avoidance System [TCAS], Wide Area Augmentation System). Finally, the solutions include better coordination between the users and operators of the NAS (called Collaborative Decision Making) and spreading the demand out across the day at busy airports rather than concentrating it at the most desirable travel times, which results in scheduling more arrivals and departures for an airport than it can realistically accommodate. Another approach under consideration is to redistribute the roles and responsibilities of pilots and controllers to maximize efficiency while maintaining safety.

In 1995, the RTCA (a consortium of government and aviation industry professionals) proposed the concept of Free Flight, which would move the NAS from a centralized, ground-based, command-and-control system to a distributed system that would allow pilots (supported by their operations control centers and advanced technologies) to chose and follow the most efficient routes, except when restrictions must be imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through Special Use Airspace, and to ensure safety of flight (see Krozel, 2000). European nations are working towards a similar concept of "Free Routes" to manage volume (Sheridan, 2001). However, the definition of these concepts is not clear. Wickens, Mavor, Parasuraman, and McGee (1998) stated that "…the concept of free flight is not defined by a universally accepted set of procedures. Different players have very different notions of what it should be, how free it will be, and over what domains of the airspace it will apply (e.g., en route versus TRACON, high altitude versus all altitudes, continental versus oceanic)" (p. 228). Wickens et al. recommended that Free Flight procedures and supporting automation should be implemented cautiously and only after substantial research and testing, and that for the foreseeable future, responsibility for the separation of aircraft and overall safety should remain consistently and unambiguously on the ground.

The operational use of Free Flight concepts required new technologies. Three major technologies were implemented during the 1990s that have become primary enablers of Free Flight capabilities. First was the implementation of the Global Positioning System (GPS), originally developed by the Department of Defense (DoD), without selective availability. GPS is a satellite-based navigation system that transmits signals that can be used to determine a vehicle or person's location in space. In the original military system, selective availability diluted the accuracy of the GPS signal so that US forces would have better navigational information than any adversarial force. The demand for access to accurate navigational information led the DoD to disable selective availability, except in the case of war. In most of the US, GPS-derived location is highly accurate (within a few meters), although it can vary depending on the number and location of satellites in the direct line of sight, how well the satellites are functioning, and atmospheric effects on signal propagation. Aircraft with GPS receivers are now able to fly direct or on user-preferred routes independent of the ground-based navigation systems when cleared by air traffic control.

The second enabling technology was Automatic Dependent Surveillance - Broadcast (ADS-B). ADS-B is an onboard system that automatically transmits its GPS-derived position, along with other information such as aircraft (or other vehicle) identification, speed, heading, and intent. Ground and airborne systems can receive and process the broadcast information. ADS-B data are more accurate and are updated more frequently than radar. The third technology was the Cockpit Display of Traffic Information (CDTI), a system for displaying traffic information to the pilot relative to their ownship position, map locations, and ground proximity. Traffic information typically includes the location of the other aircraft within a specified range, their relative or absolute altitude, direction of movement, and the ground speed of and distance to a selected aircraft. More advanced CDTIs may have algorithms that alert the pilot about potential conflicts or that provide guidance to the pilot about optimum flight paths or speeds (e.g., Lohr, Osguera-Lohr, Abbott, & Capron, 2003).

These three technologies have enabled radical changes in the operation of the NAS and in the capabilities for pilots to fly the most efficient routes. As a result, the FAA has published new arrival and departure routes based on GPS navigation. Controllers can now use ADS-B transmissions to monitor and provide vectors to aircraft operating in nonradar airspace (e.g., western Alaska; Australia is currently conducting the trial use of 5 nm separation in nonradar airspace in Queensland using ADS-B surveillance), and pilots with CDTIs have better awareness of nearby traffic and terrain when weather conditions prevent visual observation (Williams, Yost, Holland, & Tyler, 2002). One of the next logical developments is to transfer the responsibility for spacing between aircraft from the controller (who is monitoring multiple aircraft with less accurate radar data) to the pilot, who can focus on the lead aircraft and use highly accurate information on the CDTI to achieve precise spacing. Pilot self-spacing may be especially advantageous in the terminal area where aircraft are closer to each other and maneuvering for approaches to land. More accurate and steady spacing on approach would maximize the utilization of available runways while maintaining sufficient distance between aircraft to avoid wake vortices[1] from the leading aircraft and to allow sufficient time for the lead aircraft to clear the runway onto the airport taxiway.

2. Overview of Pilot Self-Spacing Concepts

Pilot self-spacing is one component of the FAA Free Flight program that is part of the NAS Modernization Plan (FAA, 2002). Multiple variations of the concept are under development by different organizations for application in the en route, terminal, and airport surface environment. Some provide almost complete autonomy for pilots to maneuver as they wish along with the responsibility for separating their aircraft from all other aircraft. This section will summarize the concepts focused on pilot self-spacing in the terminal environment.

Currently in the NAS, pilots on an IFR flight plan self-space from other aircraft in the terminal environment under Visual Meteorological Conditions (VMC) when instructed by the controller to follow a lead aircraft for arrival. Controllers may instruct a pilot to follow another aircraft in an arrival sequence to a runway once the pilot confirms the lead aircraft is in sight, thus reducing controller workload so that more attention can be focused on other aircraft. In a variation of this procedure, a pilot may be cleared to a runway but must maintain visual separation from an aircraft landing on a parallel runway (e.g., see Bone, Hammer, et al., 2003). Visual approach clearances transfer responsibility for separation to the pilot, thus reducing the controller's surveillance workload and minimizing the need for further communication.

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[1] Wake vortices are swirling currents of air produced by pressure differentials in the air passing over and under an aircraft's wings. These vortices create unstable, turbulent air for a trailing aircraft, which is especially problematic in terminal airspace because of the close proximity of aircraft. Currently, aircraft separation intervals are defined to minimize the effects of wake turbulence and accommodate radar limitations, with runway threshold separations based on the size and type of aircraft. Since heavier aircraft produce more wake turbulence, aircraft that follow need to be separated from them at greater distances (O'Connor and Rutishauser, 2001). In the US, aircraft classified as "heavy" (i.e., greater than 115.77 tons) are separated from other trailing heavy aircraft by 4 nm, from large aircraft (i.e., between 18.615 and 115.77 tons) and B757s by 5 nm, and from small aircraft (i.e., less than 18.615 tons) by 6 nm. Separation between large aircraft and heavy or large trailing aircraft is 2.5 nm, and separation between large and small aircraft is 4 nm. Small aircraft are separated from all other trailing aircraft by 2.5 nm. The International Civil Aviation Organization (ICAO) and United Kingdom separation standards are similar, ranging from 3 - 5 nm, though aircraft classes are defined by somewhat different weight categories (see www.cerfacs.fr/~wakenet/safet/operation/SURVEY1.html). Wake turbulence also depends on approach path, winds, etc.

These forms of pilot self-spacing rely on out-the-window (OTW) sightings and are therefore limited to use in good visibility conditions. Even in clear weather, however, self-spacing may be problematic because a pilot may lose sight of the lead aircraft (e.g., due to sun glare) or may incorrectly identify the aircraft to follow if more than one is in sight. Pilots may also have difficulty adjusting to speed reductions of the lead aircraft (Mundra, Cieplak, Domino, Olmos, & Stassen, 1997). Stassen (1998) indicated that conducting visual approaches is a very workload intensive task for pilots. He reviewed the Aviation Safety Reporting System (ASRS) database and found that over a 3-year period, there were 150 pilot reports of safety concerns related to this procedure. Olmos, Mundra, Cieplak, Domino, and Stassen (1998) suggested that a CDTI could help alleviate some of these problems as it would aid pilots in the identification of aircraft, assist them in maintaining the appropriate traffic to follow, and provide better information about the relative speed (e.g., closure rate) and location of other aircraft.

The RTCA Special Committee 186 (RTCA, 2003) defined the minimum aviation system performance standards for eight aircraft surveillance applications. The applications require ADS-B and CDTI capabilities, and in some cases more advanced Airborne Surveillance and Separation Assurance Processing (ASSAP) capability, which could include algorithms to provide speed guidance to the pilots or alerts if the aircraft was not conforming to minimum separation criteria. The applications are designed to enhance safety and increase capacity and efficiency by allowing aircraft to approach closer to each other than is possible with current surveillance and procedures, improve runway throughput in Instrument Meteorological Conditions (IMC) through the use of the cockpit tools, and accommodate more kinds of flight trajectories than are currently authorized.

Four of the applications are considered basic, in that they support current functions but do not necessarily lead to new procedures: Enhanced Visual Acquisition, Conflict Detection, Airport Surface Situational Awareness, and Final Approach and Runway Occupancy Awareness. The Enhanced Visual Approach (EVApp) application is considered intermediate because it supports both current functions and potentially enables new ones. The other three applications (Airborne Conflict Management, Approach Spacing for Instrument Approaches (ASIA), and Independent Closely Spaced Parallel Approaches (ICSPA) are advanced and require some degree of ASSAP capability. Of these eight applications, EVApp, ASIA, and ICSPA are relevant concepts for pilot self-spacing in the terminal environment.

In an EVApp operation (RTCA, 2003, Appendix G), the responsibilities of the controller and pilot are the same as in current operations but involve changes to the procedures. The controller identifies appropriately equipped aircraft pairs, then points out the lead aircraft to the trailing aircraft pilot using the same terminology as today (Aircraft 2 call sign, traffic, bearing, range, altitude, heading), but the concept proposes that the controller add the call sign of the leading aircraft. The trailing pilot selects the lead aircraft on the CDTI and correlates its position visually OTW, then responds “Aircraft 1 call sign in sight” rather than “traffic in sight.” The controller then instructs the pilot to “follow Aircraft 1 call sign for the visual approach.” If the pilot accepts, separation and spacing are now the responsibility of the flight crew, just as in a normal visual approach. The EVApp concept does not envision the controller issuing spacing instructions or that the pilot necessarily will attempt to reduce spacing, and there is no change to current visual separation standards. The application description states that pilots should terminate the procedure if visual contact is lost. EVApp is expected to improve the visual acquisition of traffic; aid in positive identification; reduce the probability of losing visual contact; aid pilots in judging range, closure rates, and encounter geometries; and reduce controller workload, especially in terms of communication requirements.

Appendix G (RTCA, 2003) is explicit about the CDTI features that are required to conduct the application. The required features are (a) own aircraft symbol, (b) traffic symbol and identification, (c) either the relative or absolute altitude of the traffic, (d) traffic bearing, range, and horizontal velocity vector, (e) target selection and highlighting, (f) either the target ground speed or closure rate, and (g) a range reference. The appendix also provides minimum technical specifications for the system, such as data accuracy, integrity, and timing parameters.

ASIA (RTCA, 2003, Appendix I) is a similar concept of operations in instrument approach procedures once an aircraft is established on the final approach course. The pilot assumes responsibility for separation from the lead aircraft, while the controller maintains responsibility for separation from all other aircraft. The primary advantage is that the onboard system would provide speed guidance to the pilot to maintain a designated spacing from the lead aircraft. By transferring the responsibility for spacing to the flight deck and providing the flight crew with tools to adjust their speed with respect to the lead aircraft, more accurate and less variable landing intervals could be attained during instrument approaches when visual separation is not applied. The assigned spacing is assumed to be greater than the minimum radar and wake vortex separation distances. The concept is less well developed than EVApp, with many additional issues to be researched before it can be implemented.

The EVApp and ASIA concepts are for single runway, in-trail spacing by pilots. ICSPA (RTCA, 2003, Appendix J) is for simultaneous approaches to closely spaced parallel runways once the aircraft are established on the final approach course and executing an instrument approach. It could be used for aircraft approaching runways that are as close as 2500 feet without the use of a Parallel Runway Monitor (PRM), a ground radar surveillance system certified for simultaneous approaches to runways separated by at least 2500 feet. PRM currently has a very limited deployment because of its cost and operating personnel requirements. Without it, aircraft on approach to parallel runways less than 4300 feet apart in IMC would have to be staggered to maintain minimum radar separation, thus reducing the arrival rate below what could be achieved in VMC.

