Effective Utilization of Air- and Ground-Based Technologies for Arrival Management

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Two recent simulations investigated air- and ground-based technologies for arrival management. In both studies professional air traffic controllers used prototype trajectory-based decision support tools to manage arrival flows that included airborne spacing-equipped aircraft simulators flown by professional pilots. Taken together, the results illustrate how en route arrival flow conditioning, terminal-area spacing adjustments, and airborne merging and spacing capabilities may be used for effective arrival management in future high-traffic environments.

I. Introduction

AIR Traffic Management (ATM) initiatives in both the U.S. (Next Generation Air Transportation System—NextGen) and Europe (Single European Sky ATM Research—SESAR) seek to at least double capacity over the next fifteen to twenty years.[1,2] Both programs rely heavily on advanced technologies to enable flexible, robust ATM operations that will reduce delays, improve safety, and lessen environmental impacts. Efficient arrival management is an area of particular interest because of its importance for reaching these objectives. It involves managing high volumes of aircraft flying optimized descent profiles using idle or near-idle thrust in heavy traffic environments.

Work toward improving arrival management has already led to the development and fielding of time-based metering tools.[3] Continuous Descent Arrival (CDA) procedures flown using existing aircraft Flight Management Systems (FMSs) reduce fuel consumption, noise, and emissions, but have proven difficult to execute routinely except under single stream, light traffic conditions.[4] Research is addressing methods for expanding the use of CDAs to heavier traffic environments through improved procedures,[5] the use of data link to assign required times of arrival at the runway and dynamic route changes designed to prevent disruption of CDAs,[6-8] and airborne merging and spacing along CDAs.[9] In this paper the term 'CDA' is understood to mean any optimized descent profile, including ones with short level deceleration segments.

Two recent simulations in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center[10] investigated air- and ground-based technologies for improving arrival management effectiveness.[11,12] Both studies included conditions in which professional air traffic controllers used prototype trajectory-based scheduling tools to manage arrival flows that included airborne merging and spacing-equipped aircraft flown by professional pilots. The first study focused on terminal-area feeder controller and final controller operations with aircraft on FMS routes. Traffic scenarios were partitioned such that aircraft were initially well-spaced for merging and ended with an 'uncoordinated' flow. The second study included en route operations and trajectory-based trial planning tools, and a condition in which data link communication functionality was integrated in controller displays. It also explicitly simulated an automated arrival management function: 'participating' aircraft from a dominant carrier assumed to have access to runway schedule information received arrival management messages via ACARS well prior to their planned top-of-descent points. En route controllers were responsible for integrating non-participating arrivals into the flow and managing relatively high levels of crossing traffic.

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This paper first summarizes each study along with its key findings from an ATM perspective. It then synthesizes the results and discusses their implications for NextGen research. In combination the results show arrival flow conditioning based on shared runway schedule information is important for managing aircraft on CDAs. They also show airborne merging and spacing capabilities are advantageous for improving runway throughput. The paper concludes with a discussion of related arrival management work and offers some recommendations for exploiting air- and ground-based technologies for efficient arrival management.

II. Terminal-Area Study

The first study was conducted in the AOL in August 2004 to evaluate the feasibility and potential benefits of using pilot and controller decision support tools (DSTs) to support time-based airborne spacing and merging in Dallas/Ft. Worth (DFW) terminal-area (TRACON) airspace (Figure 1). Sixteen simulation trials were conducted in each treatment combination of a 2x2 repeated measures design. In trials 'with ground tools,' air traffic controller participants managed traffic using sequencing and spacing DSTs. In trials 'with air tools' seventy-five percent of aircraft assigned to the primary landing runway were equipped for airborne spacing and merging, including flight simulators equipped with an enhanced cockpit display of traffic information (CDTI) flown by commercial pilots. All trials used two-controller teams consisting of a 'feeder' and 'final' controller (confederates served as center and tower 'ghost' controllers). In all trials controllers were responsible for separation and issued clearances by voice. All aircraft were equipped with FMSs and Automatic Dependent Surveillance-Broadcast (ADS-B) and entered airspace on charted FMS routes. Routes to the primary landing runway were altitude-separated at the merge point; routes from the southwest corner post included a level portion after the merge region (Figure 2). Each scenario began with a traffic flow entering the terminal area that was well coordinated for merging and spacing and ended with an uncoordinated flow.

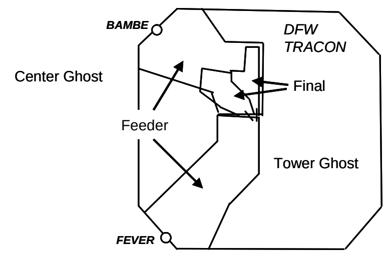

Figure 1. DFW TRACON study airspace.

