HUMAN-IN-THE-LOOP SIMULATION OF TRAJECTORY-BASED TERMINAL-AREA OPERATIONS

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Abstract

A human-in-the-loop simulation evaluated decision support tools and display enhancements for terminal-area controllers managing high-density traffic flying Optimized Profile Descents along Area Navigation routes. Twelve trials compared nominal operations with and without prototype decision support tools and displays for two treatment levels of traffic scenario and forecast wind errors; four additional trials investigated the role of an 'arrival planner' who could issue path adjustments to aircraft as they entered the terminal area under off-nominal conditions. The results indicate that while the prototype decision support tools enabled improved schedule and route conformance, and did not increase workload, they also did not significantly improve throughput or eliminate inter-arrival spacing errors at the runway threshold. The arrival planner enabled large delays to be absorbed in the terminal area, but reduced the effectiveness of the display enhancements for downstream controllers.

1 Introduction

The Super-Density Operations (SDO) element of the NASA Airspace Systems Program is investigating future concepts and technologies for controlling aircraft flying quiet, fuel-efficient Optimized Profile Descents (OPDs) on terminal-area Area Navigation/Required Navigation Performance (RNAV/RNP) routes to safely enable high runway utilization, in accordance with NextGen objectives [1]. Advanced terminal-area scheduling automation is among the enabling technologies expected to support the SDO concept as it matures through the mid-term [2]. As part of this research, a series of ground tool-focused human-in-the-loop simulations is being conducted in the Airspace Operations Laboratory at NASA Ames Research Center [3] to evaluate the use and effectiveness of prototype trajectory-based decision support tools (DSTs), display enhancements, and procedures intended to help terminal-area air traffic controllers manage high-density arrival flows with sustained high throughput, and also cope with disturbances and off-nominal events.

The topic of this paper is a simulation conducted in October 2009 that examined merging arrivals to Los Angeles International Airport (LAX) runway 24R. The present study was preceded by a June 2008 simulation in Hartsfield-Jackson Atlanta International Airport (ATL) terminal airspace in which arrivals merged to land on runway 26R. A follow-on study using runways 24R and 25L at LAX is planned for June 2010. All of these studies are exploratory in nature and limited to terminal-area airspace. Aircraft enter the simulation airspace with reasonably small schedule errors (i.e. usually less than one minute) as if en route speed and/or path adjustments derived using schedule-based advisory tools had been applied. The present study also investigated the role of an 'arrival planner' responsible for data-linking delay trajectories to aircraft with large schedule errors. These elements were included in an effort to inform a larger human-in-the-loop simulation planned for later in 2010, in which a broader SDO concept for en route arrival flow conditioning using advanced terminal-area scheduling is slated to be tested in combination with active terminal-area arrival management.

This paper first presents a review of OPD arrival management and terminal-area DST research. It then describes the experimental design, study participants and other staffing, and LAX terminal-area routes and airspace used in the present study. Next, the paper describes the prototype DST implementations in the Multi-Aircraft Control System (MACS) simulation environment in the AOL, together with the training controllers and pseudo-aircraft pilots received about their use. A results section follows that includes data on route conformance, inter-arrival spacing, schedule conformance, throughput, and subjective measures of workload, together with DST usability and acceptance. Finally, the results section discusses the role of the arrival planner in absorbing large delays as could be required to cope with off-nominal events. The paper concludes with a discussion of implications for the June 2010 terminal-area simulation and planned 2010 combined en route/terminal-area simulation.

2 Background

OPDs along RNAV/RNP routes constitute a refinement of the Continuous Descent Approach (CDA) procedure concept (e.g. [4-6]) that recognizes the acceptability of short level segments for deceleration or vertical route separation (e.g., from terrain and departure routes). As used here, OPDs typically include altitude restrictions to define a geometric vertical profile, flyable in Vertical Navigation (VNAV) mode, that is sufficiently shallow (i.e. less than about 2.5 degs) to allow for effective speed control where needed. OPDs may also include speed restrictions that supplant tactical controller speed assignments for fly-ability and predictable flow control.

While researchers have reported fuel savings from partial OPDs [6], critical noise reduction benefits are best achieved when aircraft fly uninterrupted OPDs to the runway. This requires that aircraft are set up to descend with sufficient spacing buffers to accommodate arrival time uncertainties due to forecast wind errors, pilotage, and other factors [5]. Enabling uninterrupted 'open-loop' OPDs for a large proportion of aircraft, however, incurs a corresponding throughput penalty unacceptable for sustained super-density operations. Increasing throughput levels necessitates increasing the proportion of aircraft that require controller intervention. However, interventions themselves introduce uncertainty [7] and, without gaps in the arrival flow, operations can degrade to tactical vectoring. Merging terminal-area routes and varied aircraft-type mixes exacerbate these effects. Therefore, the central problem is how best to condition arrival flows for OPDs, and subsequently intervene to effect merges and address uncertainties and off-nominal events with sufficient precision to realize OPD benefits over periods of sustained high throughput.