The primary functions of the ICSPA concept are to provide highly accurate, automated flight path management of the aircraft's trajectory, a cockpit display of the paired aircraft's location and speed, and an alert should either aircraft blunder toward the other so that the pilot could execute a predetermined breakout maneuver. No new tools or responsibilities are anticipated for ATC other than knowing which aircraft are capable of performing the application, which could be accomplished verbally when aircraft check in on the final sector frequency, and initiating ICSPA. In this concept, responsibility for lateral separation from the paired aircraft would be transferred to the pilot while the controller would retain responsibility for separation from all other aircraft. The assumption is that ICSPA would allow arrival rates to parallel runways in IMC that are closer to those achieved in VMC. Some preliminary evaluations by National Aeronautics and Space Administration (NASA) have supported the feasibility of the concept, but much more research and analysis are required before it can be implemented (RTCA, 2003). In particular, analyses are needed to justify the cost to the airlines of equipping nearly the entire fleet with the equipment and training needed to execute the application. Without extensive equipage, no significant capacity gain is anticipated.

The MITRE Center for Advanced Aviation System Development (CAASD) has conducted four simulations of a concept similar to EVApp called the CDTI Assisted Visual Separation (CAVS)[2] during visual approach (Bone, 2004). In CAVS, however, the operational definition of "visual separation" is expanded so that the pilot can explicitly substitute CDTI information for visual contact once the position of the lead aircraft on the CDTI has been correlated with its OTW position. A later stage of the concept may allow visual separation based solely on the CDTI without external correlation, but CAASD has not conducted any research on that usage. One other difference from EVApp is that the CAVS concept allows but does not require that either controllers or pilots use the call sign of the traffic to follow (TTF) in their communications. Instead the call sign could be used when it provides some operational advantage (e.g., when two identical aircraft are in close proximity and positive identification could otherwise require several communications). Controller and pilot responsibilities are not expected to change from current visual approach clearances. That is, pilots accept the responsibility to maintain surveillance of the lead aircraft and maintain safe separation from it once cleared for the approach.

The NASA Distributed Air-Ground Traffic Management (DAG-TM) Concept Element 11 (CE 11), Terminal Arrival: Self-Spacing for Merging and In-Trail Separation (NASA, 2004), is a more complex concept that may require additional automation tools on the ground and the flight deck, and specifically envisions its use in IMC. The controller would determine the optimum sequencing of aircraft arriving from multiple streams (viz, on different routes to a merge point), identify appropriately equipped aircraft pairs, and then issue a single spacing clearance to the trailing aircraft pilot (i.e., identify the TTF and assign a time-based spacing instruction). The flight crew would evaluate their ability to comply with the clearance and, if able, accept the clearance and activate their onboard guidance automation, which would provide them with flight parameter commands (primarily speed). The flight crew would then become responsible for maneuvering the aircraft (either manually or automatically through their Flight Management System) to merge into the traffic flow, to maintain their assigned in-trail spacing from the TTF, and to remain clear of other nearby aircraft shown on the CDTI.

The ATCS would remain responsible for minimum separation assurance, but otherwise would not interfere with the airborne spacing operation. To perform this operation, the controller will need information about aircraft equipage, an indication of which aircraft are performing self-spacing and what their assigned spacing value is, and information needed to monitor conformance with the clearance. To be appropriately equipped for this operation, the cockpit will need GPS, ADS-B, a CDTI, and a computational tool to provide real-time speed and heading guidance cues. The operation would be facilitated by a control-display unit showing the required and actual time- and distance-based spacing from the lead aircraft, ownship and lead aircraft groundspeed, and approach winds. Although not all aircraft are assumed to be equipped for CE 11 operations, the concept does envision that all aircraft will broadcast their GPS positions and that all surveillance displays, both air and ground, will be based on ADS-B data.

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[2] Originally, the concept was called CDTI Enhanced Flight Rules (CEFR) but was changed to reflect a more accurate description.

Currently, there is an international group (the Requirements Focus Group [RFG]) that is developing a first package of Airborne and Ground Surveillance Applications enabled primarily by ADS-B. The RFG operates under the auspices of the FAA, RTCA, the European Organization for the Safety of Air Navigation (Eurocontrol), and the European Organization for Civil Aviation Electronics (EUROCAE). The RFG Application Definition (AD) subgroup is tasked to harmonize the definition of the applications between Europe and the US as a step toward world-wide interoperability (RFG AD, 2004). The RFG has expanded to include representatives of other countries, such as Australia and Japan. Package 1 currently contains four ground applications: ATC surveillance in radar areas, ATC surveillance in non-radar areas, Airport surface surveillance, and Aircraft-derived data for ground tools. It contains six flight deck applications: Enhanced traffic situational awareness on the airport surface, Enhanced traffic situational awareness during flight operations, Enhanced visual separation on approach (VSA), Enhanced sequencing and merging (S&M), In-trail procedure in oceanic airspace, and Enhanced crossing and passing operations. The VSA and S&M applications are variations of the NASA Concept Element 11, but are more near term for potential implementation because they do not assume as much automation support. The VSA application is designed for use only in VMC.

The S&M application (RFG AD, 2004) can be conducted in either en route or terminal airspace and can be performed in both VMC and IMC. The controller retains responsibility for separation. The S&M application has four maneuver variations. The two basic maneuvers are controller instructions for a pilot to “Remain behind” a lead aircraft in the same traffic stream and to “Merge behind” a lead aircraft in a separate but merging stream. The advanced maneuvers are instructions to “Vector then remain behind” and to “Vector then merge behind.” These maneuvers are used when the trailing aircraft is too close to the TTF, and vectors are required to achieve the minimum separation. All the instructions include a spacing value to be obtained and maintained. The value can be distance-based or time-based, with time-based spacing preferred if the CDTI can display time in trail. The application definition refers to the aircraft having appropriate airborne separation assurance system (ASAS) capability, but does not define what that capability would include. The spacing value can be an absolute value (within a certain tolerance) or an “at least” value. Once the pilot accepts the clearance, the flight crew is responsible for maintaining the spacing, but the controller remains responsible for separation assurance. The objective of the S&M application is to achieve more consistent aircraft spacing and to reduce the amount of air-ground communications.

A major difference between the S&M application and the other concepts is in the sample phraseology for pointing out the lead aircraft. The concept does not define what the protocol will be, other than new procedures must be designed to ensure positive, unambiguous identification of the target aircraft. The issues concerning various protocols are continuing to be examined. The phraseology proposed as one example, however, would require the controller to point out the TTF using only its call sign. The pilot would select the aircraft on the CDTI and reply that they have identified the target and report its relative position (e.g., bearing and distance). The controller would affirm that the correct target is selected, and then issue the spacing instruction, which could include a waypoint at which the sequencing, merging, and spacing must be accomplished and an endpoint, if approved, for the pilot self-spacing. The flight crew then evaluates the clearance and either accepts or declines it. If there is an endpoint, then the pilot must contact the controller to terminate the spacing clearance when the endpoint is reached.

The VSA application is very similar to the other visual approach concepts in which the pilot correlates the OTW location of the TTF with the CDTI information, then uses that information to enhance the visual approach. VSA can only be performed in VMC, and the pilots must maintain visual contact with the TTF. Responsibility for separation from the lead aircraft is therefore transferred to the pilot, just as in current visual separation procedures during visual approaches. There is no spacing instruction from the controller (other than an implied clearance to maintain visual separation), but the pilot may take advantage of the more exact spacing information to close up if time allows. The exact phraseology for this application is not yet determined, but in the application definition, it assumes that the controller will at least include the target call sign when pointing out the TTF. It also envisions that the controller might not give some or all of the relative position currently included in a visual point out, but instead the pilot could provide this information in the sighting response to confirm that the correct aircraft is selected. This phraseology would be consistent with the S&M example, which meets another requirement that all the applications use similar phraseology.

3. Feasibility of Pilot Self-Spacing

The concept of a CDTI was first proposed in the 1940s (see Sorenson, 2000), but its potential was severely limited by the technology of the time. The US Air Force developed and tested airborne traffic displays in the 1960s and 1970s that were eventually configured into their Airborne Warning and Control System (AWACS). NASA conducted numerous analytical and experimental studies in the 1970s and 1980s about the design and use of commercial CDTIs. After TCAS was mandated for commercial airliners by the end of 1993, there were proposals that pilots could use the displays for purposes other than traffic alerting and collision avoidance, such as using the display for traffic acquisition, continuing under visual rules on approach down to the actual minimum visibility, and potentially reducing the minimum for a visual clearance (Mundra, Cieplak, Domino, & Peppard, 1993). However, the first (and so far only) additional official use of the TCAS cockpit display was for oceanic in-trail climb and descent through the altitude of a leading aircraft (Cieplak, Mundra, & Peppard 1995).

The majority of the early research focused on the design and feasibility of CDTI use by pilots. Ballin, Hoekstra, Wing, and Lohr (2002) indicate the NASA research approach has been to demonstrate CDTI feasibility for airborne operations before conducting research to integrate its use with air traffic control. In this section, we will first review more recent studies of pilot use of CDTIs for self-separation and then summarize the available literature about the implications for ATCSs.

3.1 Pilot Self-Spacing Research

Krozel (2000) reviewed the empirical literature published between 1990 and 2000 related to the NASA DAG-TM Concept Elements. He found that the majority of the studies focused on the flight deck, and most evaluated free maneuvering by the pilots in en route airspace. The results of these studies indicated that pilots believe that a CDTI improves the visual acquisition task, makes in-trail spacing feasible, and is associated with an acceptable level of workload. There have been issues with the interface design (e.g., color coding, functionality) of some of the prototype displays used in the simulations, and some negative effects associated with using the procedure. For example, higher traffic density led to increased workload and longer conflict detection times, but the crews tended to detect a conflict prior to a system alert. The location of the conflicting aircraft relative to the ownship and the maneuvers it performed also affected detection and what actions the pilot chose to take. Also, when CDTIs were used in a Free Flight environment, there were statistically significant increases in the number of air-ground transmissions. Finally, most pilots expressed strong opinions advocating a continued, active role for controllers in Free Flight operations.

Krozel (2000) noted several limitations to all the empirical studies he reviewed. Some of the major limitations were that most of the studies assumed a constant velocity for intruder aircraft (whereas real intruders will likely be maneuvering); very few if any included wind, turbulence, weather, or special use airspace effects; very few considered mixed equipage among aircraft or different classes of aircraft involved in conflicts. Few studies considered the transition from airborne separation to ground-based positive control and none of the studies considered imperfect communications. All of these factors, at least until full equipage is achieved, are real and routine parts of the NAS environment that could affect the options available to the flight crew and the feasibility of pilot self-spacing.

In 2002, Ballin et al. summarized research conducted at NASA Langley Research Center and at the National Aerospace Laboratory (NLR) of the Netherlands to evaluate the technical and operational feasibility of the autonomous airborne component of DAG-TM for both the en route and terminal areas from the flight deck perspective. They concluded that airborne autonomous operations can be reliably performed without controller intervention in the en route cruise phase of flight that pilots can strategically resolve conflicts even in highly constrained environments, and that pilot workload did not reach unacceptable levels, even for high traffic densities. The research was not as supportive of pilot self-separation in the terminal area, although it was still considered feasible. They concluded that highly constrained terminal environments with merging arrival streams would require more sophisticated airborne tools than are currently available and would likely involve only limited delegation of responsibility to the flight deck. Ballin et al. acknowledged that much more research and development are needed to understand the limits of its feasibility and to develop enabling technologies.