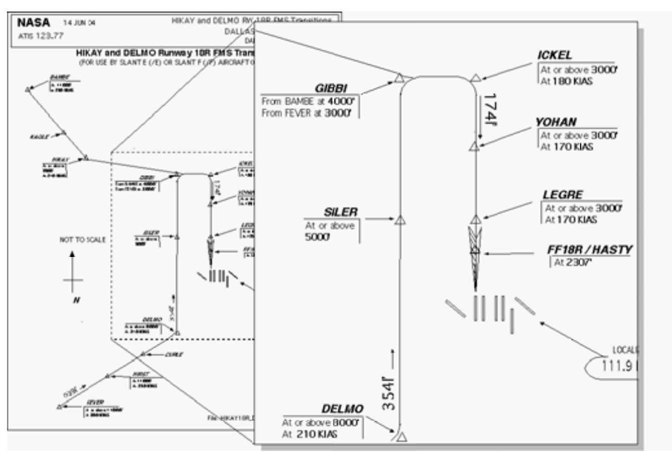

Figure 2. FMS Transitions to runway 18R.

A. Air- and Ground-Based Technologies

Air traffic controller subjects used a high-fidelity STARS (Standard Terminal Automation Replacement System) display emulation hosted on realistic large-format displays in the AOL. As a consequence of having fully FMS- and ADS-B-equipped traffic, controllers could display FMS routes and indicated airspeed was displayed beneath the aircraft target symbol in all treatment combinations.

In conditions when ground tools were available, displays also had integrated timelines and spacing advisory DSTs. The timelines showed estimated times of arrival (ETAs) at a reference point at the runway threshold computed using each aircraft's planned route through the forecast wind field, and scheduled times of arrival (STAs) based on a first-come-first-served landing sequence and a weight class-indexed matrix of temporal spacing intervals. The timelines also enabled controllers to perform slot reassignments and swaps.

Spacing advisory DSTs used the schedule and routings to advise a lead aircraft and spacing interval determined by the temporal spacing matrix. Datablocks automatically expanded to display the spacing advisory in the third line when aircraft were within 30 seconds of their advised interval. Controllers could change the advised lead aircraft and/or the spacing interval, and highlight a spacing equipage indicator to remind them that an aircraft should be complying with a spacing clearance. A 'history circle' that showed where the lead aircraft was *spacing interval* seconds ago appeared when controllers dwelled on aircraft that had a spacing advisory available. An aircraft directly following its lead aircraft at the correct spacing interval appeared centered in the history circle.

Seventy-five percent of aircraft assigned to the primary landing runway were equipped for airborne spacing, including all CDTI-equipped piloted simulators. Controller participants were briefed to issue airborne spacing clearances when conditions were suitable and cancel spacing if they saw fit.

B. Results

The histogram (plotted as lines) in Figure 3 depicts inter-arrival spacing accuracy relative to the temporal spacing matrix measured at the final approach fix (FF18R). Inter-arrival spacing improved in conditions with airborne spacing-equipped aircraft. Controller DSTs did not further improve accuracy over Air Tools alone, but did help controllers err on the conservative side relative to No Tools, suggesting an improved awareness of required spacing.

Differences in throughput measured at FF18R across conditions were not significant ($p = 0.10$) because, even in the No Tools condition, controllers were still very efficient in delivering aircraft. However, potential go-around situations not reflected in the throughput values arose most often in the No Tools condition.

Flight time and distance from each metering fix to FF18R were used as surrogate metrics for fuel efficiency. No significant differences in either flight time or flight distance were found, likely because aircraft flew coupled to the FMS an average of approximately 90 percent of the time in all conditions. However, when measured to the point when final controllers transferred control to the tower, significantly longer values were observed in the Ground Tools condition ($p < 0.05$). This suggests that with DSTs final controllers kept aircraft longer in order to monitor and ensure proper spacing.

Clearances were inferred from pilot action data in order to examine the control methods controllers employed. Speed-related clearances were reduced in Air Tools conditions. The overall number of clearances was also reduced, particularly for the final controller.

Inter-arrival spacing accuracy and clearances were both affected by how well the merging flows were initially coordinated. Figure 4 depicts spacing accuracy histograms for the coordinated flows in each condition measured when the final controller transferred control of the aircraft to the tower controller. The coordinated flows exhibit greatest accuracy for the Air & Ground Tools conditions,

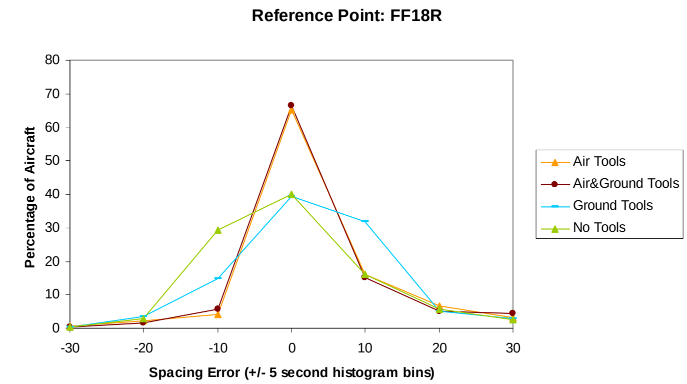

Figure 3. Spacing accuracy at the runway 18R final approach fix.

