Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)

Controller Support Tools for Schedule-Based Terminal-Area Operations

Michael Kupfer, Todd Callantine, Lynne Martin, Joey Mercer
San Jose State University/NASA Ames Research Center
Moffett Field, CA, 94035, USA
[michael.kupfer, todd.callantine, lynne.h.martin, joey.mercer]@nasa.gov

Everett Palmer
NASA Ames Research Center
Moffett Field, CA, 94035, USA
everett.palmer@nasa.gov

***Abstract*—A human-in-the-loop simulation was conducted to evaluate advanced controller support tools and display enhancements in terminal airspace. Terminal-area air traffic controllers managed aircraft arriving on optimized profile descents along Area Navigation routes following runway arrival schedules using only speed clearances in the presence of forecast wind errors and other disturbances. Three successively more advanced toolsets and three wind forecast errors comprised the experimental conditions. The results demonstrated that arrival schedule timelines (least advanced), timelines plus 'slot marker' circles, and timelines/slot markers plus speed advisories (most advanced) all enabled controllers to manage arrivals according to the runway schedules and maintain safe separation while keeping aircraft on their assigned routes. Participants preferred the timeline-plus-slot-marker toolset, in which the slot marker circles provided a spatial target useful for achieving schedule compliance. Speed advisories were the least usable. The paper discusses possible reasons behind this and suggests potential improvements.**

Keywords- decision support tools; optimized profile descents; scheduling; terminal-area arrival management

I. INTRODUCTION

Increasing capacity and reducing environmental impacts while ensuring safety are key objectives for both the NextGen and SESAR air traffic management (ATM) system modernization initiatives [1], [2]. The NASA Airspace Systems Program's Super Density Operations (SDO) research is investigating operational concepts, technologies, and procedures to support NextGen terminal-area operations. Precision scheduling of aircraft flying optimized profile descents (OPDs) along Area Navigation (RNAV) routes through extended terminal areas is central to the SDO concept for robust, high-density trajectory-based operations [3]. OPDs afford both environmental and economic benefits; avoiding extended level segments and minimizing throttle and speed brake usage can reduce fuel consumption, emissions, and noise [4]. The efficacy of the SDO concept improves when arriving aircraft remain on their assigned RNAV routes, as trajectory predictions required for scheduling become more reliable and controller situation awareness, critical for safety, is enhanced. Therefore, support tools and display enhancements are under development to help controllers assess conformance with runway schedules, manage the spacing of scheduled arrival aircraft flying OPDs, and cope with disturbances, without resorting to vectoring strategies typical of current terminal-area control practices [5], [6]. The overarching objective of the present research is to develop tools to enable OPDs for the majority of arrival traffic without sacrificing throughput.

The remainder of the paper begins by describing related work on controller support tools for arrival management. Section III then describes the controller support tools and display enhancements in detail. The experiment design and results are described in Sections IV and V, respectively, followed by a discussion of the results and possible improvements to the tools, avenues for further research, and conclusions.

II. BACKGROUND

Advanced controller aids for the terminal area have long been a subject of research, both in Europe and the U.S., as researchers have sought ways to increase the precision of terminal-area operations. In the early 1980's the German Aerospace Agency (DLR) developed the COMPAS arrival manager, introducing timelines as an interface to increase controller situational awareness [7]. In 1989, researchers at NASA Langley Research Center developed the traffic intelligence for the management of efficient runway scheduling (TIMER) concept [8]. The TIMER concept aimed to structure the arrival stream prior to the terminal area using en route metering, and time-based sequencing and spacing along fuel-efficient cruise and profile descents inside the terminal area. The goal was to build a runway schedule and, through the use of computer-generated controller aids, to improve delivery precision.

The Final Approach Spacing Tool (FAST) was a Center/TRACON Automation System (CTAS) decision-support tool for terminal-area air traffic controllers. An active version (A-FAST) used four-dimensional trajectory prediction algorithms to compute and display heading and speed advisories designed to sequence and space arrival aircraft to runways. A-FAST human factors challenges included the format and the timing of the presentation of the advisories [9]. Another CTAS tool, the Traffic Management Advisor (TMA), is currently deployed at Air Route Traffic Control Centers to support en route controllers and managers with schedule, spacing, and arrival flow management. It also uses a timeline graphical user interface (TGUI) to display schedule and sequence constraints at the traffic management position [10].

A variety of 'ghosting' displays to support merging and spacing of aircraft in the terminal area have also been developed. NAV CANADA developed the Visual Aircraft Spacing Tool (VAST). VAST uses ghost projections that translate the aircraft target information from a primary approach to the extended runway centerline of another approach, superimposing ghost images to allow for improved spacing performance [11].

More recent research and development has focused on adapting these ideas to advanced concepts that employ scheduling, RNAV/RNP routes, and OPDs. Spacing of performance-based arrivals on converging routes (SPACR) is a MITRE-developed suite of concepts that addresses merging and spacing problems for a RNAV/RNP route structure. The initial toolset required only existing flight deck and ground automation capabilities. On the flight deck, more advanced toolsets and concepts were added to allow for Flight Management System (FMS) offsets and accepting required time-of-arrival (RTA) constraints. On the ground side, the Converging Runway Display Aid (CRDA) was implemented [12].

The most recent MITRE concept is the Relative Position Indicator (RPI), an application that leverages RNAV/RNP procedures to improve predictability of merging arrival operations in the terminal area. The RPI algorithm first calculates the distance of an aircraft to a merge point along an RNAV procedure, then translates and projects this distance onto another route, and conveys this information via an indicator on the controller workstation. This ghosting information helps to further fine tune the spacing of aircraft at merge points and enables controllers to make decisions earlier reducing the need for tactical vectoring. RPI also supports complex route systems including Radius-to-Fix (RF) legs [13].

The 4D co-operative arrival manager (4D-CARMA), a successor to COMPAS, utilizes 4D-trajectory computations and provides control guidance (i.e., speed and heading) and timeline displays [7]. 4D-CARMA is currently adapted to enable OPDs within the Future Air Ground Integration (FAGI) project of the DLR [14]. A modified airspace and route structure where arrival routes merge at a late merge point is central to the concept. Aircraft capable of flying 4D trajectories execute OPDs after an automated target-time negotiation. Unequipped aircraft are subject to regular current-day control practices. Ghost projections of equipped aircraft onto the final approach path and target indicators for unequipped aircraft are also available to controllers.

Dutch ANSP Luchtverkeersleiding Nederland (LVNL) is currently investigating their Speed and Route Advisor (SARA) The system is intended to enable controllers to guide arrival traffic into Amsterdam Schiphol Airport, with improved arrival precision at the initial approach fix (IAF). Speed and route advisories are presented to controllers in a textual form in the flight data block. The tool was tested in human-in-the-loop simulations. Overall, it was rated positively by the controllers and data indicate that SARA helps to achieve a higher scheduling precision. Although the data show a decrease in objective workload (transmissions and inputs) in the SARA runs compared to the baseline runs, an increase in subjective workload (self assessment), additional (at times unnatural) vectors, level separation, and sequence changes indicates difficulties in meeting the arrival schedule. Other findings show that controller working strategies and situational awareness could potentially be negatively impacted using the SARA automation in a time-based control environment: firstly, controllers currently employ distance measures to form a mental picture of the traffic situation opposed to time. Secondly, automation that suggests solutions for traffic problems reduces controller mental activities. Additionally, the displayed advisories may differ from the advisories a controller would have issued [15].