Other studies published since 2000 are also very relevant to the flight crew aspects of pilot self-spacing in the terminal environment. One key study jointly sponsored by the FAA and the Cargo Airlines Association (CAA) involved an operational evaluation of CDTI usage by pilots that focused on the terminal environment (Operational Evaluation Coordination Group [OECG], 2000). The objective of the flight tests was to evaluate the CDTI for assisting pilots in visually acquiring traffic in the terminal area and in following the lead aircraft on final approach. The pilots of eight cargo airlines aircraft flew extended traffic patterns to two parallel runways (four aircraft per runway) during morning and afternoon test sessions. On approximately two-thirds of the patterns, the pilots used their CDTI to acquire traffic and follow the lead aircraft to the runway. On the remainder of the patterns, the pilots followed their normal procedures as a baseline for comparison. Researchers collected both objective and subjective data about pilot use of the CDTI, which found no major problems and generally elicited positive reactions about its use. Marginal VFR weather during the morning session and equipment maintenance problems resulted in an imbalanced data collection protocol, so most data were not subjected to statistical tests.

Flight crews reported that the CDTI improved their visual acquisition of traffic, but the average time to acquire traffic (measured by the time needed to respond “traffic in sight” to an ATC point out) was about the same (20 s) with and without the CDTI. One possible explanation for this result is that pilots continued to look for traffic longer when they had the CDTI, rather than just responding negatively to the point out. Other analyses also indicated the acquisition time was confounded by the separation distance and encounter geometry of the aircraft, regardless of whether the CDTI was in use. In analyzing the air-ground communications, Prinzo (2001) found that pilots reported acquiring 76% of the TTF using the CDTI compared to 63% when they did not have it available. She also reported that only 3.7% of the traffic-related communications exhibited any problems. Most of these resulted from the inconsistent use of the TTF call sign or pilots reporting unsolicited sightings. Though none of the problems resulted in any serious consequences, Prinzo recommended that the communications phraseology should be standardized and both controllers and pilots should be well trained on the procedures.

Flight crews reported the CDTI was useful for overall traffic awareness and for closing to an appropriate final approach spacing distance (OECG, 2000). There was a trend toward a 1.4 mile mean reduction in spacing at the runway threshold and a 15% reduction in time on final approach when using the CDTI. However, potential confounds require caution in interpreting these results. For example, the CDTI aircraft were closer to each other prior to the final approach course than aircraft not using the CDTI; however, the CDTI aircraft closed up on the lead by the same percentage as the baseline aircraft despite having less time and distance to do so. In a separate analysis, Mills (2000) analyzed the aircraft tracking data separately for the morning and afternoon sessions. In the morning session when visibility was low, there was a reduction from 7.3 nm (baseline) to 6.8 nm between aircraft when the CDTI was used. In the afternoon session, average spacing was 4.6 nm in the baseline condition and 3.6 nm in the CDTI condition. However, there were only 6 baseline approaches versus 35 CDTI approaches in the afternoon, so the differences may not be reliable.

The flight crews identified two issues related to CDTI use in the terminal area that need to be addressed. First, the CDTI implementation as a standalone system created problems integrating it into the normal pilot instrument scan, which may have caused additional intracockpit communications. Second, many crews reported increased head-down time when using the CDTI. Cieplak, Hahn, and Olmos (2000) suggested that the possible (no objective measures taken) increase in head-down time could result in more effective visual acquisition, thus increasing the overall efficiency of the process. They also suggested that the head-down time may have been a function of the pilots’ inexperience with the CDTI, and that it might be reduced as the pilots become more familiar with it. They concluded that the use of the CDTI for enhancing visual acquisition and visual approaches are mature concepts and have been approved by the RTCA Special Committee.

The OECG (2001) subsequently conducted a more extensive operational evaluation of the use of CDTIs for airport surface situation awareness, departure spacing, visual approach spacing, and final approach runway occupancy awareness. Sixteen equipped aircraft participated in five, 3-hour test flight sessions: three during the day and two at night to a single runway (regular airport traffic were using the parallel runway). The visual approach spacing application evaluated visual acquisition of TTF, initial spacing (prior to the final approach course), and a 20-mile final approach to the runway threshold. In some sessions, the pilots were tasked to achieve a 5 nm separation and in others to achieve a 3 nm separation at the runway threshold. Most aircraft were equipped with a basic CDTI, but some had an advanced CDTI with algorithms to display time-based separation. However, equipment problems limited the number of approaches made with the advanced systems, so the resulting data were unreliable. Finally, parts of the sessions were run in a mixed equipage environment where some aircraft were squitting ADS-B data on two different frequencies.

As in the first operational evaluation, the CDTI improved the acquisition of TTF. Through analysis of the air-ground communication tapes, Prinzo (2003) found that pilots reported visually acquiring the TTF on 76% of the point outs when using the CDTI, but only 53% of the traffic was acquired without it. Communication problems were observed in only 8 of the 320 traffic information communication sets, and most of those involved the controllers asking the pilots if they copied the initial message when their response was slow. The results of the second operational evaluation indicated that flight crews were able to use the CDTIs for spacing on approach. The average spacing distance at the threshold was 4.8 nm (*SD* = 0.5 nm) for the 5 nm approaches and 3.5 nm (*SD* = 0.7 nm) for the 3 nm approaches (OECG, 2001). During the 20 m final approach, pilots closed up on the lead aircraft by an average of 2.0 nm (*SD* = 1.0 nm) on the long spacing approaches and by 2.5 nm (*SD* = 1.1 nm) on the short spacing approaches.

Pilot reactions were generally favorable, though there were issues raised about the different CDTI displays (e.g., clutter, functionality), their location in the cockpit, and crew resource management (see also Joseph, Domino, Battiste, Bone, & Olmos, 2003). They also raised concerns about the amount of time spent looking at the CDTI, the need for a complete picture of all the traffic in a mixed equipage environment, and for well-defined operational and communication procedures. Pilot workload varied from acceptable to unacceptable depending on the CDTI used (commercial CDTIs were easier to use than the prototypes), whether they were performing initial or final spacing (they were busier on other tasks during final approach), and what spacing interval was targeted (shorter was more difficult).

Since 2000, researchers (e.g., Grimaud, Hoffman, Rognin, & Zeghal, 2003b1; Hebraud, Hoffman, Pene, Rognin, & Zehal 2004) at the Eurocontrol Experimental Centre have conducted four simulations to evaluate the feasibility of pilots performing self-spacing from a lead aircraft. The controller retained responsibility for separation in all the studies. The simulations were conducted using a part-task flight simulator flying approaches to the Paris airports. Five to seven crews participated in each simulation. The first three were conducted in low altitude, en route airspace (called extended terminal maneuvering area [E-TMA] in Europe) from cruise to initial approach using distance-based spacing. These simulations were designed primarily to evaluate the usability of ASAS displays and data entry interfaces, to evaluate three spacing instructions (remain behind, merge behind, or fly heading and merge behind a target aircraft), and to evaluate three spacing tolerances (+/- 1 nm, 0.5 nm, or 0.25 nm). Overall, the pilots were able to perform the spacing tasks within tolerance limits and thought the procedure provided positive benefits, primarily a better understanding of the situation. Though they reported an increase in workload, it was still deemed manageable. The pilots made as many as 1.5 speed adjustments per minute to achieve and maintain the instructed spacing, but the majority were relatively small adjustments (-15 kt to +5 kt). The 0.25 nm spacing tolerance required more effort and attention to perform than the larger tolerances. The number of air-ground communications made was actually reduced compared to normal procedures, despite the additional transmissions needed to identify the target aircraft and assign the spacing distance. The pilots also made recommendations for improving the ASAS display and interfaces.

The fourth simulation (Hebraud et al., 2004) evaluated the feasibility of pilots performing time-based spacing from cruise to final approach. Six flight crews each flew six test scenarios of approximately 35 minutes each. Two scenarios did not involve airborne spacing, two involved airborne spacing with an initial spacing deviation of 10%, and two involved airborne spacing with a 30% initial deviation. The assigned spacing value was 90 s, +/- 5 s. Each crewmember performed one scenario under each condition as the pilot flying and one as the pilot not flying. Each test scenario contained a merge phase and a remain-behind phase. Unlike the earlier simulations, the cockpit simulator was inserted into a previously recorded scenario to provide background radio communications. In addition, new ASAS features were included: multifunction control display unit (MCDU) pages for data input and graphics on the navigation display (ND) to help the pilots visualize the target aircraft and to support their ability to monitor the spacing intervals and perform speed adjustments.

The pilots found the ASAS to be usable and appreciated the new features, although they considered the spacing scale display interface to be “overloaded” with information. They indicated the spacing task itself, however, provided a better distribution of workload between pilots and the controller, and that communications were less frequent and less time critical during these scenarios. They reported their workload increased, but it was still at an acceptable level. However, they also pointed out that their simulated tasks were not as difficult as those in actual flights, and wondered whether the increased workload level would be acceptable in operations. The pilots were able to perform the spacing tasks well within the tolerance limits, regardless of the initial spacing deviation. Larger spacing deviations were observed during the remain-behind phase, reflecting the time needed to react to speed and altitude changes by the lead aircraft. The self-spacing task required approximately 15 speed adjustments per scenario but eliminated the need for the controller to issue speed clearances and pilots to read them back. Most of the adjustments were in the -15 kt to +5 kt range, similar to the speed adjustments observed in the previous simulations (Grimaud et al., 2003b1).

Bone and his colleagues (Bone, 2004; Bone, Domino, Helleberg, & Oswald, 2003; Bone, Helleberg, Domino, & Johnson, 2003a, b, & c) conducted a series of four, medium fidelity simulations evaluating aspects of the CAVS concept. The simulations compared speed control options (automatic versus manual), approach type (parallel versus single runway), weather (day, night, haze, and cloud layers), aircraft types (large, Boeing 757, and heavy), CDTI locations (in the primary field of view or in the forward console), and target data degradation. Overall, the results of the simulations indicated that the CAVS concept is technically and operationally feasible. The objective data showed that pilots closed at a higher rate when there was greater spacing from the lead aircraft at the clearance, and at a lower rate when the initial distance was smaller. Additionally, all 45 pilot participants agreed they would routinely perform the CAVS procedure, accepting responsibility for separation from the TTF by reference to the CDTI, under all the weather conditions tested. They were able to detect and adapt to speed changes by the TTF using only the CDTI, and were able to manage failure conditions. They strongly agreed they were more confident in spacing from the lead aircraft using the CDTI information than in using OTW visual cues. The pilots rated their overall workload performing CAVS approaches as acceptable and approximately the same as workload with current visual approaches. They generally did not think the amount of head-down time negatively affected safety, although there was variability in the ratings across the pilots. In agreement with Cieplak et al. (2000), Bone (2004) also suggested that the head-down issues may be resolved when pilots are more experienced with the procedure and the CDTI. The pilots rated the CAVS procedure as either no more difficult than most precision approaches or as more difficult but that the average line pilot could execute it. United Parcel Service has indicated they will apply for certification in 2005 to use the CAVS procedure in their Boeing 757 and 767 aircraft that are already equipped and certified to use the CDTI for traffic awareness.

Researchers at NASA-Ames (Kopardekar et al., 2003; Lee et al., 2003; Raytheon Air Traffic Management System Development and Integration Team [ATMSDI] Team, 2003) conducted an air-ground simulation in 2002, primarily to evaluate the DAG-TM free maneuvering concepts in en route airspace, but with all aircraft transitioning into a terminal arrival sector where CE 11 pilot self-spacing was conducted. Eight pilots and one terminal controller participated in the 12 simulation runs. The researchers observed that the TRACON controller's strategy changed over the course of the simulation and that he was frequently very conservative in setting the temporal spacing value. For this reason, the authors only reported subjective data for the CE 11 analyses, except to indicate that no separation violations occurred. The pilots generally thought that self-spacing in the terminal environment was safer and more efficient than current operations. They also indicated a preference for distance-based spacing over time-based spacing.