Ref. 7 reviews research on merging and spacing aircraft in the terminal area using scheduling techniques and controller DSTs. Recent research with near-term implementation objectives has concentrated on controller support for merging flows [8, 9]. Besides displays augmented with schedule timelines and ADS-B-enhanced state information, researchers have generally proposed two classes of controller DSTs beyond simple range rings and leader lines: 'slot markers' that indicate where aircraft should be for proper sequencing and spacing, and clearance advisories that specify speed and or path clearances to issue in order to achieve the proper spacing.

Slot marker-type display indicators may be based simply on the aircraft's current position [9]; they may also be driven by historic information about the lead aircraft's position [10] or predictive information about the target aircraft. Only the latter two techniques support visualizing compression effects that occur along OPDs. However, the usefulness of historic information depends on how well the lead aircraft's speed profile matches that of the target aircraft, while the usefulness of predictive information depends on the quality of the prediction vis-à-vis uncertainties. Clearance advisories are also subject to prediction uncertainties, as well as the precision with which flight crews implement them [11]. In the June 2008 simulation controller displays with predictive slot markers and schedule timelines showed no significant advantage over current-day controller displays in producing accurate wake vortex spacing at the runway threshold.

3 Simulation Study

The present simulation expanded the suite of DSTs to include speed clearance advisories. Two nominal arrival traffic scenarios were constructed, along with a third 'off-nominal' scenario in which the role of an arrival planner was investigated. Errors in forecast winds, created by biasing the actual wind speeds positively or negatively (denoted 'plus' and 'minus', respectively) from the forecast winds, were included to examine potential effects on the scheduling automation and speed advisories.

The simulation was conducted in the AOL over a one week period. Allotting for travel time, training, post-trial and post-simulation questionnaires, and debriefing, the number of trials that could be run was constrained to sixteen, yielding an unbalanced design for the nominal scenarios (Table 1). Trials were conducted in randomized order.

Table 1. Number of experimental trials for each treatment combination.

Trials with **No DSTs**:		*Scenario* Nominal A	*Scenario* Nominal B	*Scenario* Off-Nominal w/ Arrival Planner
Wind Error Bias	Plus	2	1	1
Wind Error Bias	Minus	1	2	1

Trials with **DSTs**:		*Scenario* Nominal A	*Scenario* Nominal B	*Scenario* Off-Nominal w/ Arrival Planner
Wind Error Bias	Plus	2	1	1
Wind Error Bias	Minus	1	2	1

The remainder of this section describes the study participants and additional staffing, LAX airspace and RNAV OPDs, traffic scenarios, forecast wind errors, controller DSTs, and training.

3.1 Participants

Four professional terminal-area air traffic controllers with between 23 and 30 years of experience who had retired an average of 17 months ago participated in the study. One acted as the supervisor when not serving as the arrival planner. Three additional retired air traffic controllers acted as en route and tower confederates. Pseudo-pilots were experienced in MACS terminal-area operations. The June 2008 simulation demonstrated that a single pseudo-pilot assigned to a sector could become overloaded during fast-paced terminal-area vectoring; therefore, two pseudo-pilots staffed the Final controller test sector.

3.2 Airspace and Route Structure

Fig. 1 illustrates the test airspace and RNAV route structure. The RNAV routes from the east follow the existing published arrival and approach procedures; those from the northwest overlay published arrivals and nominal base-leg vectoring paths. A NASA Ames-developed tool called TRAC [12] was used to design the RNAV routes with speed and altitude restrictions that yield continuous descent path angles less than 2.5 degrees along which speed control may be effectively applied. The Feeder sector 201 was also enlarged from its actual size to accommodate aircraft on the KIMMO arrival; implications of this decision are discussed in the results section.