The EUROCONTROL 'point merge' concept takes a different approach by eschewing new tools, relying instead on airspace redesign and existing technology to merge arrival aircraft flying OPDs along RNAV routes. A set of predefined route legs equidistant from a merge point enable path shortening and stretching. Controllers establish an arrival sequence aircraft by sending aircraft direct to the merge point, enabling the aircraft to remain in Lateral Navigation (LNAV) mode. Simulations showed that the concept was applicable even under high traffic loads while reducing controller workload. Additionally, safety was within acceptable bounds, while spacing accuracy and predictability were increased [16].

Like other more recent research focused on controller tools for managing arrivals, the current work assumes that aircraft use flight management automation while flying along RNAV routes and follow an arrival schedule. Based on 4D-trajectories and arrival schedules, tools and displays were developed to allow terminal area controllers to correct residual spacing errors and cope with disturbances using speed control only.

III. CONTROLLER SUPPORT TOOLS

This paper describes a human-in-the-loop simulation evaluation of controller support tools that have undergone iterative development during the course of previous 'controller managed spacing' (CMS) simulations [17]. Previous simulations concerned the design of OPDs in the test airspace, evaluating controllability using speed clearances along assigned routes, and the design of representative traffic scenarios and suitable disturbances. The current simulation focuses on controller performance and human factors evaluation of the support tools.

Three main controller support tools were developed that, based on the degree to which they change current-day operations, anticipate successively increasing levels of innovation. The associated tool conditions were denoted 'timeline condition', 'slot marker condition', and 'advisory condition'. Timelines, already used in air traffic control, were considered to be the least advanced toolset. Slot markers added the next level of advance in controller support. It was estimated that only limited additional tool augmentation compared to the timeline condition was required to translate time-based schedule information into spatial representations on the controller scope. The speed advisories represent the most advanced toolset, because more complex automation is added:

the tool recommends a solution to the controller rather than leaving the controller to work out a solution. Because earlier simulations showed a clear advantage in performance when tools were available [17], the experimental conditions did not include a 'no-tools' case. Display enhancements associated with the tools (i.e., data block early/late indications, indicated airspeed (IAS) of the slot marker), as well as other tools for managing relative spacing (i.e., spacing 'cones', J rings, spacing ('splat') tool, route display, ground speed in flight data block, and IAS indicator of aircraft target), were also tested.

The tools employed in this study were integrated into the Standard Terminal Automation Replacement System (STARS) emulation that is part of the Multi Aircraft Control System (MACS) software. MACS provides an environment for rapid prototyping, human-in-the-loop air traffic simulations, and evaluation of the current and future air/ground operations [18]. The next paragraphs describe the tools and their functionality in detail.

A. *Timelines*

Timelines were used to provide a graphical depiction of the relationship between the estimated times-of-arrival (ETAs) and scheduled times-of-arrivals (STAs) of aircraft crossing a specified location. A MACS timeline (Fig. 1(a)), based on the filed flight plans, planned landing speeds, and forecast winds together with (in this study) actual winds from 1500 ft above ground level, computes ground-based trajectories to determine ETAs for the simulated aircraft. Schedules then use the ETAs to compute STAs and arrival sequences according to specified scheduling criteria, including minimum wake-vortex spacing requirements, a buffer (0.5 nmi for this study, corresponding to approximately 15 s at final approach speeds), and a time advance parameter that may help reduce the delay of a trailing aircraft (30 s for this study). The timelines enable controllers to assess schedule conformance by comparing an aircraft's ETA (on the left side) with its STA (on the right). If the ETA is ahead of the STA, the aircraft requires delay. Conversely, if the ETA is behind the STA, the aircraft needs to be advanced. A freeze horizon is specified (20 mins before current STA in this study) inside which STAs are frozen to provide controllers with steady control targets. Once frozen, the respective ETA- and STA-markers on the timeline change from hollow to filled-in. Controllers can dwell over an aircraft callsign on the timeline or over the flight data block (FDB) to display a spacing bracket that shows the required temporal separation to the leading and trailing aircraft. This information helps to identify gaps, or slack, in the schedule.

In the study, a display enhancement was designed to complement the information provided by the timeline. An early/late indication equal to the ETA-STA error of an aircraft (denoted by 'E' or 'L', followed by the error) is displayed in the third line of the FDB if the error is greater or equal to five seconds (Fig. 1(b), Fig 1(c)). Errors less than two minutes are displayed with one-second precision, otherwise with one-minute precision.

B. *Slot Marker*

The slot marker circles are a type of ghosting display that present the time-based schedule information spatially on the traffic display. They indicate where an aircraft would be if it were to fly the nominal RNAV arrival route through the forecast wind field, meeting all published restrictions, and arriving on time at its STA (in this study, at the runway). This means that an aircraft in the center of its slot marker circle should arrive on schedule and consequently be properly spaced behind its lead (providing the lead aircraft is also in the center of its slot marker). In the study, the slot marker radius was defined to be the distance equal to 7.5 s of flying time at the current nominal speed (approximately 0.25 nmi at final approach speeds). Therefore, the slot marker size decreases as the charted speed decreases. The slot markers were always dimly visible; dwelling on a FDB or a callsign on the timeline highlighted the corresponding aircraft's slot marker. The current IAS of the slot marker was also displayed next to it (Fig. 1(c)). This information was included to help the controller stay aware of the charted speeds.

C. *Speed Advisory*

Speed advisories go a step further, offering suggested air speeds that controllers could issue to correct schedule errors. In the study, the underlying algorithm attempted to find a single speed that, if flown until slowing to meet a charted restriction at a specified downstream waypoint, would put the aircraft on schedule. Thus, a speed advisory is comprised of both a speed and reference waypoint. Speed advisories replaced the early/late indication in the third line of the FDB during experimental trials in the advisory condition (Fig. 1(d)). A speed advisory was displayed only when an aircraft's ETA-STA error exceeded five seconds, and only if the algorithm succeeded in finding a speed that it predicted would correct the error by the outer marker. Otherwise, the early/late indication was displayed. Speed advisory computations are subject to errors, because the algorithm uses forecast wind information to perform the required trajectory predictions. Moreover, as formulated for this study, the algorithm has been found to produce advisories that are at times counterintuitive or misaligned with controller objectives; these issues are discussed in Section VI.