NASA-Ames researchers subsequently conducted a simulation specifically to evaluate CE 11 pilot-spacing for merging and following on final approach in IMC (Raytheon ATMSDI Team, 2004). Nine pilots participated in the study; two flew a high fidelity, motion-based flight simulator and the rest used computer-based simulators to fly their aircraft. Additional confederate pilots controlled the other aircraft flying in the scenarios, but no data were collected on their performance. There were four conditions in the experiment: a no-tools condition, which replicated current procedures and used distance-based spacing; a ground-tools only condition in which the controllers had special tools to employ time-based spacing; an air-tools only condition in which 75% of the aircraft were equipped with a Paired Dependent Approach (PDA) tool that provided time-based spacing guidance to the pilots, and an air and ground tools condition. All the aircraft were equipped with ADS-B and a CDTI, with all targets updating at 1 s intervals. The PDA tool was coupled to the autothrottle continuous speed maintenance, so that aircraft speeds were automatically adjusted within a range of 150 to 250 kt to maintain proper spacing. The PDA tool also displayed a color-coded box around the ownship to indicate whether the spacing was within limits (10 s ahead to 20 s behind), or ahead or behind those limits. Four controllers (two working north and south feeder positions and two working final positions to Runways 13 Right and 18 Right) participated in the simulation of Dallas-Fort Worth (DFW) airspace. Two confederate controllers staffed the en route sectors controlling aircraft into the terminal area and the DFW tower. Data were collected over 32 simulation runs, 8 in each condition.

The pilots rated the flight deck tools favorably in terms of usability, usefulness, and situation awareness. They rated their workload as moderately low in all conditions. Controller use of the call sign for the TTF in the spacing clearance did not appear to cause confusion or frequency congestion. The objective results of the simulation, however, did not support the use of the flight deck tools for self-spacing. There were no differences in inter-arrival spacing precision between any of the conditions, and the No Tools condition produced the shortest flight times. The latter result was attributed to the lack of flexibility to maneuver off the FMS routes once established on self-spacing. The PDA algorithms also resulted in more speed changes than is typical for final approaches, and the amplitude of the changes was greater than normal and required additional changes to the flap settings, which could increase pilot workload. Despite the lack of favorable performance results, the authors concluded that the concept is still feasible, but the flight deck tools and procedures need further development.

3.2 Effects of Pilot Self-Spacing on Air Traffic Control

In reviewing the empirical literature on Free Flight, Krozel (2000) summarized the following findings regarding their impact on the air traffic service provider. On the positive side, controllers found that workload in Free Flight conditions was often lower than they expected, but that increasing amounts of traffic density increased both visual and cognitive workload. In high density airspace, controllers had difficulty detecting conflicts and recognizing potential conflicts between aircraft in a timely manner, but color coding of aircraft by altitude on the controller display was found to reduce detection time. When pilots used CDTIs in Free Flight, there was a statistically significant increase in communication transmissions, but the current pilot-controller voice channel appeared to be adequate. The level of intent information (e.g., whether pilots notified controllers of trajectory changes before executing a maneuver) also affected controller operational errors and conflict prediction times. Lower levels of pilot intent information were more problematic, especially under high traffic densities. These general findings are based on relatively few studies, and most of them were in an en route environment.

3.2.1 Operational Evaluations

Although the focus of the two operational evaluations of CDTI use (OECG, 2000, 2001) was on the flight crew, researchers collected some data about the effects of pilot use of the CDTI on the TRACON controllers. In the first evaluation, a separate controller managed aircraft flying approaches to each of the parallel runways. After each set of four aircraft completed their approaches, the controllers provided a rating of their workload for that pattern. After the morning and afternoon sessions, the three controllers who worked the traffic (they alternated so that a single controller did not have to work for 3 consecutive hours) completed a three-part questionnaire about their experience and participated in a debriefing session with the researchers and the traffic coordinator.

The controllers rated their workload as low to moderate because they were only working four aircraft on a single runway, but it was about the same as normal operations with a similar number of aircraft, weather conditions, etc. The controllers also rated that pilot use of the CDTI had a positive effect on maintaining a safe and efficient traffic flow and on providing control information, even though they could only tell that the pilots were using the CDTI a little more than half the time. They also rated that CDTI use had a moderately positive effect on communications, even though there was a statistically significant increase in the frequency and duration of communications when the pilot was using the CDTI. These increases may reflect the addition of the lead aircraft call signs in the communications or simply the attempt to maximize the usage of CDTI information.

During the debriefing, the controllers indicated the CDTI provided better awareness of traffic for the pilots and enabled the controllers to point out TTF earlier than normal. Pilot use of the lead aircraft call sign gave the controller increased certainty that the pilots were following the right aircraft. Other perceived benefits were that pilots were better able to maintain their own spacing (thus requiring fewer speed instructions), followed the lead aircraft somewhat closer, and turned onto the base leg of the pattern earlier when they were using the CDTI. There was no evidence that pilots using the lead aircraft call sign in their communications created any confusion, although the potential for confusion may exist with more traffic. The controllers did express three potential concerns about pilot use of the CDTI. First, they were concerned that pilots might try to follow aircraft that they did not see clearly out the window. That is, they might accept a visual clearance using the CDTI without positive visual contact. Second, they were concerned that pilots might close up too much for wake vortex avoidance. Finally, they were concerned that pilots might use the information on the CDTI to initiate requests for sequencing or to question controller intentions, thus increasing controller workload. Only this last concern actually occurred during the operational evaluation.

In the second operational evaluation (OECG, 2001), three TRACON controllers, supported by two traffic coordinators, controlled the traffic using a standard radar display. The controllers were instructed to use different pronunciation techniques for call signs between the aircraft being called and the aircraft target to minimize potential confusion by the TTF pilots thinking the call was for them. In the mixed equipage segments, the controllers could only use the TTF call sign for aircraft pairs that had common equipage. The controllers either used the flight strips to determine equipage or entered the equipage information into the scratchpad area of the aircraft data block.

When not controlling traffic, the controllers evaluated an ADS-B display of traffic (called the Safe Flight 21, or SF-21, display) that was operating in shadow mode. The SF-21 display had many of the same control functions as the standard system but could display traffic based on surveillance data from radar only, ADS-B only, radar and ADS-B linked, or radar and ADS-B unlinked. The controllers could also manipulate the ADS-B display update rate from 1 to 9 s and could set the display range as low as 1 mile compared to the normal minimum setting of 6 miles.

Two Human Factors Specialists observed the controllers during each session and maintained a log of relevant events. The controllers provided ratings after each test session on a critical incident form, a controller questionnaire, and an open-ended form on which the controllers could indicate ways in which pilot use of the CDTI either helped or hindered air traffic control operations. The critical incident form asked them to rate what effect, if any, pilot use of the CDTI had on five air traffic control factors: maintaining a safe traffic flow, maintaining an efficient traffic flow, maintaining attention and situation awareness, prioritizing actions, and communicating effectively. They rated the effects separately for the initial approach, final approach, and visual acquisition parts of the flight tests. Overall, the ratings were positive for maintaining a safe and an efficient traffic flow, although there were differences between day and night and between long and short spacing criteria (see Table 1). Use of the CDTI also had a somewhat positive effect on attention and situation awareness during the approach phases.

Table 1. Summary of Controller Critical Incident Ratings (from OECG, 2001)

Flight Period/Task	**Effect of CDTI**				
	Maintaining Safe Traffic Flow	**Maintaining Efficient Traffic Flow**	**Maintaining Attention and Situation Awareness**	**Prioritizing Actions**	**Communicating Effectively**
Visual Acquisition	Somewhat positive, but lower during day (lower visibility) than night	Somewhat positive	No effect	No effect	No effect
Initial Approach	Somewhat positive, but more positive when long spacing criterion was used (5 mi or 120 s) than short spacing (3 mi or 90 s)	Moderately positive	Somewhat positive	No effect	Somewhat positive
Final Approach		Somewhat positive	Somewhat positive	No effect	No effect

The difference in the ratings for visual acquisition between day and night periods was more a function of visibility than time of day. During the hazy day periods, pilots had difficulty visually acquiring the traffic. The controllers commented that when visibility was good they could clear aircraft to follow and then just monitor the traffic without further communication. When the visibility was poor, they had to continue communicating until the traffic or airport was in sight. As a result, the requirement for visual acquisition of the traffic makes the CDTI less useful when it is most needed, in marginal VMC.

The controller questionnaire asked the controllers to rate their workload, use of TTF call sign, performance, and acceptability of each ADS-B application. The controllers also rated the usability and acceptability of the SF-21 display computer-human interface. After each session, the human factors observers debriefed the controllers and traffic coordinators. The results from the controller questionnaires are shown in Table 2.

Table 2. Summary of Controller Questionnaire Ratings (from OECG, 2001)

Flight Period/Task	Questionnaire Ratings			
	Controller Workload	Pilot Use of CDTI		
		Flight Crew Operations	Air Traffic Operations	Use of TTF Call Sign
Visual Acquisition	Full Equipage: Somewhat high; about equal to normal workload; higher during the day (low visibility). Mixed Equipage: Somewhat high; moderately higher than normal; higher than in full equipage.	Mixed Equipage: Somewhat negative effect (especially during day/low visibility conditions).	Mixed Equipage: Rated as somewhat complicating operations, especially during the day. Rated procedure unacceptable for use at own facility.	Mixed Equipage: The requirement to determine equipage and make calls differently was somewhat confusing and unacceptable. Otherwise, use of TTF call sign was rated as somewhat useful when used by pilots (especially to confirm TTF). No positive effect when used by controllers.
Initial Approach	Somewhat low; lower than normal. Higher when actively vectoring aircraft and at night (winds, low ceiling).	Somewhat positive.	Moderately facilitated operations. Somewhat agreed procedure would be acceptable at own facility.	Somewhat useful when used by pilots to reply to point out. No effect when used by controllers.
Final Approach	Somewhat low; lower than normal. Higher when short spacing criterion used (3 mi or 90 s).			

For the visual acquisition task, controller workload was rated as about equal to normal workload when all aircraft were visible on the CDTIs, but it was higher than normal under the mixed equipage condition. Controller workload was rated somewhat low and lower than normal during the initial and final approach phases. Pilot use of the CDTI for visual acquisition in a mixed equipage environment was rated as having a somewhat negative effect on flight crew and air traffic operations, and was rated not acceptable for use at the controllers' own facilities. The effect of pilot use of the CDTI on air traffic operations and flight crew operations was somewhat to moderately positive for the initial and final approach phases. The use of the TTF call sign by pilots was rated somewhat useful in all phases. Controller use of TTF call sign had no positive effect, and was somewhat confusing and unacceptable in the mixed equipage environment.

The controllers indicated that the SF-21 display was an improvement over their existing display, but that ADS-B and radar data should be linked for it to be useful. They also indicated that the ADS-B position should be updated on the display at approximately the same rate as radar.

UPS has continued to use the CDTI for pilot situation awareness, and teleconferences conducted with controllers and UPS pilot representatives have reported no operational issues associated with its use (R. Bone, personal communication, March 29, 2005).

3.2.2 Eurocontrol Simulations

Researchers at the Eurocontrol Experimental Centre have conducted a series of six simulations since 2000 focusing on the controllers' perspective of pilot self-spacing. In 2001, they conducted two simulations in extended Paris terminal airspace from cruise to initial approach (Grimaud, Hoffman, Rognin, & Zeghal, 2001). The participants ran the scenarios twice, once using current procedures and once with airborne spacing delegation. All aircraft in the simulation were capable of performing self-spacing. In the first experiment, six controllers used current procedures (paper flight strips, no advanced tools); in the second, the working environment was stripless, but the six controllers were required to mark spacing delegations on the screen. Insufficient training and technical problems with the new interface affected controller performance in the second simulation.