3.3 Traffic Scenarios

Two arrival traffic scenarios (denoted 'A' and 'B') of approximately 45 minutes duration represented nominal traffic to which en route flow conditioning is assumed to have been applied. The scenarios unfold differently in different actual wind conditions; Table 2 lists characteristics of the nominal A and B scenarios. Both scenarios include a larger proportion of SADDE arrivals than observed in actual LAX traffic samples, in order to produce more merges onto the final approach. Scenario A has a large number merges while scenario B has more aircraft arriving sequentially from the same direction. The 'theoretical maximum throughput' value was obtained for no-wind conditions using TRAC's capability to perform first-come-first-served scheduling on recorded

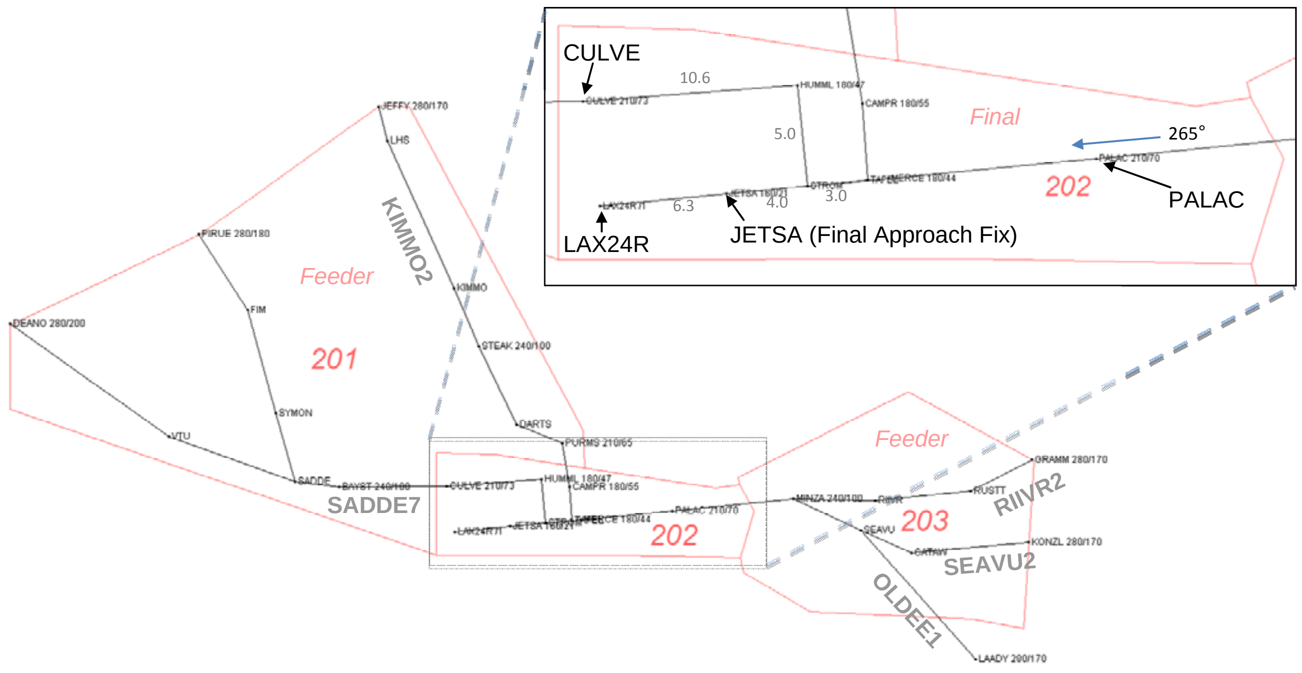

Fig. 1 Simulation airspace and RNAV routes to LAX runway 24R.

traffic samples, using a standard U.S. 3/4/5 nautical mile wake vortex spacing matrix.

A third 'off-nominal' scenario was also constructed to explore operations in which an arrival planner was responsible for issuing path adjustments to aircraft needing large terminal-area delays (i.e., more than approximately two minutes) that would be difficult to achieve with speed adjustments alone. The off-nominal scenario includes aircraft assigned to the KIMMO arrival. In trials using this scenario subject controllers were also tasked with constructing gaps in the arrival schedule, as might be required in response to emergencies or other off-nominal events.

All simulated aircraft were ADS-B and Flight Management System (FMS)-equipped; aircraft in the off-nominal scenario were additionally equipped for data communication, in order to receive trajectory modifications data-linked by the arrival planner.

Table 2 Nominal Scenario Characteristics

Characteristic	*Scenario* A	B
(Number of) SADDE Arrivals	15	12
RIIVR/SEAVU/OLDEE Arrivals	8	13
KIMMO Arrivals	0	0
Large Wake Category Aircraft	19	21
B757 Wake Category Aircraft	1	1
Heavy Wake Category Aircraft	3	3
Merges on Final Approach	13	8
Theoretical Maximum Throughput	34.0	33.2

3.4 Forecast Wind Errors

The aircraft flew in winds that were positively ('Plus') or negatively ('Minus') biased from the forecast winds by approximately ten knots at terminal-area altitudes (Fig. 2). All modeled winds are out of 265 degrees (i.e., a headwind aligned with the landing runway). A consistent wind-error bias is not likely in reality, and may cause 'worst-case' scheduling automation and clearance advisory performance (depending on route geometry).