D. *Other Tools*

Fielded STARS functionalities emulated in MACS were also available to controllers during the study in all three conditions. First, controllers could enable 'spacing cones' (or 'bats') that visualize the required distance-based minimum wake-vortex spacing as a cone of the appropriate length that extends forward from the aircraft target (Fig. 1(e)). The underlying logic derives aircraft-type information from the scheduled arrival sequence to determine the required spacing. Thus, the cones provide a mechanism by which final controllers can assess the relative distance spacing between aircraft, in contrast to the temporal spacing information provided by the slot markers and timelines. Controllers in the simulation had the option to individually enable or disable the spacing cones for all, or for specific aircraft. The controllers also had available J-rings and a spacing ('splat') tool currently implemented in STARS to assess relative aircraft spacing. J-rings are circles of controller-specified size plotted around an aircraft target on the traffic display (e.g., a 3 nmi radius) that afford assessment of the spacing between the aircraft and surrounding aircraft. The spacing tool allows controllers to measure distances between two points on the traffic display.

These may be aircraft targets or any other points in space (e.g., waypoints). Furthermore, MACS FDBs used in the study were configured to include ground speed (GS) information, which is useful in assessing actual winds.

Two additional tools not currently in STARS were available to controllers as well. First, controllers could click on an aircraft's callsign to display its filed route (Fig. 1(e)). The route was plotted as a line on the controller screen accompanied by information about altitudes and ETAs at waypoints along the route. This capability could reasonably be implemented in a future RNAV environment. Second, IAS was displayed adjacent to aircraft targets in all conditions, because it was assumed this information would likely become available with the current implementation of Automatic Dependent Surveillance-Broadcast (ADS-B) (Fig. 1(b-d)). This information can be used to assess wind conditions by comparing it with the GS displayed in the FDB. Also, when used together with the slot marker IAS, it helps estimate whether an aircraft is closing on its slot marker. Implications of the assumption about IAS information in ADS-B messages are discussed in Section VI.

IV. Experiment

A human-in-the-loop simulation was conducted to compare how subjects used the three toolsets to control traffic given different forecast wind errors and other disturbances. This section describes the elements of the simulation in detail.

A. *Experiment Design*

The simulation was conducted in two parts. The first consisted of a two-and-a-half day training period that included twelve training runs. Data were collected in the second part over a subsequent four-and-a-half day period. Besides the timeline, slot marker, and advisory tool conditions, three different forecast-wind errors (denoted the 'plus-bias', 'minus-bias', and 'no-bias' wind conditions) were simulated. Experimental trials were conducted in each of the three tools conditions under each of three wind conditions using two base traffic scenarios, for a total of eighteen data collection runs. Each run lasted 60 minutes, and was followed by a post-run questionnaire and a break. Participants answered a post-simulation questionnaire and participated in a final debrief discussion following the data-collection period.

B. *Airspace and Route Structure*

The aircraft flew OPDs on merging RNAV routes to runways 24R and 25L at Los Angeles International Airport (LAX). LAX was chosen for this study because it is already adopting OPDs in congested airspace. Fig. 2 shows a map of the simulated airspace with the sector boundaries, the charted routes, and the route waypoints together with their charted speed and altitude restrictions. The simulation airspace was comprised of three feeder sectors, ZUMA, FEEDER and FEEDER SOUTH, and two final sectors, STADIUM and DOWNE. The sector boundaries were adapted slightly from the actual operational sectors.

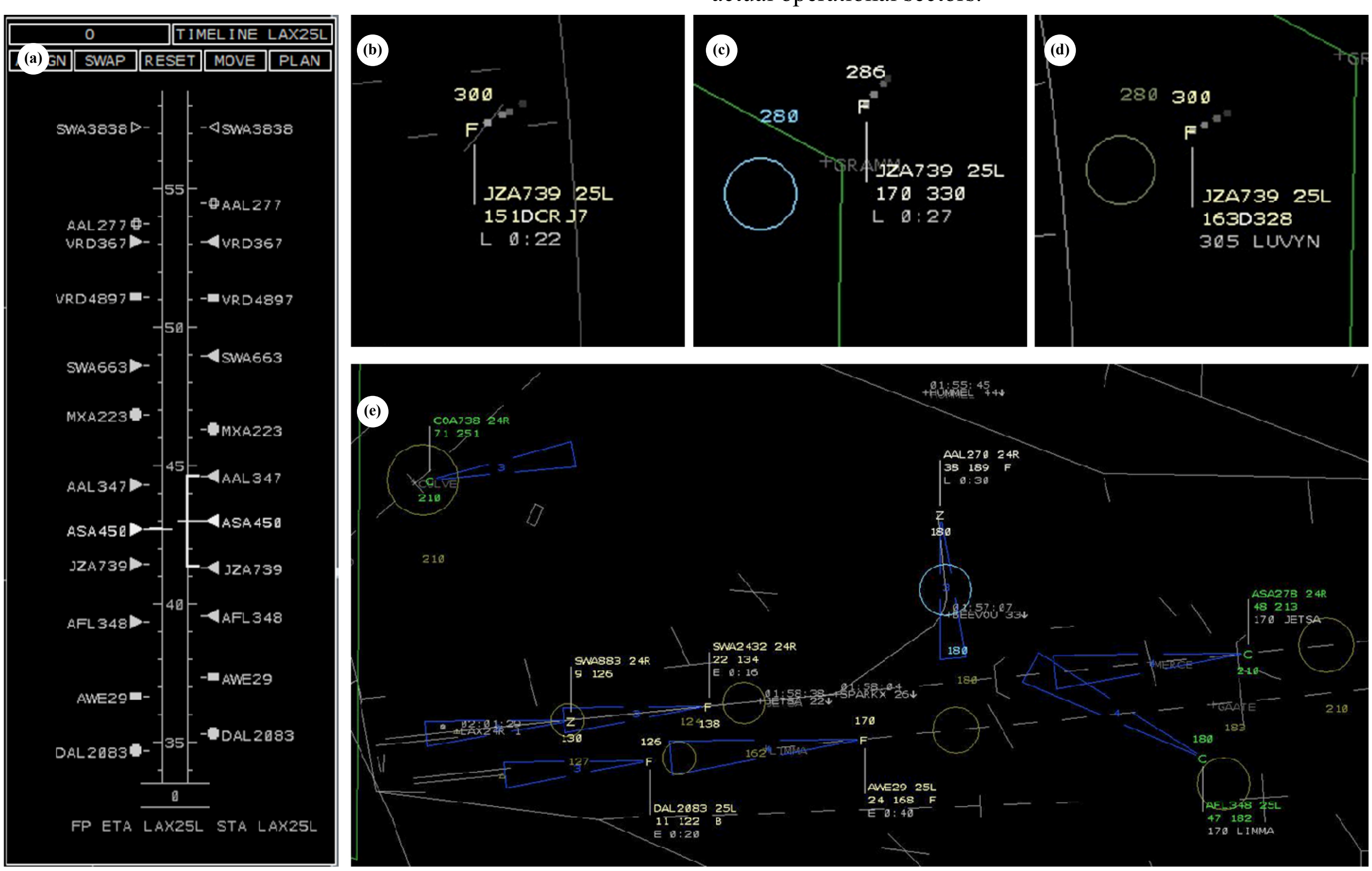

Figure 1. In clockwise order, from left: (a) timeline incl. a spacing bracket, (b) FDB in timeline condition, (c) dwelled FDB and slot marker in slot marker condition, (d) FDB and slot marker in advisory condition, (e) spacing cones and route display.