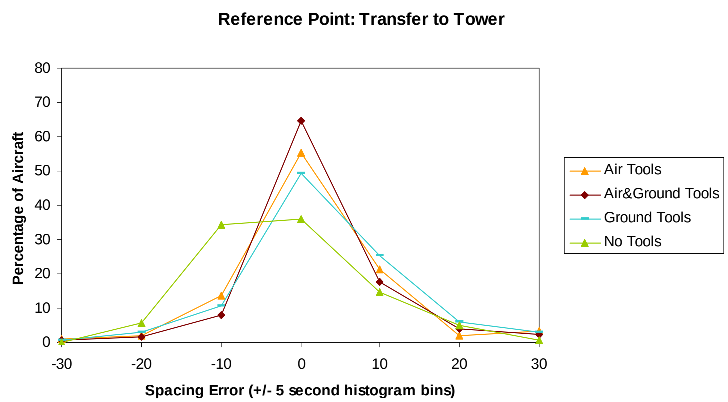

Figure 4. Spacing accuracy for aircraft in coordinated flows.

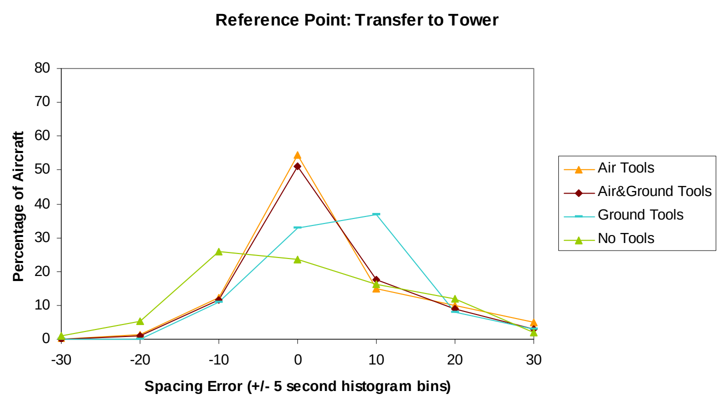

Figure 5. Spacing accuracy for aircraft in uncoordinated flows.

followed by Air Tools, then Ground Tools. Figure 5 shows accuracy measures for aircraft in uncoordinated flows. These results suggest that with airborne spacing, controllers can achieve better spacing accuracy even when merging flows are not well coordinated. Again the Ground Tools produced more conservative spacing, whereas No Tools showed broad variation in spacing accuracy.

Controllers issued proportionally more clearances to aircraft in uncoordinated flows. For each condition Figures 6 and 7 show the proportion of aircraft in coordinated and uncoordinated flows, respectively, that received a given type of clearance. For the coordinated flows, spacing clearances comprised a greater proportion of all the clearances issued, and both controllers issued smaller proportions of heading vectors and temporary altitudes that disrupt FMS operations. The relative proportions of clearances issued by the feeder and final controllers in the Ground Tools and No Tools conditions are much closer for the uncoordinated flows.

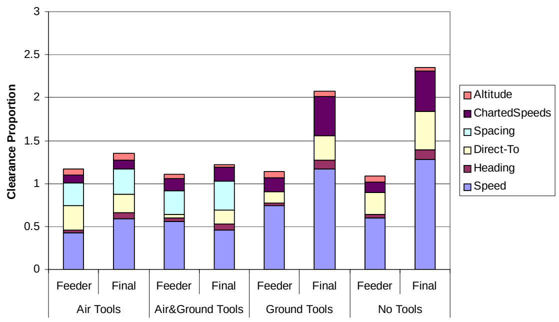

Figure 6. Proportions of different clearance types issued to aircraft in coordinated flows.

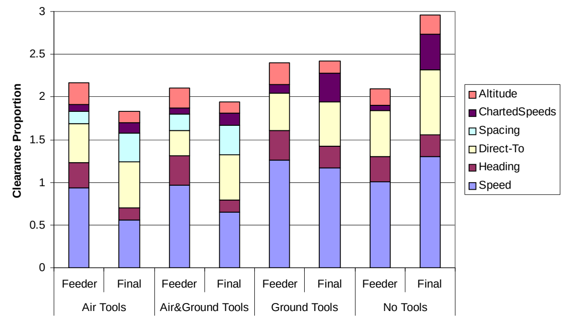

Figure 7. Proportions of different clearance types issued to aircraft in uncoordinated flows.

Controllers also issued proportionally fewer heading vectors in spacing conditions. An analysis of geographical locations at which controllers issued heading vectors suggests a trend toward earlier vectoring by the Feeder controller in the Air & Ground Tools condition relative to No Tools. Moreover, with Air & Ground Tools controllers issued the majority of heading vectors to aircraft in uncoordinated flows. Similar effects were observed for temporary altitude clearances. Generally speaking, aircraft in flows that were well-coordinated to merge used FMS autopilot modes—Lateral Navigation (LNAV) and Vertical Navigation (VNAV)—more consistently.

Subjective workload measures were collected via Workload Assessment Keypads (WAKs). At five minute intervals during each trial, a chime sounded and buttons labeled 1 to 7 on the WAKs illuminated, signaling controllers to rate their perceived workload on a 1 to 7 scale. The average WAK workload ratings remained in an acceptable range for all conditions and differences between conditions were insignificant. Subjective workload rankings of the conditions were also included as part of a post-simulation questionnaire. Rankings were lower for conditions with ground tools, implying the DSTs improved awareness of the traffic situation. Rankings also reflected a perceived workload increase from maintaining responsibility for separation even after delegating spacing tasks to aircraft.