3.5 Controller DSTs

The simulation was conducted using MACS emulations of the Standard Terminal Automation Replacement System (STARS) Graphical User Interface that provided a rich operational environment. In all conditions, controllers could use the interface to access a visual representation of any aircraft's FMS routes for simulated aircraft. ADS-B was also assumed to provide indicated airspeed

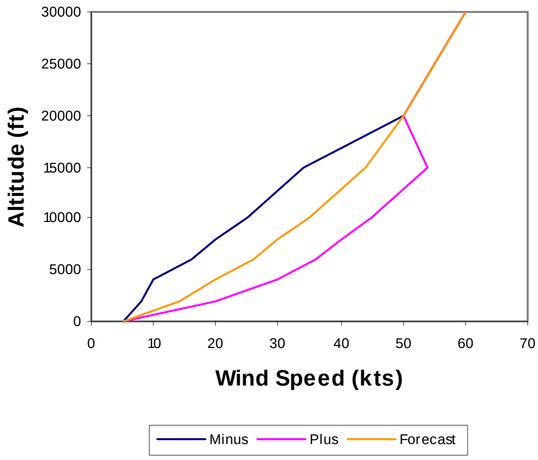

Fig. 2 Actual winds biased from forecast winds used for trajectory predictions.

information that was displayed below each aircraft's target symbol in all conditions.

In the 'DST' conditions schedule timelines were also displayed. The two Feeder controllers staffing sectors 201 and 203 had both a runway schedule timeline and a timeline for a location just inside the Final (202) sector (CULVE or PALAC, respectively). A Feeder controller could compare the two schedules to learn how the automation expected her flow to merge with the other Feeder controller's flow. The Final controller's display included a single runway schedule timeline (Fig. 3). The scheduling automation was configured to add a fifteen second buffer to the required time spacing between aircraft, corresponding to approximately one half nautical mile of extra in-trail spacing at the runway.

Slot markers appeared for dwelled-upon aircraft in trials with DSTs (Fig. 4). The slot marker was driven by the scheduled time of arrival for the aircraft at the runway and the nominal speed profile for the aircraft along its RNAV route. The radius of the slot marker circle represents ten seconds of flying time, so the circles grow smaller as aircraft ground speeds decrease. The ten-second value is less than the scheduling buffer, so that aircraft need not end up centered within their slot marker to have the required legal distance spacing at the runway. The slot marker configuration was unchanged from the June 2008 simulation.

Speed advisories were added to the controller DST suite for the present study. Fig. 4

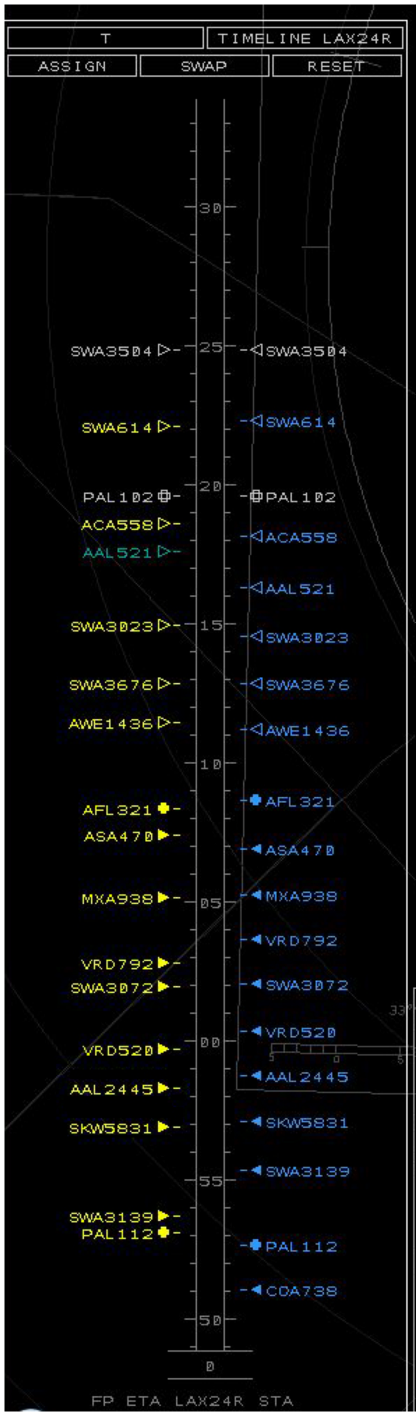

Fig. 3 LAX24R schedule timeline with aircraft wake category symbols. Estimated arrival times are shown on the left; the right side shows scheduled times of arrival, with the wake category symbols filled in for aircraft with 'frozen' scheduled times.