The controller participants delegated spacing to the pilots of 60% and 45% of the aircraft in the test scenarios in the first and second simulations, respectively. Compared to the baseline scenarios, there was an overall reduction (20% and 13% in the two simulations, respectively) in controller communications, despite the additional communications needed to initiate self-spacing. Most of the reductions resulted because of the lessened need for the controllers to issue speed instructions because the pilots were adjusting the speed on their own. The controllers also gave their maneuvering instructions further away from the initial approach fix when pilots used self-spacing. Grimaud et al. (2001) concluded that pilot self-spacing allowed the controllers to establish sequences earlier and to maintain them more easily. Though their analysis of the aircraft trajectories showed only a small (3%) improvement in flight efficiency, the controllers were positive about the concept of pilot self-spacing, stressing the benefits of reduced workload, better anticipation of traffic sequences, and quality of control. They were concerned, however, that their workload could increase under degraded circumstances in which self-spacing had to be cancelled. Although they thought the concept would improve safety by increasing pilot awareness, they were concerned about the pilots' ability to perform the task operationally.

Two more, small-scale simulations were conducted in 2002 to evaluate the use of pilot self-spacing in the terminal area from the initial approach fix to landing. Grimaud, Hoffman, Rognin, and Zeghal (2003a) recognized there were differences between the terminal and E-TMA that could affect the feasibility of pilot self-spacing for air traffic controllers. The two primary differences are that aircraft normally follow a standard trajectory and merge at a geographical point in the extended airspace, but that controllers typically vector aircraft in the terminal area to merge along an axis (e.g., the downwind leg of the approach). In addition, E-TMA controllers have to build and then maintain a sequence of aircraft to an initial approach fix, but terminal controllers are handed sequences of aircraft at the initial approach fix that they then must merge at the final approach fix.

In the June 2002 evaluation, four controllers participated in a simulation of a simplified approach sector to two initial approach fixes to Orly airport. The purpose of the simulation was to identify relevant airspace and procedures for self-spacing in the terminal area. All aircraft were capable of self-spacing, the traffic level was low (20 arrivals per hour), there were no departure aircraft, and they used standard, distance-based separation. During the debriefing, the controllers reported that there could be benefits to receiving aircraft executing airborne spacing, but the benefit would be greater if it was time-based. The controllers also mentioned, however, that using a standard trajectory in the terminal area may not be as efficient as vectoring, potentially making self-spacing incompatible with optimum operations in that airspace. They also suggested that multiple merge points should be created. As with the previous simulations, they expressed concerns about the impact on controller operations if the situation became degraded and self-spacing had to be terminated.

The November 2002 simulation was more complex, although it still involved only four controller participants, one of whom had also participated in June. Two approach sectors were simulated: one to Orly with two initial approach fixes and one base and one downwind leg; and the other to De Gaulle airport with two initial approach fixes, both of which were on the base leg. The 50-minute scenarios contained 31 arrivals per hour to each airport (considered a medium-high traffic load). All the aircraft were equipped for self-spacing. As in the June 2002 simulation, there were no departure aircraft included. There were three simulation conditions: no pilot self-spacing and using standard trajectories, pilot self-spacing using standard distance-based criteria, and pilot self-spacing using a time-based criterion of 90 s. The controllers used flight progress strips but did not have an arrival manager sequencing tool for any of the conditions. For the self-spacing conditions, graphical markings were displayed on the radar scope to indicate which aircraft were self-spacing and which aircraft was the TTF. Unfortunately, there were several problems with the simulation (insufficient controller training, poor simulator performance that disrupted the scenarios, software bugs, and simulation pilot overload) that limited the usefulness of the quantitative data, although the authors considered the qualitative findings to be valid.

The qualitative data indicated that the controllers found the spacing instructions usable in the terminal area, but the procedure would require changes in working methods (no radar vectoring, integration at a point, combining the initial and intermediate approach positions, and having two controllers staff the single position rather than one). The controllers also thought self-spacing reduced the overall communications needed and resulted in fewer late instructions, thus reducing their workload. They preferred time-based spacing but were concerned about adequate wake vortex separation using that procedure. They also found the heading-then-merge instruction to be difficult, because it required more monitoring than the merge only instruction. They recommended providing more information on the display and shortening the communication phraseology used to set up self-spacing. It was also observed that controllers were reluctant to cancel self-spacing and tended to treat groups of aircraft in a flow as a block and to integrate them as a block. When there was a need to reissue spacing instructions, they sometimes found it easier and faster to revert to conventional control. The controllers' primary concerns were about recovering from abnormal situations and having clear emergency procedures, especially when they were managing long sequences of aircraft.

A fifth simulation was conducted in late 2003 (Grimaud, Hoffman, Rognin, & Zeghal, 2004). It was similar to the November 2002 simulation, with the following three exceptions. First, there were only two experimental conditions: no pilot self-spacing and time-based self-spacing. Second, multiple, parallel holding legs (extensions on a path prior to a turn) were added to the standard trajectories so that the controllers could expedite or delay aircraft without canceling self-spacing. Third, the number of aircraft in each scenario was increased to 34 arrivals per hour, representing a very high traffic level. As many as seven self-spacing aircraft could enter the scenario in a sequence. Six controllers participated in the two weeks of training and two weeks of data collection exercises.

The controllers issued spacing instructions to approximately 85% of the aircraft during the simulation. The majority of the instructions (83%) were for heading then merge, which was deemed more difficult in the previous simulation. They perceived that the procedure reduced their workload and time on frequency, increased anticipation in sequence building, and produced more regular spacing on final. As a result, the controllers thought they could handle more aircraft, but were concerned about their ability to detect unexpected events or recover from degraded situations. The objective data supported the controller perceptions. Even with the additional target selection instructions, there were reductions of 28-48% in the number of maneuvering instructions issued with self-spacing compared to conventional control. In addition, the majority of instructions were issued 30-35 nm before the final approach fix with self-spacing compared to 10 nm prior to the fix with conventional control. The self-spacing results indicate the controllers could integrate the flows earlier and did not have to do as much vectoring as the aircraft neared the final fix. Controller eye fixations were also concentrated between 5 and 20 nm from the final approach fix using conventional control but were spread farther away (15 to 40 nm) from the fix in the self-spacing condition.

Measures of flow quality showed positive effects for self-spacing. With self-spacing, 75% of the aircraft were within 5 s of the 90 s target time, compared to only 31% with conventional control. The time and distance flown were reduced by 10% and 5%, respectively, when using airborne spacing compared to normal control procedures. The overall decrease in communications with self-spacing translated into a median of only four clearances per aircraft compared to nine with conventional control. In an analysis of safety impacts, 16 out of the 1072 controlled aircraft were separated at some point by less than 3 nm with all the instances of potential loss of separation occurring in the normal condition. There was, however, a small percentage of instances in which controllers issued self-spacing clearances when the required applicability conditions (e.g., sufficient initial spacing, compatible speeds) did not exist, but Grimaud et al. (2004) concluded that no serious consequences resulted.

Overall, the controllers perceived the procedure as usable and beneficial. The objective data provided substantial support for their perceptions and for efficiencies gained from using self-spacing. There were some differences in performance between the two sectors in the simulation, which indicate self-spacing may be more beneficial in some situations than in others. As in most other studies, this simulation did not address abnormal or degraded situations, or the interaction with other automation tools (e.g., arrival manager to sequence the flow between sectors).

A subsequent simulation was conducted in November and December of 2004 by the researchers at Eurocontrol. Though a complete report was not available at the time this literature review was written, a short summary of the results was available from the Eurocontrol website (see http://www.eurocontrol.fr/projects/cospace/archive/CoSpace_ground04_earlyresults_1.2.pdf retrieved February 28, 2005). The purpose of the simulation was to evaluate the integration of an arrival manager (AMAN) and airborne spacing (ASAS) tool. The researchers simulated generic airspace based on the Paris South area that included two en route sectors feeding a terminal approach sector to a single runway. Four en route and four approach controllers participated. The en route sector was staffed with an executive and a planning controller on each run. In the terminal sector, the pickup and feeder positions were merged when spacing instructions were implemented, with one controller staffing that position and another acting as the sequence planner. On the controller display, graphical links showed which aircraft were self-spacing, and AMAN displayed a timeline with sequences of aircraft and any corresponding delays at each position. The results indicated that most of the delays were absorbed before aircraft entered terminal airspace, and that spacing intervals at the final approach fix were more accurate when the ASAS and AMAN tools were used. There were also fewer instructions issued to aircraft in both sectors, but with the most drastic decreases found in the terminal area, indicating that most of the operational benefits are likely to be observed in that airspace.

3.2.3 U.S. Simulations

The MITRE simulations of the CAVS concept (Bone, 2004) were primarily focused on the flight deck use of the CDTI, but air traffic controllers participated in the development and execution of the simulations, particularly in deciding that the communications protocol should make the use of the TTF call sign optional. Though controllers were initially uncertain and apprehensive about the CAVS procedure, their union supports continued research on the concept. While no additional ATC infrastructure will likely be required, the controllers will need to know whether the aircraft and flight crew are capable of executing the procedure. The method of providing this information is still under development. Bone commented that controllers will have a key role in the successful implementation of CAVS.

The NASA Ames simulation (Kopardekar et al., 2003; Lee et al., 2003; Raytheon ATMSDI Team, 2003) that included pilot self-spacing in the terminal area as part of the larger en route free maneuvering and trajectory negotiation evaluation produced limited results about the effects on air traffic control. Only one TRACON controller participated, and he had difficulties determining when and how to apply the procedure. The primary problem was the mismatch between the distance-based separation information provided by the radar and the time-based, in-trail spacing task required in the simulation. In particular, the controller was uncertain about the pilot's responsibility when the aircraft spacing was less than the time requirement but greater than the distance requirement. The authors recognized that the terminal self-spacing concept was not exercised sufficiently to draw any conclusions about its benefits and feasibility.

In the CE 11 simulation (Raytheon ATMSDI Team, 2004), there were two conditions in which the controllers had a number of special tools to support time-based spacing of the arriving aircraft. The tools included a graphic timeline with estimated and scheduled time of arrival to the runway; a spacing advisory in the third line of the data block (the controller had to dwell on the data block for the third line to be displayed) showing the lead aircraft, assigned spacing interval, and the actual spacing interval; an indicator in the data block that an aircraft was either capable of self-spacing or engaged in self-spacing; a circle around the self-spacing aircraft to graphically indicate whether the aircraft was conforming to the assigned spacing interval; an alphanumeric indicator of whether the aircraft was early or late; and the indicated airspeed of the aircraft. In all conditions, the controller remained responsible for separation.

Controller ratings of their performance were generally high and their workload ratings were moderately low in all conditions, with little variation between them. The rating data were not tested for statistical significance, but overall the use of the ground tools appeared to impose a slight increase in workload for both controller positions. Presumably having to interact with the tools to assign spacing and then monitor for conformance added to their normal workload. The ground tool features were rated as moderately to very acceptable and useful, except the timeline display which was rated poorly. The timeline display provided an important piece of information for time-based metering especially in the Ground Tools Only condition, in which the pilots had no tools to support the required spacing. However, some controllers found that using the timeline was time-consuming and frustrating, especially when short cutting aircraft would provide operational benefits. Other research (McAnulty, Zingale, & Willems, 2005) has also shown that the use of a separate list for time-based metering required a substantial amount of the controller's visual attention and resulted in increased workload.

Other aspects of the simulation also affected controller workload levels. The Feeder position reported slightly higher workload than the Final position in the Flight Deck Tool conditions. Other data indicated that implementing pilot self-spacing limited the controllers flexibility to direct short cut vectors or to change speeds (e.g., if the aircraft were already flying at minimal safe speeds and needed to slow even further), and the PDA-directed speed changes did not fit the controllers mental model of how aircraft should perform on approach. There were some additional pilot-initiated communications about spacing problems, which could add to the controllers' workload. Finally, the controllers reported having to closely monitor aircraft that were self-spacing because they were still responsible for separation. The controllers developed strategies to wait until later in the approach to assign self-spacing, although the pilots preferred to begin self-spacing earlier. Overall, the controllers cleared the pilots to self-space on approximately 90% of the equipped aircraft. The controllers indicated that having some unequipped aircraft might actually be beneficial because they would fly a normal speed profile and break the "accordion effect" that occurs when a sequence of self-spacing aircraft speed up or slow down to maintain their relative position.