Controllers rated all operations as safe, but ranked conditions with Ground Tools—and No Tools—as safer than all conditions with airborne spacing. Controllers also ranked the conditions according to their preference for use. A majority of controllers preferred the Air&Ground Tools condition, while the Air Tools condition was least preferable. Controller comments generally mirrored these rankings. In a mixed spacing equipage situation in which an unequipped aircraft was following a self-spacing aircraft, controllers noted problems issuing speeds to maintain proper separation because the lead aircraft was flying variable speeds to maintain its target spacing. Finally, the controllers felt the concept would work better if they were relieved of distance-based separation requirements for self spacing aircraft.

III. Dominant Carrier Arrival Management Study

The second study was conducted in the AOL in September 2006 to evaluate a concept in which a dominant carrier with access to runway schedule information could aid in conditioning arrival flows and conduct merging and spacing operations with its equipped fleet. The concept is an adaptation of the Trajectory-Oriented Operations with Limited Delegation concept,[13] tailored to align closely with the efforts of the U.S. Merging and Spacing working group, which includes United Parcel Service (UPS), FAA, MITRE, and NASA participants. Air traffic controllers who were responsible for separation managed a heavy eastbound arrival flow into Louisville Standiford airport (SDF). Nearly ninety percent of arrivals were participating UPS Boeing 757s and 767s equipped with FMSs and ADS-B 'out,' including piloted CDTI-equipped simulators. Traffic scenarios began several hundred miles from the airport, with high levels of crossing traffic in two high-altitude en route sectors and one low-altitude en route sector, and merging arrival streams in the terminal area. One professional air traffic controller staffed each sector (including the terminal area) (Figure 8). Arrivals (including FMS-equipped non-participating aircraft) flew merging Area Navigation (RNAV) CDAs to a single runway (Figure 9). A 2x3 repeated measures design was used to test two airborne conditions (participating aircraft not equipped, or equipped, for airborne merging and spacing, denoted 'No Spacing' and 'Spacing,' respectively) against three ground-side conditions (current operations, controller DSTs for scheduling and spacing, and the same DSTs integrated with data link, denoted 'No Tools,' 'Tools,' and 'Data Link,' respectively). Two experimental trials were conducted in each treatment combination. All trials simulated a process of automatically data linking arrival management messages via ACARS to participating aircraft based upon shared runway schedule information. Controllers were responsible for integrating non-participating arrivals into the flows.

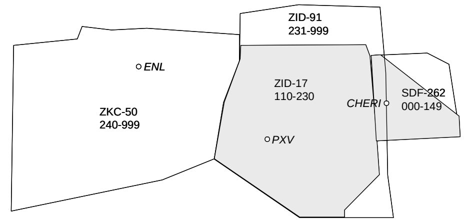

Figure 8. ZKC/ZID en route and SDF TRACON study airspace.