The routes were designed based on existing Standard Terminal Arrival Routes (STARs) and approaches using the Trajectory-Based Route Analysis and Control (TRAC) tool [19]. Altitude restrictions were imposed to yield a 2.4° descent angle, sufficiently shallow to allow for speed control along the OPDs. Speed restrictions supplanted tactical controller speed assignments for fly-ability and predictable flow control. Aircraft on the SADDE7 STAR were assigned to runway 24R; traffic on the SEAVU2, OLDEE1, SHIVE1 and LEENA2 STARs landed on runway 25L. Aircraft on the RIIVR2 STAR were allocated to both runways. Current-day LAX arrival traffic was analyzed to determine the aircraft types and traffic-load distribution.

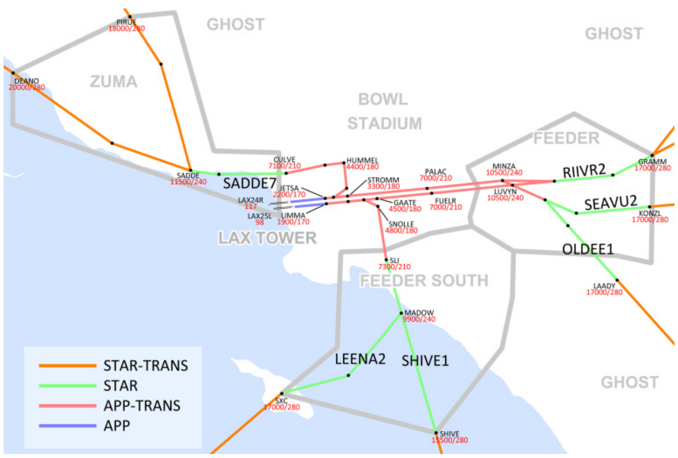

Figure 2. Simulated LAX airspace.

C. Participants

The three feeder sector positions and two final sector positions were staffed with retired terminal-area air traffic controllers with between 23 and 30 years of experience, who had been retired an average of 24 months. The tower controller and the en route "ghost" controller, responsible for the areas surrounding the test sectors, were staffed with retired confederate controllers. Pseudo-pilots were active commercial pilots and/or local aviation students who were experienced in MACS terminal-area operations.

D. Winds

Forecast wind errors serve as the principal source of uncertainty in the simulation, affecting the ETAs used to determine the STAs. The forecast winds were kept constant and the actual winds varied. In the plus-bias wind condition the forecast winds were 10 kts stronger than the actual winds. In the minus-bias wind condition the forecast winds were 10 kts less than the actual winds. In the no-bias wind condition, the actual and forecast winds were the same. In all conditions, winds were simulated at altitudes below 20,000 feet, and at altitudes below 1,500 feet the forecast wind profile matched the actual wind profile. Winds were always out of 265°, a headwind aligned with the landing runway.

E. Scenarios

Traffic scenarios were designed to emulate the effect of future en route scheduling and control. Two different base traffic scenarios were used. Both included 25 aircraft flying to each runway. The scenarios were built under the assumption that en-route facilities can deliver aircraft to the terminal-area entry fixes with nominal runway-schedule errors no greater than 60 s early or 30 s late. Those values are based on the current TMA metering precision and on the expected improvements of future TMA enhancements. However, due to the wind forecast errors, the actual ETA-STA errors differed from that range. Fig. 3 shows the runway schedule error measured at the entry fixes, averaged over both scenarios under all conditions. For the most part, the schedule errors were within the intended bounds. Additionally, during each run, scripted disturbances were added by instructing pseudo pilots to change the airspeed of one pre-specified aircraft per runway without controller knowledge. For example, a scripted disturbance could cause an aircraft to slow from 240 kts to 210 kts 8 nmi later than it nominally would. If they remained undetected, the disturbances caused an approximately 20 s change in arrival time.

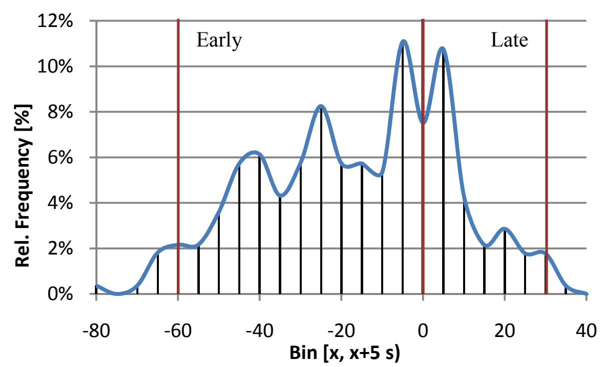

Figure 3. Average runway schedule error measured at the entry fixes (data from no-control-intervention runs; 6 runs, N = 300 aircraft).

F. Controller Tasks

The controller task was to efficiently manage schedule conformance and deliver aircraft to the outer marker and runway properly spaced, while coping with the disturbances and wind forecast errors. The controllers were advised to use the tools to avoid vectoring and manage the arrival traffic with speed instructions alone. The feeder controller task was to accept aircraft radio check-ins from the pseudo-pilots, issue a "descend-via" (i.e., descent via the RIIVR2 arrival) and approach clearance along the RNAV routes to the assigned runway, and try to deliver the flights as close as possible to their STAs. The final controllers were tasked with fine-tuning the schedule conformance and ensuring proper spacing at the runway.

G. Data Collection

Simulation data logs recording various metrics such as trajectory and flight state information, pilot and controller entries, schedule data, etc., were collected from every controller and pseudo-pilot workstation. Voice communications between controllers and pilots were recorded using an emulation of the FAA's Voice Switching and Communication System (VSCS). Additionally, controller and pilot interface actions were recorded as screen capture videos.

Subjective data included workload data and questionnaire responses. Following an Air Traffic Workload Input Technique (ATWIT)-based procedure [20], controllers were prompted every five minutes to input a rating between one (low) and six (high) of their current workload level using a workload assessment scale embedded in the MACS software. Controllers completed questionnaires after each data-collection run, and a comprehensive post-simulation questionnaire prior to the final debrief session.

V. RESULTS

The results of the study highlight two key findings:

- Using all three toolsets, the controllers were able to keep aircraft on their routes, mitigate schedule errors, and ensure sufficient wake-vortex spacing between the aircraft.
- Subjective results show that controllers preferred the slot markers and found the speed advisories the least usable of the main tools.

The following subsections present details of the data analysis.

A. Objective Results

1) Route Conformance

Fig. 4 shows the track plots for all 900 aircraft in all 18 runs, illustrating that controllers succeeded in enabling aircraft to fly OPDs while remaining on their RNAV routes. Aircraft remained in LNAV mode 100% of the time. Route conformance within 1 nmi was approximately 99.5% (95% within 500 ft). No significant differences were found between the various conditions ($\alpha = 0.05$).