The controllers rated the acceptability of pilot merging and self-spacing as acceptable (4.3 on a 5-point scale). They rated the controllers' responsibilities as operationally acceptable, but with the lowest rating for the Air Tools Only condition (2.7 on a 5-point scale). The authors (Raytheon ATMSDI Team, 2004) concluded that the CE 11 concept is feasible, despite the lack of positive performance results (see Section 4.1) for time-based spacing operations. They attribute the results to the state of development of the air and ground spacing tools, rather than to inherent limitations in the concept. The results raise concerns, however, about whether the concept would be beneficial, especially under more difficult circumstances (more aircraft, not all aircraft ADS-B equipped, weather complications, etc.) in which the concept and spacing tools are most needed.

4. Status of Pilot Self-Spacing

The next two subsections summarize the literature on the feasibility of pilot self-spacing from the flight deck and air traffic control perspectives, respectively. The third subsection evaluates the status of the self-spacing concepts on the basis of the literature reviewed, and draws conclusions about their operational use or additional research and development needs.

4.1 Feasibility of Pilot Self-Spacing

Operational experience has demonstrated that it is feasible for pilots to use cockpit displays that present data about nearby aircraft. TCAS displays have been mandated for most commercial aircraft since 1993, and CDTIs incorporating ADS-B data have been in use in western Alaska since 2001. In addition, UPS has been certified to use CDTIs for improved pilot situation awareness. Both operational trials (Mills, 2000; OECG, 2000, 2001; Prinzo, 2002, 2003) and laboratory simulations (e.g., Bone, 2004; Grimaud et al., 2003b1; Hebraud et al., 2004; Kopardekar et al., 2003; Lee at al., 2003; Raytheon ATMSDI Team, 2004) showed that pilots used CDTIs effectively in the terminal environment to improve their awareness of the traffic situation, to visually acquire a higher percentage of traffic point outs, to maintain adequate separation, and to reduce the spacing at the threshold to assigned distances within required tolerances. The use of the CDTI was especially effective when weather conditions were good (i.e., VMC), but visibility was limited (e.g., at night, in haze, flying toward the sun). In those conditions, the CDTI helped the pilots identify the TTF and provided information about its speed, distance, altitude, etc. that would otherwise have been difficult if not impossible to determine.

Pilots have generally evaluated the CDTIs positively, indicating that they improved flight deck operations and increased safety without increasing pilot workload to unacceptable levels. However, there have been issues raised about the design of the CDTIs, their integration into the cockpit and how they affect crew resource management, the amount of head-down time that results from their use, and the spacing criteria assigned (e.g., Joseph et al., 2003). Basic, commercial CDTIs have been evaluated as acceptable for providing the pilots with useful information for traffic awareness and spacing. More advanced CDTIs with prototype algorithms that provide speed guidance have been less acceptable, however. Appropriate procedures and crew training may address concerns about resource management issues as well as concerns about head-down time. Head-down time may also become less of an issue as pilots gain more experience with the systems, or may even result in a beneficial tradeoff (Bone, 2004; Cieplak et al., 2000). Pilots found the assigned spacing criteria to be acceptable except at shorter spacing distances (i.e., 3 nm, OECG, 2001) or unless the tolerance limits were too stringent (i.e., .25 nm, Grimaud et al., 2003b1).

The hypothesized problem that pilots could become confused by the use of the TTF call sign has not been supported; Prinzo (2002, 2003) found very few communication problems, and none that were consequential. The results pertaining to the effect on the number of communications made have varied. Some studies have shown an increase in air-ground communications when pilots used the CDTI (e.g., Krozel, 2000; OECG, 2000) while others showed a decrease (Grimaud et al., 2003b1). The differences may reflect the length of time the pilots were self-spacing in these studies and the number of clearances the controllers issued when the pilots were not using the

CDTI. But even when there were increased communications, the current radio system was adequate. The literature contains only limited evidence (Bone, 2004) that pilots are able to continue self-spacing procedures when the CDTI data are degraded or lost, but the same procedure (promptly contact air traffic control) used for visual self-spacing in VMC would likely apply. We recommend that some criterion be developed, similar to a minimum descent altitude, that better defines a minimum point at which the pilot must contact air traffic control if neither the airport nor lead aircraft is clearly in sight and the ADS-B data are degraded. It is apparent from the literature that the pilots should be well trained on using the CDTI functions, on recommended modes of operation, and on specific procedures for degraded or emergency conditions.

4.2 Status of Pilot Self-Spacing Effects on Air Traffic Control

The literature supports pilot use of CDTIs with respect to its effect on air traffic controllers and control operations. Early research (Krozel, 2000) focused primarily on pilots' Free Flight operations in en route airspace and found that controller workload was lower than expected, especially when the traffic was not too dense and the controllers were aware of the pilots' intentions. More recent research with controllers in the terminal area has produced results that address the effect of pilot self-spacing on ATC during approach. The OECG (2000) reported that, when pilots were using basic CDTI functions, controller workload was the same as it normally is for a similar number of aircraft and environmental conditions, despite a significant increase in voice communications. The controllers rated that pilot use of the CDTI had positive effects on maintaining a safe and efficient traffic flow and on providing control information. They perceived that the pilots using the CDTI were more aware of the surrounding traffic, that the controllers could point out TTF earlier in the traffic pattern and needed to issue fewer speed instructions, that pilots followed the lead aircraft more closely, and that the aircraft turned onto the base leg sooner.

The more extensive flight trials conducted in the second operational evaluation (OECG, 2001) provided additional support as well as some limitations of pilot use of the CDTI. The controllers rated CDTI use as having an overall positive effect on maintaining a safe and efficient traffic flow, but less so when visibility was limited and when pilots were trying to space to a 3 nm rather than a 5 nm criterion. When performing visual acquisition with full equipage, controller workload was about the same as it normally is under similar circumstances. Under mixed equipage scenarios, however, controller workload was higher than normal, and pilot use of the CDTI had a negative effect on flight crew operations and complicated air traffic control operations. Controllers had to determine the equipage for each aircraft pair and make traffic calls differentially, which increased their workload and was rated as confusing and operationally unacceptable. However, part of the problem could be attributed to the method of conveying equipage information (on the paper flight strip unless the controller had taken the extra step to enter it into the aircrafts' scratchpads) and the communications protocol used in this evaluation. Pilots also had more difficulty correlating the traffic on the CDTI with the OTW view, and took longer to respond to traffic point outs. After visual acquisition, pilot use of the CDTI had a positive effect on executing the initial and final approach phases, where controller workload was again rated lower than normal. For all three phases, pilot use of the TTF call sign was rated as somewhat useful, but controller use of the call sign was not effective.

The series of Eurocontrol simulations (Grimaud et al., 2001, 2003a, 2004) demonstrated that controllers would assign pilot self-spacing on 45 - 85% of the equipped aircraft, which resulted in reduced air-ground communications, earlier clearances, and modest improvements in flight efficiency. The controllers were positive toward the concept, perceiving that it reduced their workload, increased their ability to plan sequences, and produced more regular spacing intervals on final approach. They preferred time-based spacing over distance-based spacing and found the heading-then-merge instruction was more difficult and required more monitoring than the simple merge instruction. The controllers indicated that changes would be needed to their normal procedures to accommodate pilot self-spacing, but these were predicated on the aircraft entering the terminal airspace already self-spacing and flying a standard arrival trajectory. The primary controller concerns were about degraded conditions (not included in the simulations) in which self-spacing would have to be cancelled and the controller would have to resume responsibility, and about having clear emergency procedures. These simulations were informative, but should be considered with the understanding that there are differences in the Paris airspace and in controller staffing and procedures compared to US operations, and that technical problems affected one of the simulations.

The MITRE simulations of the CAVS concept (Bone, 2004) had little controller involvement, although they were instrumental in developing the communications protocol in which controllers or pilots could use the TTF call sign if it was operationally advantageous, though neither would be required to do so. This approach may help minimize some of the negative impacts identified in a mixed equipage environment (OECG, 2001). The controller union has expressed interest in further research on the CAVS procedure, despite initial apprehension. Bone (2004) stated that controllers need to know the capabilities of the aircraft for performing CAVS, but the method of providing the information has not been determined, and there has been no discussion as to what the controller would do with the information if it was available. If differential actions were required based on aircraft capability, it could increase controller workload and affect its operational acceptability. Under the current CAVS concept, however, these issues may not be problematic because the traffic point out is identical to the existing visual point out, which requires visual contact to confirm acquisition.

The controller participants in the CE 11 simulation (Raytheon ATMSDI Team, 2004) assigned self-spacing to 90% of the equipped aircraft, and rated the self-spacing concept as operationally acceptable despite a small increase in their workload. Self-spacing was rated least acceptable in the Air Tools Only condition in which controllers did not have tools available to support time-based spacing. PDA speed changes did not fit the controller mental model of normal aircraft behavior, and the assignment of self-spacing in the Feeder sector limited the controllers' ability to vector the aircraft. As a result, the controllers waited to issue the self-spacing clearance later than the pilots preferred. The ground tools, when available, were considered acceptable except for the timeline display, which required too much attention. This simulation did not demonstrate any operational efficiencies in using the procedure, but this was attributed to problems with the additional tools employed in the cockpit and on the ground.

Overall, these studies support pilot use of basic CDTI information and functionality. The results show that the CDTI improves pilot situation awareness of traffic, helps in acquiring TTF, and supports adequate separation (detecting changes in lead aircraft speed). The results also show that self-spacing can somewhat improve the regularity of spacing at the threshold and reduce the time on final. All these effects demonstrate improvements in the safety and efficiency of air traffic operations. The biggest difficulty encountered with pilot CDTI use is with visual acquisition in a mixed equipage environment, which was found to increase controller and pilot workload. Whether mixed equipage operations are feasible depends on the concept and the procedures required.

The results from both the flight deck and air traffic control studies indicate that concepts requiring advanced flight deck and ground tools are not mature and require further development before they become operationally feasible. Studies on the more advanced concepts indicate that speed commands increased pilot workload and were inconsistent with controller expectations, and flying standard trajectories limited controller flexibility in issuing vectors. Ground tools tended to increase controller workload, and some were considered too complex and time consuming.

4.3 Status of the Pilot Self-Spacing Concepts

The concepts for pilot self-spacing in the terminal area differ from one another primarily in terms of their environmental conditions for use, minimum equipage on the flight deck and the ground, the radio communications protocol, visual contact requirements, issuance of spacing instructions, and separation responsibility (see Table 3). The EVApp and VSA concepts are nearly identical, except for the communications protocol. The EVApp concept uses the standard U.S. communications phraseology for a visual clearance to follow the lead aircraft, although it proposes that the controller and pilot may use the call sign of the TTF as additional information. The VSA concept does not specify the communications phraseology but recommends using the call sign for the TTF. It may also include a reversal of the current protocol so that the controller only issues the TTF call sign and the pilot responds with the location of the lead aircraft. Because the VSA communications procedure is not finalized, the two concepts can be considered essentially the same. Both concepts represent an enhancement to the standard visual approach procedure. These concepts can be used only in the terminal area under VMC, and require only a CDTI to provide needed information to the pilot about the TTF, who must at least be squittering ADS-B data. No additional automation support such as speed guidance or conformance alerts would be required. The flight crew must maintain continuous visual contact with the lead aircraft and promptly notify air traffic control when contact is lost, just as in current visual clearance procedures. In these concepts, the controller does not issue spacing instructions (spacing time or distance is at the option of the flight crew), and the flight crew assumes the responsibility for separation (e.g., wake vortex minimum) as well as spacing.