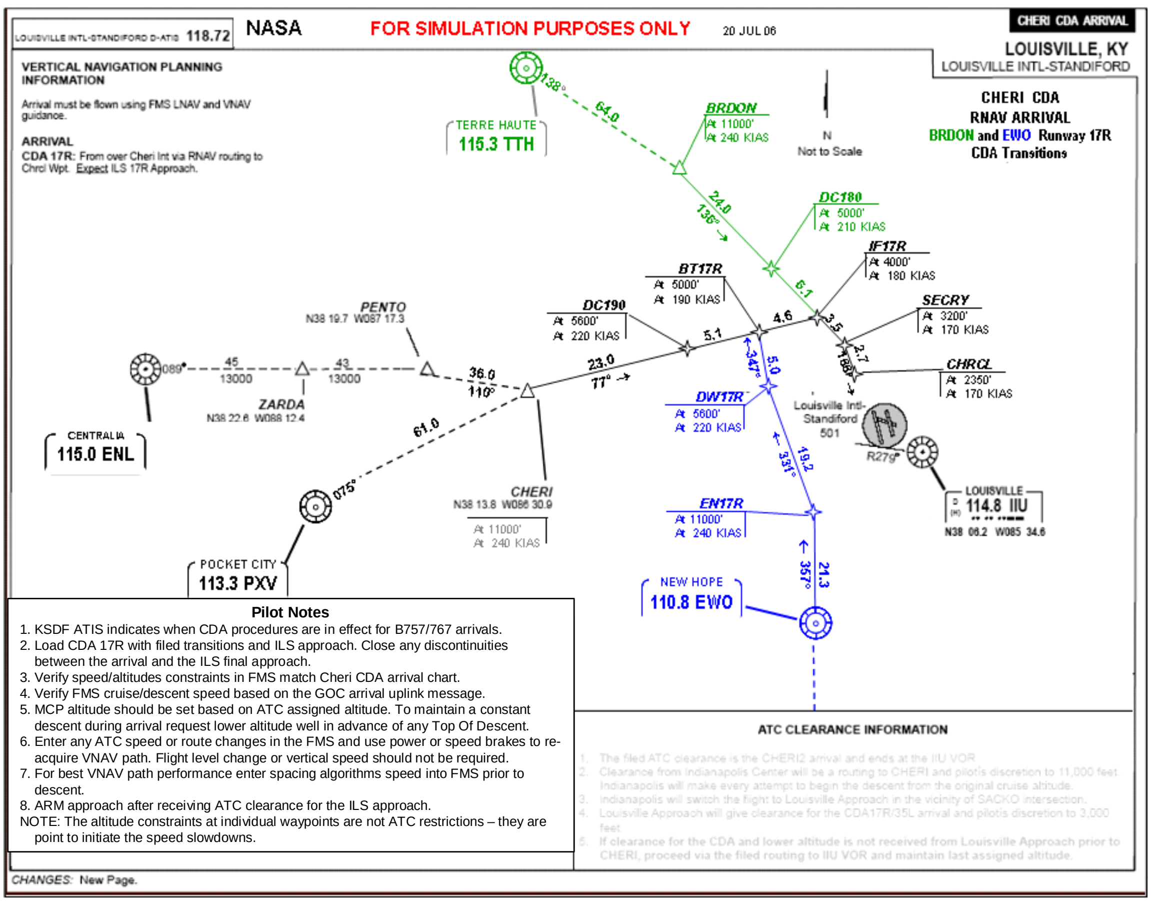

Figure 9. Merging RNAV CDA transitions to SDF runway 17R.

C. Air- and Ground-Based Technologies

Air traffic controller participants again used high-fidelity display emulations hosted on realistic large-format displays in the AOL (DSR (Display System Replacement) displays for en route sectors, STARS for the terminal-area). Controllers could display FMS routes.

In the Tools and Data Link conditions when ground tools were available, controller DSTs included timeline displays, speed advisories, a medium term conflict probe, a responsive trial planning function, and spacing status information. The timelines showed ETAs and STAs for the SDF 17R arrivals. A matrix of temporal spacing intervals was derived from the standard wake vortex separation matrix applied through the simulated wind fields, with an additional five second buffer. ETAs were computed based on an aircraft's flight plan routing, the charted CDAs, ADS-B-reported state information and an airline-supplied cost index; STAs were computed from the ETAs and temporal spacing matrix.

When SDF arrivals crossed an arc 300 nmi from the landing runway, the arrival management automation froze their STAs and computed a cruise/descent speed profile for meeting the STA along the CDA routing. If the aircraft was equipped for airborne spacing the arrival management system would further assess whether the scheduled lead aircraft was appropriately equipped and within range to conduct airborne merging and spacing operations. The arrival management automation then uplinked an arrival message to participating aircraft. The arrival message contained the destination airport, scheduled runway, STA, and cruise/descent speed schedule. If applicable it also contained the lead aircraft, assigned spacing interval, and merge point with the lead aircraft. The message content was designed to enable on-time arrivals with minimum spacing using different levels of FMS equipage. Had the simulation included Required Time of Arrival (RTA)-capable aircraft, those aircraft could have used the STA as an RTA instead of flying the cruise/descent speed schedule in VNAV.

In data link conditions the speed advisory and trial planning DSTs were integrated with data link communications, so that controllers could issue schedule-based speed advisories, and route and altitude trial plans, to equipped aircraft via data communication. All participating aircraft could receive data communication messages. Transfer of communications was also automated. Ref. 10 describes the DSTs and data link integration in detail.

Spacing history circles were again provided during Spacing trials. An algorithm based on the EUROCONTROL CoSpace logic[14] provided airborne merging and spacing functionality. The algorithm was refined from that used in the terminal-area study, and used target speed increments or decrements of five knots to maintain the required spacing. Pilots were briefed to engage spacing when in range of their assigned lead aircraft. Controllers were free to issue speed clearances that canceled spacing operations.

D. Results

Airborne spacing again contributed to improved spacing accuracy. Figure 10 depicts histograms (as lines) of the actual spacing minus the required spacing for aircraft that used airborne spacing and the same aircraft in conditions without airborne spacing. Significant differences in the mean ($p < 0.001$) and variance ($p < 0.001$) of the inter-arrival spacing for these aircraft were observed.

The impact of the arrival management automation was analyzed in terms of arrival time error, defined as an aircraft's actual time of arrival (ATA) at the runway scheduling point minus its STA (i.e., an aircraft that arrives before its STA has a negative arrival time error). The data were partitioned for participating ($n = 40$ per treatment combination) and non-participating aircraft ($n = 10$ per treatment combination), because effects were expected to differ between those categories. The results reflect some large errors due to twice having to reintegrate an aircraft into the arrival flow in the terminal area.

Figure 11 compares the observed arrival time errors for Spacing trials versus those with No Spacing (mean values are diamonds;

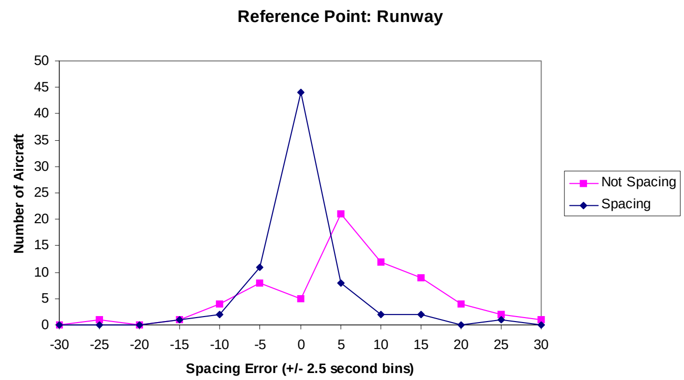

Figure 10. Spacing accuracy at SDF 17R for aircraft when spacing and in conditions without airborne spacing.