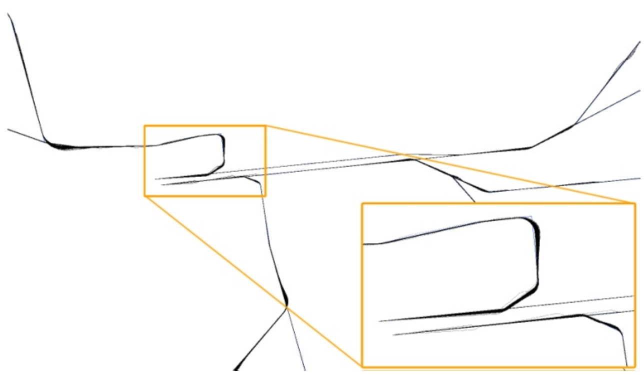

Figure 4. LAX airspace: tracks from all simulated aircraft (N = 900).

2) Spacing Accuracy

Spacing accuracy concerns the relative spacing between consecutive arrivals relative to their required minimum wake-vortex spacing distance. No significant difference in spacing accuracy was found for any of the tools or wind conditions ($\alpha = 0.05$). Fig. 5 shows the accuracy achieved at the runway threshold for the three tool conditions. For all runs in all conditions, the mean spacing error was 0.53 nmi ($\sigma = 0.27$ nmi). The peak near 0.5 nmi corresponds to the scheduling buffer used in the study. The relatively small variance indicates controllers were also largely successful in avoiding excess spacing, which is important for maintaining throughput. Overall, five spacing violations were observed, three of which occurred in runs in the timeline/no-bias wind condition. However, only one was due to controller error; the other violations were pseudo-pilot errors or simulation artifacts.

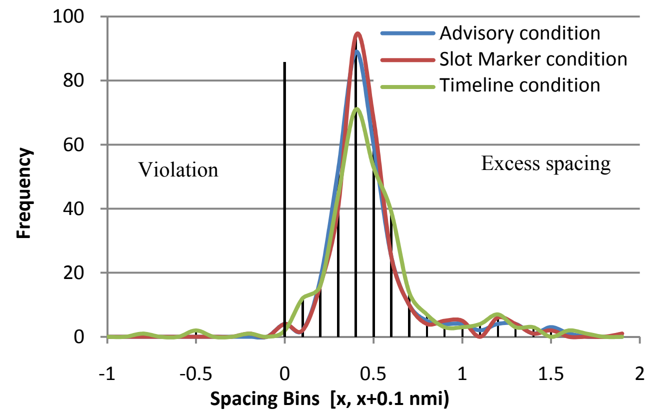

Figure 5. Inter-arrival spacing between consecutive aircraft measured at the runway threshold, by tool condition.

3) Schedule Conformance

Schedule conformance refers to how well controllers ensure aircraft conform to the runway arrival schedule (ETA-STA difference). While Fig. 3 shows the initial runway schedule errors measured at the terminal-area entry fixes, Fig. 6 shows the runway schedule conformance measured when aircraft crossed the runway threshold, averaged over all runs. The data show that controllers were able to reduce the ETA-STA errors of the aircraft as they transited the terminal area. The distribution in Fig. 6 peaks around -5 s ($\mu = -1.21$ s, $\sigma = 5.21$ s). The curve is steeper on the left, indicating controller effort not to exceed the 0.5 nmi schedule buffer. The curve is more gradual on the right as excess spacing is somewhat inefficient, but safe.

Decomposed by tool condition, the data show that the advisory and the slot marker condition are very similar (Fig. 7). No statistical difference was found between the slot marker and advisory condition ($\alpha = 0.05$). The timeline condition, however, is significantly different from the other two tools conditions (advisory vs. timeline condition: $t(299) = 1.97$, $p < 0.01$; slot marker vs. timeline condition: $t(299) = 1.97$, $p < 0.01$).

The three wind conditions also differ significantly from each other. In the no-bias wind condition the controllers delivered the aircraft practically on schedule ($\mu = -1.12$ s, $\sigma = 4.63$ s). In this condition there was no wind bias that resulted in the aircraft target drifting off schedule. In the minus-bias wind condition the distribution is shifted to the left, to the early side ($\mu = -4.5$ s, $\sigma = 3.71$ s). Conversely, in the plus-bias wind condition more aircraft are delayed ($\mu = 1.94$ s, $\sigma = 5.07$ s). Here, the actual winds are stronger than the forecast winds, which influence the slot marker circles and advisories. T-tests for paired samples indicated significant differences (minus-bias vs. no-bias: $t(299) = 1.97$, $p < 0.01$; minus-bias vs. plus-bias: $t(299) = 1.97$, $p < 0.01$; no−bias vs. plus−bias: $t(299) = 1.97$, $p < 0.01$).

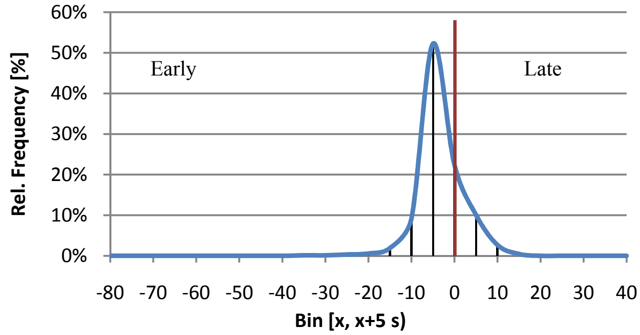

Figure 6. Average ETA-STA error measured at the runway threshold (data from 18 simulation runs, N = 900 aircraft).

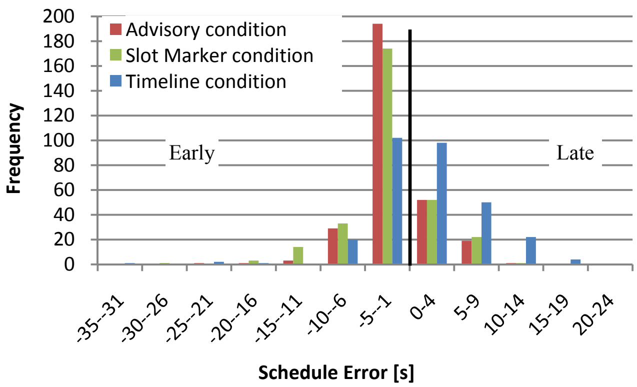

Figure 7. ETA-STA error measured at the runway threshold, by tool condition.