The literature provides substantial support for the feasibility of these concepts for both the flight deck and air traffic controller. The pilots only use the basic CDTI functionality to locate nearby aircraft, acquire the TTF, and obtain information about the TTF trajectory (e.g., speed, heading, and altitude). Pilot capabilities for performing these functions have been well documented. Because pilots are not assigned a specific spacing interval, their workload can be self-managed; if they recognize a large gap and are able to reduce spacing, they can execute a speed adjustment. If not, they can maintain their current spacing using the CDTI to supplement the OTW view. For the controller, the procedure is identical to that used for current visual approaches, with the option of adding the TTF call sign to the point out or having the pilot respond with the call sign when acknowledging that the traffic is in sight. There is no requirement for the controller to determine equipage, to make traffic calls differentially based on equipage, or to assign a specific spacing distance or time. Although visual acquisition takes as long on average when pilots use the CDTI, there is a significant increase in the percentage of targets they acquire (Prinzo, 2003), reducing the need for additional traffic point outs. Controllers also reported that pilots were able to follow the lead aircraft more closely and with fewer controller-instructed speed adjustments, thus improving the efficiency of air traffic operations and reducing controller workload without sacrificing safety.

Table 3. Comparison of Pilot Self-spacing Concepts

Concept	**Operating Environment**	**Minimum Equipage**	**Radio Protocol**	**Traffic Contact**	**Spacing Instruction**	**Responsible for Separation**
Enhanced Visual Approach	VMC (terminal area only)	CDTI Display	Same as visual clearance; TTF call sign recommended	Maintain visual contact; termination rule needed	None issued	Pilot
Visual Separation on Approach	VMC (terminal area only)	CDTI Display	Unspecified	Continuous visual contact	None issued	Pilot
CDTI Assisted Visual Separation	Marginal VMC (terminal area)	CDTI Display	Same as visual clearance; TTF call sign optional	Initial visual contact only	None issued but could assign speed	Pilot
Approach Spacing for Instrument Approaches	VMC or IMC on final approach to a single runway	CDTI plus unspecified speed guidance	To be determined	CDTI only	Preset or transmitted	Pilot for lead aircraft; controller for others
Independent Closely Spaced Parallel Approaches	VMC or IMC on final approach to parallel runways	CDTI plus cockpit path and breakout alerts	Same as current phraseology	CDTI only	Maintain flight path and lateral separation	Pilot for lateral; controller for in trail
Sequencing & Merging	Terminal and en route	CDTI Display with unspecified speed and heading guidance	Unspecified; controller may use TTF call sign and pilot reports position	CDTI only	Time or distance; absolute or “at least” value	Air traffic controller
Concept Element 11	IMC (terminal area)	CDTI with ground and cockpit tools	Assign TTF and spacing in single transmission	CDTI only	Controller issued; time based	Air traffic controller

Operational safety assessments and hazard analyses (RTCA, 2003 App G) have determined that neither a collision with the leading aircraft nor a wake vortex upset are credible events for these procedures, assuming that the system meets the minimum system performance standards, that the required information and functionality are available on the CDTI, and that visual contact is maintained with the TTF. If visual contact is lost, the pilot must contact air traffic control to resume separation assurance or execute a fallback maneuver, such as a go around. Rules for terminating the approach when visual contact is lost must be established. Concern about the crew identifying the wrong TTF resulting in an incident or accident with a third aircraft was judged to be completely mitigated by the EVApp procedures. Concern about erroneous distance data on the CDTI require that pilot training emphasize the bounds of potential distance error measurements and minimum safe wake vortex separation distances. The available research indicates the EVApp concept may be used operationally. In fact, it is likely that UPS has been using CDTI data for these purposes under their certification to use the CDTI for improved situation awareness (Bone, personal communication, January 7, 2005). Hazard, safety, and performance analyses are ongoing for the VSA concept, but the similarity between EVApp and VSA is so great that it could likely be used operationally if the same assumptions are met. These concepts reflect improved pilot knowledge of the situation (traffic information) over visual observation, which they can then use to maneuver their aircraft on approach to landing.

The CAVS concept is also very similar to the EVApp and VSA concepts, and thus has similar support in the research literature. A minor difference is that use of the TTF call sign is explicitly optional for both pilots and controllers in CAVS, and its use based on whether it provides an operational benefit. The communications protocol is not finalized in either of the other two concepts, although they imply that use of the call sign will be recommended. Certainly, the proposed CAVS protocol avoids any of the complications for controllers observed in Operational Evaluation 2 (OECG, 2001).

The major difference between CAVS and the EVApp and VSA concepts is that after initial visual contact, the CAVS concept explicitly allows the pilot to continue the approach even if OTW contact with the lead aircraft is lost. The pilots would be responsible for separating from the TTF using only the CDTI, and then notifying the tower if they were unable to reestablish contact with the lead aircraft. This procedure would require a modification to current flight regulations, and could have safety implications if the CDTI data were severely degraded. The operational safety analysis of EVApp (RTCA 2003, Appendix G) concluded that, if visual contact with the TTF were lost, a collision could only occur if the CDTI displayed incorrect information and the crew used this information long enough for separation to be lost. An operational safety assessment of CAVS also considered the hazards of complete loss of CDTI data and the presentation of hazardously misleading information on the CDTI (FAA, 2003c). The risk was judged to be low as long as the system was developed to the Minimum Aviation System Performance Standards (RTCA, 2003) and met the development assurance requirements so that the probability of either hazard occurring would be remote. However, the report proposed a requirement that the FAA develop operating procedures to assure reversion to air traffic control separation assurance if needed. The procedures would likely be similar to current procedures for reversion.

Much work has been conducted that demonstrates the accuracy and reliability of ADS-B data (e.g., Cieplak, 2004). The 95% interval estimate for horizontal position accuracy in multiple tests ranged from +/- 20 to 90 feet for ADS-B data in comparison to +/- 600 to 2000 feet for terminal primary radar systems. Use of ADS-B data for aircraft separation has already been approved and implemented in some areas. Air traffic controllers are authorized to provide radar-like services in western Alaska using ADS-B data (Bone & Reagan, 2004) and the Australian Civil Aviation Safety Authority (2004) has approved, on a trial basis, the use of ADS-B data for providing 5 nm separation in specified en route airspace. The general literature supports the feasibility of pilot use of a CDTI to self-space from a lead aircraft. The four simulations conducted by MITRE (e.g., Bone, 2004) specifically tested the CAVS concept and found uniformly positive results. All the pilots involved indicated they would use the CAVS application in their flight operations. Both operational evaluations (OECG, 2000, 2001) also demonstrated that pilot self-spacing was beneficial to air traffic operations and reduced controller workload, except during visual acquisition when visibility was limited or in a mixed equipage environment when the controller had to determine appropriate equipage between aircraft pairs and use different communications protocols to point out the traffic. However, limited visibility also affects acquisition of traffic for visual clearances, so that factor applies to current operational procedures as well.

Though the CAVS concept (and EVApp and VSA) includes a requirement that controllers be aware of aircraft equipage and only assign self-spacing to appropriately equipped pairs, it is unclear why this is necessary. All three of these concepts are enhancements to a normal visual clearance, and all require at least initial visual acquisition and correlation of the OTW traffic with the CDTI data. The controller is expected to point out traffic and assign TTF, just as in a regular visual clearance. If the aircraft are appropriately equipped, and the crews are trained in the use of the CDTI, then they can execute the procedure. As far as the controller is concerned, the crew could be executing a visual approach.

Though not necessary, it may be beneficial for the controller to be aware that the crew is executing CAVS. For example, if weather conditions are marginal for executing visual approaches, CAVS-capable aircraft may still be able to continue using the procedure. In addition, in the unlikely event that aircraft must revert to air traffic control for radar separation assurance, the controller would have a better awareness of which aircraft are affected. The CAVS concept only calls for notifying the tower controller if visual contact is lost, but if the ADS-B data became degraded or lost prior to transfer to the tower, then the flight crew would need to contact the TRACON controller for separation assurance. Advance notification that the procedure was in progress would prepare the controller for such a radio call. The notification could be embedded in the acceptance of the clearance. For example, pilot use of the TTF call sign could signify that they were using the CDTI. An alternative would be for the pilot to notify the controller that the flight crew was executing a CAVS approach once visual contact was lost.

Other than these issues, the research supports the operational use of CAVS. CAVS would be especially appropriate for situations like those experienced by UPS at their Louisville hub, where all the pilots are employed by the same company and trained to their specifications, and where the controllers are knowledgeable about ADS-B, the CAVS concept, and the equipage of the UPS aircraft. Operational use of CAVS at Louisville would provide an opportunity for further assessment of the concept to identify any problems, develop remedial procedures, and quantify its operational benefits. These evaluations would be beneficial for refining the current concept and would provide additional information for developing more advanced procedures currently under consideration. Finally, these data would provide information for developing future concepts and systems needed to meet the requirements of the Next Generation Air Transportation System (Joint Planning and Development Office [JPDO], 2004), which envisions vastly expanded use of pilot self-separation by 2025.

The ASIA concept is not completely developed (RTCA, 2003, Appendix I). It assumes that some additional flight deck tools and interfaces may be needed, but only speculates what they might be (e.g., speed commands, wake vortex alerts). Neither the communications protocol, the spacing intervals (however, these would not be less than current separation values), nor the instruction process (preset, controller issued, or pilot option) have been determined. There also have been no cost-benefit analyses to determine if the benefits of the procedure would support the cost of equipage. Although work has been done to develop advanced tools (e.g., Lohr, Oseguera-Lohr, Abbott, & Capron, 2003), they have not always worked well in simulations and operational evaluations (e.g., OECG, 2001), have created additional workload for the pilots, and produced aircraft performance that was inconsistent with controller expectations (Raytheon ATMSDI Team, 2004).

The ASIA concept also requires significant additional development and testing before it can be implemented. While there is some support in the literature based on the NASA-Ames and Eurocontrol simulations that pilots can use the CDTI to maneuver while on instrument approaches, the flight deck tools currently available are not adequate, and there is only limited evidence that the procedure would be cost beneficial. Before further development is conducted on air traffic control information and tool requirements, the feasibility and cost-justification of the cockpit tools and procedures need to be demonstrated (e.g., Ballin et al., 2002).

In the interim, the question remains as to whether pilots should use the increased situation awareness about a lead aircraft's position and speed provided by the basic CDTI to close a large gap manually if time and their workload allow. That is equivalent to asking whether pilots should be able to conduct the equivalent of an EVApp or VSA application in IMC. Under these circumstances, the TRACON controller would continue to provide separation assurance and the pilots would continue to fly an instrument approach, making this usage an enhancement to the current procedure. While this modified approach has not been directly tested, it could be conducted at the pilot's discretion unless the controller has issued a speed restriction. The major concerns with this implementation are whether using the CDTI would distract the pilot from the difficult task of flying an instrument approach, and whether the controller perceives the overtaking aircraft as posing a separation risk. Pilot performance and self-reports from Operational Evaluation 2 (OECG, 2001) indicate that pilots would be unlikely to attempt to shorten the gap from a lead aircraft if they were heavily loaded with other tasks on final approach, and that they would not likely try to close the spacing to near minimum separation criteria under these conditions.