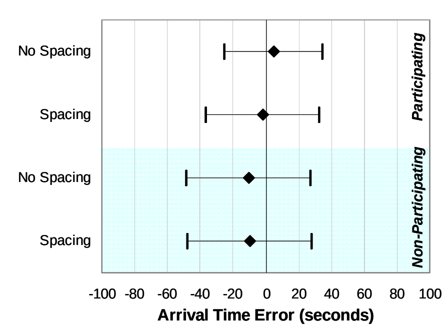

Figure 11. Arrival time errors in conditions with and without airborne spacing.

bars represent one standard deviation in each direction), showing only a marginally significant reduction in the mean arrival time error for participating aircraft in Spacing conditions ($p < 0.07$). Figure 12, however, shows controller DSTs in Tools conditions reduced arrival time variability significantly over No Tools conditions, even for participating aircraft ($p < 0.001$). A consistent result was not observed in the Data Link condition. A possible explanation with future research implications is that the integrated data link functionality made it *too* easy for controllers to uplink speed advisories formulated under considerable uncertainty, such as those that could sometimes be produced during descents.

Figure 12 also shows non-participating aircraft arrived on average 26 seconds earlier in the No Tools condition than in the Tools condition ($p < 0.047$) with a much larger variability ($p < 0.001$). This likely resulted from controllers' tendency to speed up non-participating aircraft at the beginning of a bank of arrivals because they did not have information about where terminal-area merges were planned in the schedule.

Schedule conformance results for all treatment combinations (Figure 13) do not reveal any additional significant differences. Generally speaking, the data indicate that collaborative arrival flow conditioning by the automation and controllers improved on-time arrival performance. Fine-tuning the arrival flow with the aid of DSTs was also beneficial. The small but significant reduction in the mean and variance of the inter-arrival spacing observed in Spacing trials translates into a throughput increase of one or two aircraft per hour.

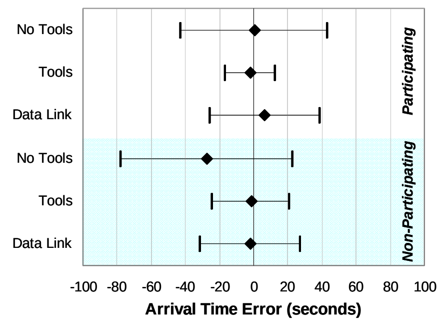

Figure 12. Arrival time error for each ground-side condition.

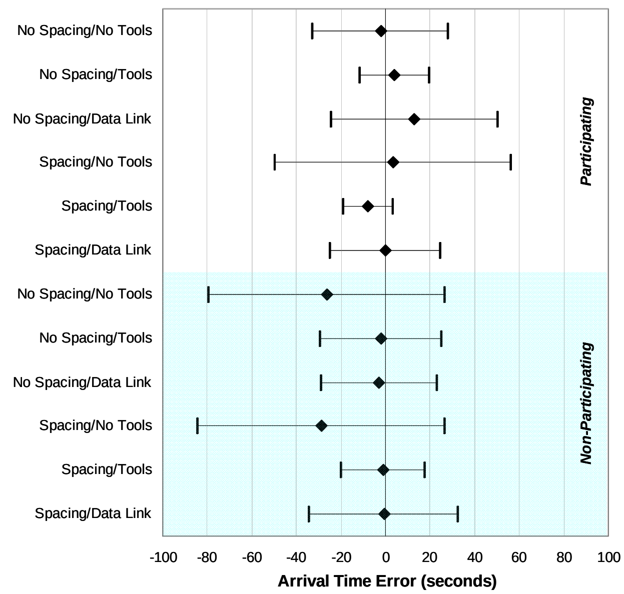

Figure 13. Arrival time error for all treatment combinations.

To manage CDA arrivals in the presence of high levels of crossing traffic, en route controllers adopted the current-day strategy of issuing arrivals early pilot's discretion descent clearances to a lower interim altitude (24,000 ft), then issuing the CDA descent clearance from the interim altitude. This strategy likely also contributed to the observed schedule conformance variability. Controllers were for the most part able to safely manage CDA arrivals in the presence of high levels of crossing traffic in all treatment combinations. However, one separation violation involving an SDF arrival was recorded.

Prior studies have noted some level of flight crew difficulty in managing aircraft energy during a CDA.[5,15] An analysis was therefore conducted to examine whether high levels of crossing traffic and spacing may have resulted in late descents and speed changes during the descent that in turn caused problems meeting downstream altitude and speed restrictions. In all conditions, some aircraft indeed crossed CHERI at altitudes considerably higher than the charted 11,000 ft crossing altitude, suggesting they were held high for traffic. Pilot and controller participants were briefed that when using airborne spacing aircraft were not required to comply with the 240 kt speed restriction at CHERI; accordingly, spacing aircraft showed the greatest incidence of excessive speed crossing CHERI. The majority of speed deviations involving aircraft not equipped for spacing were observed in the No Tools condition.