B. Subjective results

1) Usability and usefulness

Controllers were asked a number of questions about how they felt they managed the previous run. For example, controllers were asked how much they used each of the main tools over the three tool conditions and how useful they were. Note that the slot markers and the advisories were not available in every condition. Participants reported they used the timeline significantly more often ($\chi^2(2) = 8.897$, $p = 0.012$) in the timeline condition (93% of the time) when compared with the other two conditions where they reported using the timeline much less (46.6% and 43.3% of the time) (Fig. 8). This would suggest that participants could use the timeline but it was not their first choice of tool. Although there was a statistical difference between the amount controllers said they used the slot markers in the slot marker condition versus the advisory condition, it was not a meaningful difference, because controllers said they used the slot markers 93% of the time in the advisory condition and 90% of the time in the slot marker condition. However, this *is* meaningful in terms of the tools. While controllers reported that they used the slot marker 93% of the time in the advisory condition, but they only used the advisories 30% of the time – which indicates they chose not to use the most advanced tool. Controllers' comments support that they preferred the slot markers over the advisories and the timelines as their "tool of choice". Controllers used the early/late indicators about the same amount in the timeline and slot marker conditions but more than they reported using the advisories that replaced them in the advisory condition.

The post-study questionnaire asked controllers to rate how useful each tool was and how usable it was. Responses to these two questions are highly correlated ($\tau = 0.661$, $p = 0.005$) and show that, in general, if participants thought a tool was useful they also thought it had a high level of usability (Fig. 9). The slot markers were rated as "very useful" ($\mu = 4.6$) with "high usability" ($\mu = 5$), and the timeline was still rated positively as both "useful" ($\mu = 4$) and "usable" ($\mu = 4.2$). Another positive aspect of the timeline was that it was the only one of the three main tools that no one said they would have liked to have been able to turn off. The speed advisory, however, was rated lower and more variably. Overall, participants said the advisories were "somewhat useful" ($\mu = 2.8$) and "somewhat usable" ($\mu = 2.75$), and three participants also responded that they would have liked to be able to turn them off or use them for information only.

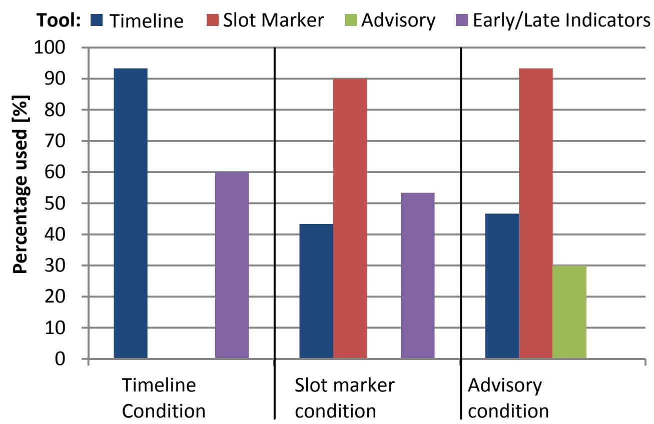

Figure 8. Amount participants "used" the tools in each condition.

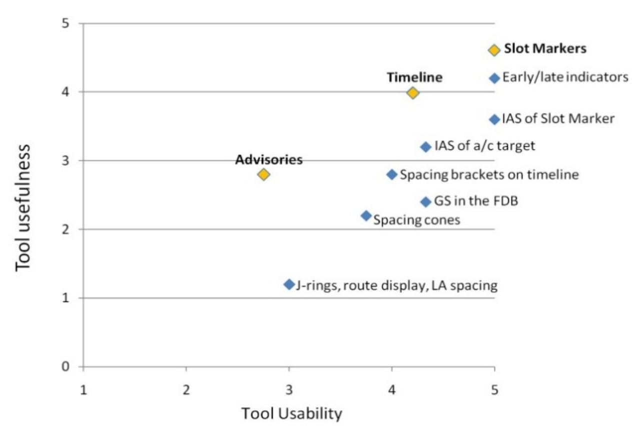

Figure 9. Post study questionnaire: tool usability vs. tool usefulness.

2) Workload

Real-time controller workload was measured using an ATWIT based procedure [20]. Workload data were also collected in post-run questionnaires using the NASA-TLX [21]. For both metrics, for all controllers, on an overall average, workload was perceived as "low" (ATWIT: $\mu = 1.85$, $\sigma = 0.53$;

TLX: μ = 2.57, σ = 1.36). When the ATWIT and TLX scores were organized and compared by tool condition, there were no significant differences between participants' ratings of their workload. However, differences between the wind conditions for both metrics were found. Wilcoxon Signed Rank tests showed that the difference between ATWIT workload ratings in the no-bias and the minus-bias wind conditions was significant ($p = 0.046$). Also, the difference between the no-bias and the plus-bias wind condition was significant ($p = 0.024$). The difference between the minus-bias and plus-bias wind conditions was not significant (no-bias: $\mu = 1.529$, $\sigma = 0.409$; minus-bias: $\mu = 1.665$, $\sigma = 0.385$; plus-bias: μ = 1.691, σ = 0.434). The load in the no-bias wind condition was rated lower on average for all six TLX scales. The plus-bias wind condition was rated with the highest load for all except the effort scale. Generally, in terms of mean ratings, the plus-bias wind condition was clearly experienced as a harder and higher workload condition than the no-bias wind condition.

The next Section discusses the implications of these results, augmenting them with specific controller comments drawn from the questionnaires.

VI. Discussion

Controller tools that support schedule-based terminal area operations have been iteratively refined through the course of CMS research; however, human factors data provided by the current study, including controller sentiment and comments about strategies for using the tools, enable further consideration of possible improvements as well as the benefits that could be expected from the operational implementation of one or more of the proposed tools. This section discusses the timelines, slot markers, and speed advisories from this perspective.

A. Timelines

Controllers used the timelines frequently in every tool condition, and although they rated them very useful and usable overall, some controllers expressed concerns about situational awareness, because a timeline "took my attentions away from the radar screen." Indeed, controllers identified strategies for controlling aircraft to the schedule that relied heavily on the accompanying early/late indicators (which were also rated very useful and usable): "Speed control until the early late indication disappeared, then the timeline to fine tune the last five seconds" (comment from a timeline condition post-run questionnaire). This suggests that timelines may be most useful for providing an overview of the schedule and sequence, but that controllers would welcome more precise early/late indicators that display errors down to one second in the FDB on the traffic display (where their attention is often focused), rather than having to scan the timeline in an attempt to obtain fine-grained information.

Several other options exist for increasing the usefulness of the timeline as a 'schedule overview' tool. While the spacing brackets can be used to identify gaps in the schedule, adding indicators in the center of the timeline (e.g., colored bars) this slack can more quickly be visualized. This feature might aid controllers in assessing where a gap could be 'built' for an unscheduled aircraft. Similar to the brackets used to indicate required spacing on the STA side of the timeline, brackets could be added to the ETA side of timeline to indicate the earliest and latest ETA predicted to be achievable with speed adjustments alone. Such a feature may help controllers evaluate the feasibility of potential solutions to disruptions in the traffic flow. A number of timeline functions implemented in MACS were not exercised in this study (e.g., the capability to manually effect a reschedule, or swap two aircraft). These functions may also be advantageous in cases where the arrival flow requires re-planning.