Like the ASIA concept, ICSPA is another "probe" application whose operational roles, procedures, requirements, and benefits have not been fully validated (RTCA, 2003, Appendix J). The primary function of the ICSPA concept is to provide separation assurance by alerting pilots that their aircraft is deviating from the approach or that the aircraft on the parallel approach is intruding into their airspace.   Noncertified ICSPA algorithms have been subjected to limited testing with results that supported the feasibility of the concept for the flight deck, but also identified additional research issues. In addition to ADS-B equipage and highly accurate ICSPA algorithms, the concept makes several assumptions that are not currently met at many airports. The concept requires a highly accurate navigation guidance system, such as augmented GPS, for maintaining the aircraft flight path once established on the final approach. The CDTI must be able to display traffic at short ranges, because the aircraft may only be 2500 feet apart laterally. Minimum CDTI display ranges are typically much higher than would be acceptable for this usage. ICSPA assumes that TCAS will be inhibited for the aircraft on the parallel approach (otherwise, it would alert; ICSPA alerts will be functioning for those aircraft), but that it would continue to operate for all other aircraft. TCAS currently cannot perform this operation. No additional tools are assumed for the TRACON final approach controller to conduct ICSPA, but additional tools (e.g., TMA) may be needed for upstream sector controllers to provide a sufficient and timely flow into the parallel approach courses for the application to provide any benefit for increasing airport acceptance rates. Finally, the concept assumes a high level of fleet equipage with trained pilots willing to accept the ICSPA clearance for the application to provide sufficient benefits to justify the costs.

ICSPA requires substantial, additional research and development of the operational concept, procedures, and the flight deck technology to support its operational use. The assumed requirements of the concept need to be validated, and the potential for sufficient operational efficiencies need to be confirmed. Until these efforts are successfully completed, no further evaluation of the impact of the ICSPA application on air traffic control is warranted, especially when no new ground tools or substantial changes in controller procedures are anticipated.

The S&M application for the terminal area and CE 11 are highly similar in their objectives and operational procedures. Both are designed to allow more consistent aircraft spacing of traffic streams on approach to landing in IMC by transferring the responsibility for merging and maintaining assigned in-trail spacing to the flight crew while the air traffic controller retains responsibility for separation. Both consider the possibility of additional flight deck tools to support accurate spacing. The biggest difference between these concepts is in the proposed communications protocol. Although not finalized, the S&M protocol currently involves a multiple transmission procedure that has been used consistently in the Eurocontrol simulations. In this protocol, the controller instructs the pilot to select the lead aircraft, the pilot does so and responds with the position information of the TTF, and then the controller assigns the merging and spacing information. In addition, the instructions may include a heading vector prior to merging or self-spacing. This protocol has been used in all the Eurocontrol simulations, but only one (Grimaud et al., 2003a) reported any results or comment about it. In that simulation, the controllers recommended that the communications phraseology should be shortened. The CE 11 protocol calls for the controller to identify the lead aircraft and issue the spacing instructions in a single transmission. This procedure was used in the NASA-Ames simulation, which only reported that the use of the lead aircraft call sign was not confusing and was considered beneficial (Raytheon ATMSDI Team, 2004). Because there does not appear to be any serious complications caused by the different protocols, the two concepts are considered similar enough to make their current status identical.

The available literature indicates that, within limits, pilots are capable of achieving and maintaining spacing behind a lead aircraft without an unacceptable increase in workload, and that controllers perceive this redistribution of responsibility to have positive benefits. ADS-B data presented on the CDTI is more precise than the radar data presented to the controller, so more accurate spacing is possible. The pilots can also focus the spacing task on the single lead aircraft while the controller monitors all aircraft to ensure minimum separation. The Eurocontrol simulations (e.g., Grimaud et al., 2003b1; Hebraud et al., 2004) of the S&M concept and the NASA simulations of CE 11 (Raytheon ATMSDI Team, 2004) have been generally supportive of the concepts' feasibility from both the pilot and controller perspectives.

Several limiting factors on the use of these concepts have been identified, however. One involves the spacing distance; a 3 nm target was judged more difficult than 5 nm because it was close to minimum radar separation (OECG, 2001). Another involves the spacing tolerance limit; although pilots have demonstrated the ability to maintain very close time or distance tolerances, a .25 nm limit was rated more difficult than .5 nm or greater (Grimaud et al., 2003b1). Pilots in the Eurocontrol simulations (e.g., Hebraud et al., 2004) had to make numerous, though relatively small, adjustments to their speed to maintain the assigned spacing. While these adjustments increased their workload, the reduction in speed instructions made by the controller was judged to be beneficial (Grimaud et al., 2003b1). The CE 11 simulations, however, indicated that the PDA speed guidance tool requires further development before it can be used operationally. The frequency and amplitude of the speed changes commanded by the tool could lead to passenger discomfort, increase fuel consumption, necessitate excessive flap adjustments, and cause the aircraft to perform in ways that are inconsistent with controller expectations (Raytheon ATMDSI Team, 2004). The phase of flight also affects the ability of pilots to perform merging and self-spacing. Pilots in the CE 11 simulation preferred to receive spacing clearances early in the approach phase and reported that it was more difficult to implement self-spacing instructions when they were given late in the approach. The controllers in this simulation tended to give the clearances later in the approach because it allowed them to retain more flexibility for vectoring the aircraft. Pilots in Operational Evaluation 2 also reported that self-spacing was easier on initial approach than final approach when they have to configure the aircraft for landing (OECG, 2001). Finally, controllers found the heading-then-merge procedure to be more difficult than instructions to merge or remain behind (Grimaud et al., 2003b).

While both S&M and CE 11 applications appear to be conceptually feasible, the literature is less supportive about whether they are operationally suitable or beneficial. Both the Eurocontrol and NASA simulations found that assigning pilot self-spacing early in the approach restricted the flexibility of controllers to vector aircraft onto short cuts, or required modifications to the airspace route structure (e.g., Grimaud et al., 2004). The CE 11 simulation found no operational benefits for self-spacing (Raytheon ATMDSI Team, 2004). In fact, aircraft flight times were shortest in the baseline condition which did not involve pilot self-spacing. Most of the Eurocontrol simulations found only marginal improvements in flight efficiency (e.g., Grimaud et al., 2001). Many of these simulations were, however, severely limited by the numbers of participants and data collection runs, artificial circumstances, and simulation problems. The most extensive simulation (Grimaud et al., 2004) used six controllers who trained for two weeks followed by two weeks of data collection. The traffic volumes in the scenarios were considered to be very high, and multiple, parallel trajectories were added to enable more flexibility in the approach routes. The controllers assigned self-spacing to nearly all the equipped aircraft. With self-spacing, 75% of the aircraft were within 5 seconds of their target spacing, average flight time and distance were reduced by 10% and 5%, respectively, and there was a substantial reduction in the number of maneuvering instructions. The results of this simulation need to be replicated, given the number of negative results observed in other studies. However, it does support the possibility that, under certain conditions, the S&M and CE 11 concepts may provide some operational benefit.

The maximum operational benefit of pilot self-spacing is likely to be realized when these concepts are utilized in conjunction with controller support tools, such as TMA. TMA provides en route controllers with data about aircraft arrival times, enabling them to more efficiently sequence aircraft before they enter the next sector. A recent simulation by Sollenberger, Willems, Della Rocco, Koros, and Truitt (2004) demonstrated that more delays were absorbed in a high altitude en route sector, enabling benefits in efficiency to be observed in the low altitude sector. If TMA is effectively utilized to build sequences with appropriate spacing intervals as aircraft enter terminal airspace, then pilot self-spacing could be used to maintain those efficiencies through to landing. The recent study by Eurocontrol (2005) also indicates that when spacing intervals are effectively established in en route airspace through the use of an arrival manager and aircraft spacing tool, arrival delays can be effectively absorbed in that sector, and benefits, including more accurate spacing intervals and a need to issue fewer control instructions, can be realized in terminal airspace. Once established, these more accurate spacing intervals can then be used by pilots to self-space their aircraft in an arrival stream.

5. Summary and Recommendations

We summarized several pilot self-spacing concepts and the available research evaluating concept feasibility and the effect on ATCS workload and performance. We focused primarily on concepts involving pilot self-spacing during sequencing and merging and on final approach.

Some of the concepts, such as CAVS, EVApp, and VSA, are considered more basic in that they would be used in VMC, involve little or no change to current procedures, and would not require advanced CDTI functionality. As a result, pilot use of the CDTI in VMC would likely make additional controller tools unnecessary. We therefore consider these concepts more ready for operational implementation than the more advanced concepts: ASIA, ICSPA, NASA DAG TM CE11, and S&M (though for S&M the most difficult aspect was found with respect to pilots maintaining long in-trail sequences when time-based). The more advanced concepts would be used in IMC, and require more substantial modifications to current procedures as well as more sophisticated CDTI capabilities. These capabilities would need to be developed further and evaluated to determine whether the anticipated operational benefits are realized. If benefits are found, tools that provide the controller with information about aircraft equipage and capabilities would then need to be developed and evaluated. Some proposed tools (e.g., timeline with runway ETAs, spacing designators in the data block) were included in the recent NASA simulation (Raytheon ATMSDTI Team, 2004). However, the results of that simulation indicated that controllers sometimes chose not to use the tools because they were difficult to monitor. More research is therefore needed to determine which controller workstation tools are necessary to support the task and provide the most benefit. The results from most flight deck and air traffic control studies indicate that the advanced concepts are not yet mature and require further development before they become operationally feasible.

A considerable body of research indicates that pilot use of the CDTI to assist in visually acquiring traffic and following a lead aircraft is beneficial, and that pilot workload is generally acceptable. Controller reactions to pilot use of the CDTI have also been generally positive. The issues that remain on the flight deck side concern specifics of the CDTI design, placement in the cockpit, and the amount of head-down time observed with its use. On the controller side, concerns with pilot use of the CDTI were greater when pilots were tasked with maintaining shorter spacing distances from a lead aircraft, when used in a mixed equipage environment, and in poor weather conditions.

The majority of the studies conducted to examine the influence of self-spacing concepts on controllers have been conducted under conditions in which all aircraft were equipped with at least the information necessary to determine traffic location and intent, conducted in good weather, and without aircraft equipment problems that would require pilots to seek assistance from the controller. The few studies that did incorporate some of these issues suggest that problems may arise under these conditions. Additional studies are needed to investigate whether the more advanced self-spacing concepts are viable under a range of operational conditions and provide the benefits anticipated. These studies would also address issues about when and how to revert to air traffic control for separation assurance.

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Acronyms

AD	Application Definition
ADS-B	Automatic Dependent Surveillance - Broadcast
AMAN	Arrival Manager
ARTCC	Air Route Traffic Control Center
ATMSDI	Air Traffic Management System Development and Integration
ASAS	Airborne Separation Assurance System
ASIA	Approach Spacing for Instrument Approaches
ASRS	Aviation Safety Reporting System
ASSAP	Airborne Surveillance and Separation Assurance Processing
ATC	Air Traffic Control
ATCS	Air Traffic Control Specialist
ATCSCC	Air Traffic Control System Command Center
AWACS	Airborne Warning and Control System
CAA	Cargo Airlines Association
CAASD	Center for Advanced Aviation System Development
CAVS	CDTI Assisted Visual Separation
CDTI	Cockpit Display of Traffic Information
CE 11	Concept Element 11
CEFR	CDTI Enhanced Flight Rules
DAG TM	Distributed Air-Ground Traffic Management
DFW	Dallas-Fort Worth
DoD	Department of Defense
E-TMA	Extended Terminal Maneuvering Area
EUROCAE	European Organization for Civil Aviation Electronics
EVApp	Enhanced Visual Approach
FAA	Federal Aviation Administration
GPS	Global Positioning System
ICSPA	Independent Closely Spaced Parallel Approaches
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
JPDO	Joint Planning and Development Office
MCDU	Multifunction Control Display Unit
MSL	Mean Sea Level
NAS	National Airspace System (Holland)
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NLR	National Aerospace Laboratory
OECG	Operational Evaluation Coordination Group
OTW	Out-The-Window
PDA	Paired Dependent Approach
PRM	Parallel Runway Monitor
RFG	Requirements Focus Group
S&M	Sequencing and Merging
TCAS	Traffic Alert and Collision Avoidance System
TMA	Traffic Management Advisor

TRACON	Terminal Radar Approach Controls
TTF	Traffic to Follow
URET	User Request Evaluation Tool
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omnidirectional Range
VSA	Visual Separation on Approach