Relative energy metrics were computed by dividing the weight-independent specific energy due to an aircraft's actual crossing speed and altitude by that at the charted crossing speed and altitude. On average aircraft conducting airborne spacing had a significantly higher relative energy at CHERI than aircraft that were not spacing ($p < 0.001$). Almost no aircraft were low on energy at CHERI, which is typical at the first crossing restriction following an idle descent. Most high energy levels at CHERI did not carry forward to downstream restrictions, but increased variability in downstream energy levels was observed for spacing aircraft due to target speed adjustments commanded by the spacing logic.

Subjective workload measures were again collected via WAKs at five minute intervals during each trial. All four test sectors exhibited no significant differences between conditions. Controller debriefings indicated airborne spacing helped reduce workload in en route sectors, once controllers identified a 'comfort zone' for canceling and resuming spacing. Breaks in the descent due to temporary altitude clearances caused a 'ripple effect,' with difficult-to-manage speed offsets arising between successive aircraft. Controllers deemed using advisory DSTs to condition non-participating aircraft reasonable, and found data link 'great'—as long as messages were immediately accepted. Controllers also stressed the value of the timeline DST as a coordination and situation awareness tool.

IV. Discussion

The two human-in-the-loop studies have some notable commonalities—and differences—in the ATM environments each simulated and in the analyses that were performed. Taken together, they illustrate the importance of arrival flow conditioning via shared runway schedule information together with downstream adjustments for efficient high-density terminal-area operations. They also emphasize the importance of energy management along CDAs and demonstrate that airborne spacing provides an incremental throughput advantage. This section discusses these and related issues in light of other relevant research.

A. Arrival Flow Conditioning

Arrival flow conditioning, or how well arrival traffic was spaced upon entry to the terminal area, was an important issue in both studies. The terminal-area study used traffic scenarios partitioned to represent the effects of good versus poor arrival flow conditioning and showed a well-conditioned arrival flow was always helpful, regardless of whether controllers have DSTs or airborne spacing is used.[11] The dominant-carrier study illustrated a collaborative approach to achieving well-conditioned flows by automatically data linking an arrival messages to participating aircraft while controllers integrate non-participating aircraft into the flow. Current time-based metering operations, as well as related CDA and arrival management research, also recognize the importance of arrival flow conditioning. Ref. 16 describes a simulation method for translating inter-arrival spacing requirements into required longitudinal separation at a transition altitude beyond which aircraft fly comparable speed profiles along a CDA. The approach considers nominal variations in winds, aircraft weight, and pilotage, and incorporates a specified probability of aircraft requiring downstream adjustments to produce separation criteria for each lead/trail weight class combination. Near-term arrival management simulation research also emphasizes planning the arrival flow in advance.[17]

A variety of schedule-related issues are central to effective arrival flow planning. First, schedules should consider merging arrival flows. Route geometry, altitude separation, and lead and trail aircraft speed profiles affect whether separation criteria are met at merge points. Both studies described in this paper used routes that avoided small-angle merges at low altitudes when flows were highly compressed. Altitude separation was used at the merge point in the terminal-area study. Schedule point selection is also important. Runway scheduling is attractive because CDAs should be assigned early in any case to maximize benefits. A runway-based schedule can also be shared by all arrival controllers (including final and tower controllers) and it interfaces cleanly with surface operations. However, runway scheduling demands trajectory predictions over greater distances and a larger range of altitudes than scheduling to an earlier point. It is also subject to uncertainties due to aircraft and FMS differences that affect Vertical Navigation (VNAV) usage, aircraft configuration-change effects, and approach performance. Trajectory predictions in both studies used wind forecasts that were close to the actual winds relative to differences that may be encountered in practice.

Issues also surround the manner in which arrival schedules are shared among Air Navigation Service Providers (ANSPs) and carriers. These include how, and by what horizon, carrier and ANSP sequence adjustments must be made, and how schedule-based DSTs are integrated with airline operations planning and ANSP systems. The principal argument for carrier involvement is that ANSPs cannot be expected to consider each carrier's business-related sequencing and scheduling considerations (for this reason, separate carrier-centered arrival scheduling systems are already in use[7]). The collaborative scheduling picture that emerges from these considerations is one in which carriers consider their individual needs and provide ANSP scheduling automation with their desired runways and sequences as early as possible. A 'master schedule' formulated according to the carrier preferences is shared among participating carriers; carriers assist in adjusting their aircraft to meet the scheduled sequence; en route ANSPs integrate non-participating aircraft into the flow. Collaborative arrival flow conditioning on the established sequence begins after the schedule freeze horizon. Carriers handle their arrivals; ANSPs condition non-participating arrivals. ANSPs continue to use arrival management DSTs to make small adjustments to the flows at points selected to afford implementation of the adjustments by flight crews and monitoring by the controllers. Suitably equipped arriving aircraft support ANSP trajectory prediction by supplying wind updates. Access to the evolving ANSP schedule enables carriers to stay aware of schedule changes that may affect their operations.