Controller acceptance of the timelines also depends to some degree on the accuracy of the underlying schedule, particularly the ETAs that, together with the scheduling criteria, dictate the STAs. CMS research has thus far assumed the availability of planned landing speeds to support trajectory predictions, but it is not certain whether this information may become available. The usability of the timeline therefore merits re-examination in the case where this information is not available.

B. Slot Markers

The slot marker circles were rated the most usable and useful of all the tools, likely because they translated the time-based schedule information into a spatial target. Controllers commented that "using them helped to adjust aircraft" and identified usage strategies in line with the slot marker design (e.g., "speed control to stay in the circle"). From this perspective, the design was highly successful. As implemented, the slot markers did introduce some uncertainty along the last portion of the final approach, because aircraft performance in this region differed slightly from the performance of the slot marker. An aircraft in the center of its slot marker circle would begin to drift out of the marker during this last portion of the flight. However, by this point, the final controllers may have turned their attention to the relative spacing between aircraft, so that this small inaccuracy did not impact operations.

Slot marker usability may also depend on schedule conformance. In the study, ETA-STA errors were well bounded, so that an aircraft's slot marker circle always appeared relatively near its associated aircraft target. If this were not the case, controllers frequently could be forced to disambiguate slot markers by dwelling on aircraft of interest. Even so, this situation could be confusing in merge situations when slot markers appear well ahead or behind their associated aircraft. The extent to which the usefulness of the slot markers is tied to the current schedule conformance requires further investigation. Also, controllers did note that as the slot marker size decreased the slot marker circles could be confused with circular indications on the terminal-area video map.

Another factor that may have led controllers to rate the slot markers highly is the capability to compare the IAS of the slot marker to the aircraft IAS. This made it easy for controllers to determine potential speed adjustments and detect disturbances (controllers detected all of the scripted disturbances introduced by the pseudo-pilots almost immediately). While the IAS of the slot marker is known from the nominal speed profile along the RNAV route, the IAS of the aircraft target was assumed to be available via ADS-B. In addition, the aircraft IAS was useful for assessing the current winds through comparison with the GS displayed in the FDB. However, recent discussions about

ADS-B message content indicate the availability of IAS information is uncertain. Other options for obtaining IAS information (i.e., computing it using 'now-cast' winds) could be pursued, but may be susceptible to errors. Alternatives to displaying IAS (e.g., displaying the GS of the slot marker) could limit the usefulness of the slot markers.

C. Speed Advisories

The pre-study training did not compel controllers to use the speed advisories, but rather to treat them as recommendations that could help them formulate speed clearances. The data indicate that controllers did not use the speed advisories frequently, and when they did use them, they "didn't always seem to work." There are several possible reasons controllers may have rated the speed advisories as less useful and usable than the other main tools. First, the advisory design, in which it attempted to determine a single speed clearance that corrects the ETA-STA error by a downstream waypoint after which no more speed changes are required, did not match the controller desire to correct errors by the time they transferred control of an aircraft to the next sector. In some cases, the advised waypoint at which nominal speeds would be resumed was located in the next sector, such that the error would be corrected over an extended period of time. In addition, the single-speed design does not match the common current-day strategy of issuing 'step-down' speeds in the terminal-area.

Second, some advisories could be counterintuitive or rejected by the flight crew. Fig. 10 depicts three possible advisories, one for delaying an aircraft, and two for advancing an aircraft. The nominal speed profile is 210 kts, then a deceleration to cross GAATE at 180 kts, followed by another deceleration to cross JETSA at 170 kts (red profile in Fig. 10). For the case where an aircraft is ahead of schedule, the advisory might specify an earlier deceleration such as '190 GAATE' (Fig. 10, profile (a)). More complicated advisories may result if an aircraft is behind schedule. In one case, an advisory might specify that the aircraft should accelerate to a faster-than-nominal speed before slowing to cross a downstream point, such as '220 JETSA' (Fig. 10, profile (b)). A flight crew could reject such an advisory because they are uncomfortable or unwilling to increase speed on final approach (particularly if the speed increase requires reconfiguring the aircraft). Alternatively, an advisory might specify that an aircraft that is late should *decelerate* (e.g. '200 JETSA'), but then hold the speed such that it eventually flies faster than the nominal profile (Fig. 10, profile (c)). A controller may find such an advisory counterintuitive, as the advised speed may be slower than the speed of the slot marker, which is ahead of the aircraft. This particular advisory also has the problem of taking a long time to achieve the desired result.

Third, the advisories are computed using the forecast winds, introducing uncertainty. In the plus- and minus-bias wind conditions, controllers tended to ignore the advisories and use their own understanding of the actual winds to formulate speed clearances (e.g., "some aircraft I keep 10 kts faster than the charted speeds to make it work" - comment from an advisory condition post-run questionnaire).

Since the study, the speed advisory logic has been adjusted to better match controller strategies by determining speed advisories that correct the ETA-STA error within the current sector. This is expected to improve controller acceptance of the speed advisories. The speed advisories require re-evaluation in future simulations. Whether the applied changes have any significant impact on efficiency is a subject of further research.

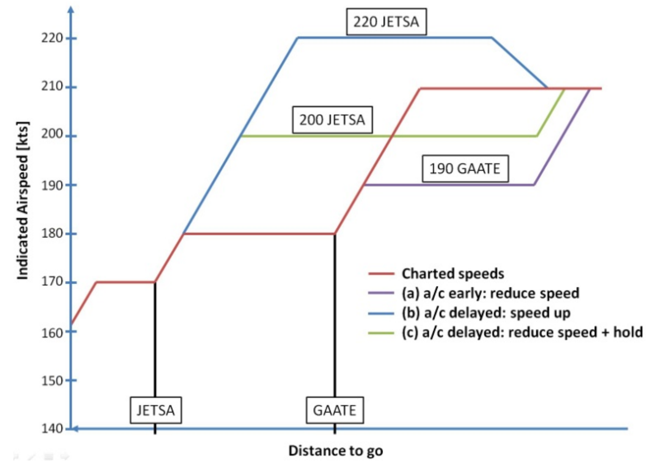

Figure 10. Speed profiles for different speed advisory implementations.

The above considerations highlight the benefits that could be achieved by introducing tools for use by terminal-area controllers for cases where schedule conformance is relatively good. In particular, given implementation costs, the timelines (together with early/late indications) are an attractive first step toward supporting schedule-based RNAV operations. In the study, slot markers provided additional benefits and garnered high ratings from controllers, but questions remain as to whether they would justify their implementation costs in cases where the errors to be corrected are larger, or the IAS information is not available. The same can be said of (improved) speed advisories. In general, additional research is needed to ensure the tools complement each other in situations where, without them, efficient control would be difficult.

VII. CONCLUSIONS

The SDO concept [3] requires precise control to arrival schedules and maintaining high route conformance in order to enable environmentally friendly and more economical OPDs. The current study investigated the performance of three successively more advanced trajectory-based controller support toolsets designed to help controllers in achieving those goals. The outcome of the study shows that under the simulated conditions, the tools helped to make the SDO concept viable: subject controllers, in each case, were able to correct runway schedule errors that reflect the application of future en-route traffic management, and avoid spacing violations. Controllers used speed clearances alone, enabling aircraft to execute OPDs while remaining on their RNAV routes.

The timelines received high usefulness and usability ratings, as did the associated early/late indications. Controllers preferred the slot markers, as they proved effective in translating the time-based schedule information to a spatial target for control. The speed advisories, as implemented for the study, suffered from a mismatch with controller strategies, and were little used during the simulation. The speed advisories were modified for future work to better suit controller needs.

Future research will explore scenarios with larger schedule errors and off-nominal events (e.g., missed approaches, unscheduled aircraft, etc.). This research will also leverage path control (initially as predefined alternative RNAV route options) to provide the controllability necessary for larger required delays. In addition, the research will explore the process by which rescheduling may be used to restore nominal operations that rely solely on speed control. The tools developed for this study will consequently require modification to support additional degrees of freedom.

The relatively low complexity of the scenarios tested in this study was reflected in the workload ratings. The ATWIT rating scale was not sensitive enough to detect small fluctuations in controller workload and therefore did not reveal possible differences between conditions. Future work will also utilize more complex scenarios that incorporate departures and arrivals to neighboring airports.

ACKNOWLEDGMENTS

The authors thank Tom Prevot, Al Globus, Richard Jacoby, and James Wong for invaluable MACS software support and tool development. John Robinson supported the research as lead of the Super Density Operations research focus area.

REFERENCES

[1] Joint Planning and Development Office, "Concept of operations for the next generation air transportation system", Version 3.0, 2009.

[2] SESAR Consortium, "SESAR definition phase deliverable 3—the ATM target concept," DLM-0612-001-02-00, 2007.

[3] D. Isaacson, J. Robinson III, H. Swenson, and D. Denery "A concept for robust, high density terminal air traffic operations," 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX, 2010.

[4] J.-P. Clarke, N. T. Ho, L. Ren, J. A. Brown, K. R. Elmer, K.-O. Tong, and J. K. Wat, "Continuous descent approach: design and flight test for Louisville International Airport," Journal of Aircraft, Vol. 41, No. 5, 2004, pp. 1054-1066.

[5] T. Becher, D. Barker, and A. Smith, "Methods for maintaining benefits for merging aircraft on terminal RNAV routes," Proceeding from the 23rd Digital Avionics System Conference, Washington, D.C., USA, 2004.

[6] J. Shepley, "Near-term terminal area automation for arrival coordination," Eighth USA/Europe Air Traffic Management Research and Development Seminar, Napa, CA, USA, 2009.

[7] H. Helmke, R. Hann, M. Uebbing-Rumke, D. Müller, and D. Wittkowski, "Time-based arrival management for dual threshold operation and continous descent approaches," 8th USA/Europe ATM Seminar, Napa, CA, USA, 2009.

[8] L. Credeur and W. Capron, "Simulation of TIMER, a time-based, terminal air traffic, flow-management concept," NASA TM-2870, 1989.

[9] C. M. Quinn and J. E. Robinson III, "A human factors evaluation of active final approach spacing tool concepts," 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli, Italy, 2000.

[10] H. N. Swenson, T. Hoang, S. Engelland, D. Vincent, T. Sanders, B. Sanford, and K. Heere, "Design and operational evaluation of the traffic management advisor at the Fort Worth Air Route Traffic Control Center," 1st USA/Europe Air Traffic Management R&D Seminar, Saclay, France, 1997.

[11] NAV CANADA, "Visual aircraft spacing tool (VAST)", System Information Document, NAV CANADA, Ottawa, OT, Canada, 2003.

[12] T. A. Becher, D. R. Barker, and A. P. Smith, "Near-to-mid term solution for efficient merging of aircraft on uncoordinated terminal RNAV routes", 24th Digital Avionics Systems Conference, Washington D.C, USA, 2005.

[13] P. MacWilliams and D. Porter, "An assessment of a controller aid for merging and sequencing traffic on performance-based arrival routes," MITRE Technical Paper, MITRE Corp., McLean, VA, USA, 2007.

[14] A. Kuenz and C. Edinger, "Future air ground integration: a scalable concept to start with green approaches today", 27th International Congress of the Aeronautical Sciences (ICAS), Nice, France, 2010.

[15] E. Oprins, D. Zwaaf, F. Eriksson, K. van de Merve, R. Roe, „Impact of future time-based operations on situation awareness of air traffic controllers", 8th USA/Europe ATM Seminar, Napa, CA, USA, 2009.

[16] L. Boursier, B. Favennec, E. Hoffman, A. Trzmiel, F. Vergne, and K. Zeghal, "Merging arrival flows without heading instructions", 7th USA/Europe Air Traffic Management R&D Seminar, Barcelona, Spain, 2007.

[17] T. Callantine, E. Palmer, and M. Kupfer, "Human-in-the-loop simulation of trajectory-based terminal-area operations", 27th International Congress of the Aeronautical Sciences (ICAS), Nice, France, 2010.

[18] T. Prevôt, P. Lee, T. Callantine, J. Mercer, J. Homola, N. Smith, et al., "Human-in-the-loop evaluation of NextGen concepts in the Airspace Operations Laboratory", Proceedings of the AIAA Modeling and Simulation Technologies (MST) Conference, Toronto, Canada, 2010.

[19] T. Callantine, "An integrated tool for NextGen concept design, fast-time simulation, and analysis," Proceedings of the AIAA Modeling and Simulation Technologies (MST) Conference, Honolulu, HI, 2008.

[20] E. S. Stein, "Air trafic controller workload: An examination of workload probe (DOTIFAA/ CT-TN84124)," Atlantic City International Aiport, NJ, Federal Aviation Administration Technical Center, 1985.

[21] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (task load index): results of empirical and theoretical research," in Human mental workload, P. A. Hancock and N. Meshkati, Eds. Amsterdam, The Netherlands, Elsevier, 1988, pp. 139-183.

AUTHOR BIOGRAPHIES

Michael Kupfer earned his "Dipl.-Ing." degree from the Dresden Technical University, Germany. His research interests include Super Density Operations in the terminal area and Very Closely Spaced Parallel Approaches.

Dr. Todd J. Callantine earned his Ph.D. from the Georgia Institute of Technology in Industrial and Systems Engineering and has conducted air traffic management research at NASA Ames Research Center for the past fifteen years.

Dr. Lynne Martin earned her Ph.D. in Applied Social Psychology at the University of Surrey**.** Her research interests include human performance, terminal area operations, and human-automation interaction.

Joey Mercer received his M.S. in Human Factors from San Jose State University. For the past several years he has been investigating human factors issues related to medium- and far-term air traffic management concepts and operations.

Dr. Everett Palmer has electrical and industrial engineering degrees from Stanford University. For the last ten years he has been working in the Airspace Operation Laboratory on human-in-the-loop simulations of NextGen air traffic control concepts. He served for two years as the co-lead of the JPDO's Environmental Working Group's Operations Standing Committee.