B. Terminal-Area Flow Adjustments

Both studies investigated integrated controller DSTs for monitoring and adjusting the compressing arrival flows. The capability to make adjustments to achieve proper inter-arrival spacing has long been recognized as important[18]; profile variability and arrival time errors that accrue during CDAs have been observed in more recent studies, affirming this need.[5,6,12,15] The ease with which controllers can make adjustments and their effectiveness depends, first, on knowledge of the adjustments required, and second, on the means available to make them. In both studies, timeline DSTs provided controllers with a clear understanding of the arrival schedule. Analysis of the terminal area study data further showed that controllers could make required adjustments using less disruptive clearances when arrival flows were well-conditioned. The studies and related research suggest an iterative fine-tuning process that avoids over-control works best to null schedule conformance errors.

Again aircraft and FMS differences, pilot procedures, and the design of CDAs and airspace have implications for the effectiveness of terminal-area flow adjustments. Adjustments should be conducted along portions of the CDAs where pilots can effect the adjustment with the greatest likelihood of maintaining their planned vertical profile (see Ref. 15 for a discussion of pilot workload variation at different points along a CDA). If possible CDAs should include straight segments with shallow flight path angles to afford decelerations. Pilot participants in the second study agreed that energy management is easier when engine thrust is above idle. Furthermore, adjustments in progress during transfer of communications should be avoided in order to minimize controller workload associated with the additional coordination required.

The studies described here both assumed arrival routings were separated from departure routings, in keeping with the increasing importance of RNAV/RNP-separated arrival and departure routes in future ATM concepts.[19] Lateral maneuvers (e.g. small vectors or direct-to clearances that do not significantly impact the VNAV profile) further require that there is sufficient room to maneuver between routes. Some additional route design factors are described below.

C. Airborne Spacing

Airborne merging and spacing improved inter-arrival spacing accuracy in both studies. An important difference between the studies was the manner in which airborne merging and spacing guidance was engaged. In the first study, controllers were responsible for issuing spacing clearances or canceling them by issuing a speed clearance. The idea was to issue spacing clearances when the aircraft were nearly properly spaced, in order to ‘lock in’ the desired spacing. In the second study, pilots could engage spacing whenever their aircraft was within ADS-B range of their assigned lead and in an appropriate position. One effect of this procedure was that spacing guidance could be activated much further from the destination airport than in the first study, which controllers found helpful. However, spacing aircraft experienced energy management problems along the CDAs.

In both studies the proportion of aircraft in the arrival flows that were unequipped for spacing was high enough that controllers could not manage the unequipped aircraft as isolated ‘special cases.’ This is likely to remain the case for some time. Latter phases of planned airborne spacing deployment by the U.S. Merging and Spacing working group that seek to extend operations to multiple runways, and to airports not dominated by a single carrier, recognize the continued importance of schedule conformance in ensuring proper spacing between equipped and unequipped aircraft.[20] By the mid-term (2015) time frame an ANSP-mediated process is envisioned by which an equitable master schedule would be created that considers the scheduling preferences of multiple participating carriers. Schedule conformance would be achieved through a collaborative process similar to that described above, although by that time not all carriers participating in schedule formulation need be responsible for conditioning arrivals themselves via in-house advisory capabilities.

Operations in which airborne spacing in the terminal area provides the sole means of achieving the proper inter-arrival spacing have been investigated by researchers at EUROCONTROL, leading to route/airspace design requirements for spacing operations.[21] For example, legs should be added to standard trajectories to enable controllers to expedite or delay aircraft while keeping the aircraft on FMS trajectories (cf. Ref. 17). Routes should also be structured so that a range of possible arrival paths are available, segregated from departures and over-flights. The difference in path length should correspond at least to the size of a ‘slot.’ In addition, “sequencing legs” should be vertically separated, straight and parallel to afford easy visualization, separated so as not to lose space, and of a length appropriate for avoiding difficult merge situations. These and other requirements yield a very ‘clean’ airspace configuration and highly organized traffic flows—and may usefully translate to RNAV/RNP route design. Finally, with all aircraft equipped for spacing and without schedule-based DSTs, Ref. 21 reports seventy-five percent of aircraft arrived within five seconds of their target spacing. These results are only slightly better than those in the terminal-area study (Figure 3), suggesting any performance decrement due to the presence of unequipped aircraft may be relatively small.

V. Conclusion

Taken together, the studies provide insights into the potential for integrating air- and ground-based technologies to meet NextGen objectives. The results indicate it is possible to conduct CDAs in high-density airspace, although research is needed to provide the highest possible trajectory prediction accuracy and ease of fine-tuning arrival flows while minimizing energy management problems. Airborne spacing can provide a throughput increment and, if mature guidance is employed properly, a controller workload decrement. Research should address the development of enhanced air- and ground-based arrival management technologies to manage high-density traffic, as well as the design of RNAV/RNP CDA and departure routes servicing multiple runways and proximate airports. The use of reduced or dynamic spacing matrices also requires research. For NextGen operations all of these issues must be addressed in the context of dynamic routings and airspace.

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