also shows an example of a speed advisory that would appear when the aircraft was expected to arrive outside its slot marker. The advisory was

Fig. 4 Slot marker with nominal charted profile speed ("280") displayed in green, and speed advisory in the third line of the data block.

formulated as a speed to fly before decelerating to meet a charted speed restriction at a waypoint, with nominal charted speeds thereafter (e.g., "Maintain 265 kts, cross BAYST at 240 kts, then charted speeds"). The advisory algorithm attempts to find a speed to fly to the next waypoint, and failing that, to the subsequent waypoint. The speed advisory semantics did not match the behavior of the pseudo-pilot controls precisely, leading to advisory clearance execution inaccuracies; these effects may have influenced the observed spacing conformance.

Finally, in trials that explored off-nominal operations, the arrival planner could data-link trial-planned trajectories to aircraft in order to partially absorb large delays that could be difficult to absorb with speed alone. Fig. 5 shows a trial plan trajectory for an aircraft that has been handed off to the arrival planner outside the terminal-area boundary. For reference, two waypoints inside the terminal were identified that would provide one or two minutes of delay from the nominal route (TRTLE and HITOP, respectively, in Fig. 5).

3.6 Training

The subject controllers were all experienced with the AOL simulation environment. All but one participated in developmental simulations conducted during the DST-prototyping phase of the study, but none had used the speed advisory functionality as it was finally implemented. After an initial briefing, the controllers received

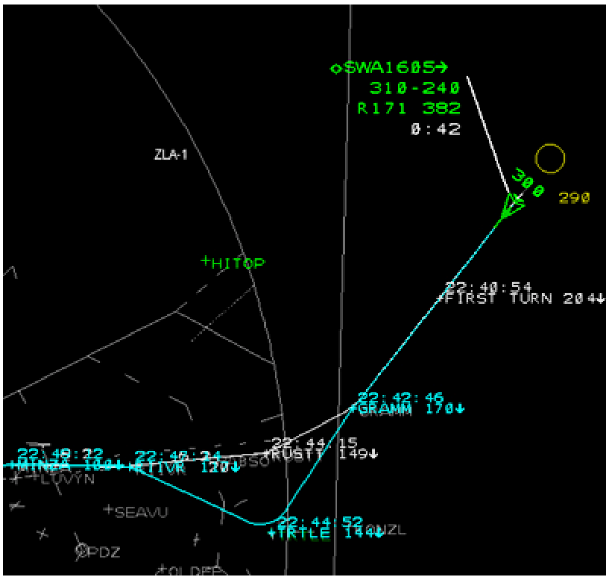

Fig. 5 Path adjustment trial plan created by arrival planner.

hands-on training for six training scenarios spanning two half-days.

During nominal operations Feeder controllers were expected to accept handoffs from the Center confederates, and clear aircraft to continue the OPD along their assigned RNAV route (e.g., "AAL123 descend via the SADDE7 arrival"). In conditions with DSTs they were then expected to consult the schedule timelines and issue speed advisories as required to keep aircraft on their assigned RNAV routes, and converging on their slot markers, before handing them off to the Final controller. Similarly, the Final controller was expected to merge the aircraft and, in conditions with DSTs, use speed advisories alone to establish aircraft inside their slot marker circles before handing them off to the Tower confederate.

4 Results

This section presents the results of the simulation. Route conformance results are followed by spacing conformance, schedule conformance, and throughput results. The section then presents on-line workload ratings and usability results gleaned from questionnaire responses for trials with nominal operations. Finally, the section briefly discusses observations from the off-nominal trials.

4.1 Route Conformance

Aircraft track data processed using TRAC show that with DSTs controllers were successfully able to delay aircraft using speed clearances while keeping aircraft on their RNAV routes. In isolated cases, controllers issued direct-to clearances to advance aircraft (Fig. 6). In trials without DSTs, however, controllers issued a large number of direct-to clearances and heading vectors (Fig. 7). The northwest Feeder took particular advantage of sector 201's enlarged size to clear a majority of aircraft direct to waypoints on the downwind legs. The Final controller then used heading vectors to perform merges as observed in current LAX operations, in some cases altering the arrival sequence from that scheduled at the start of the trial.

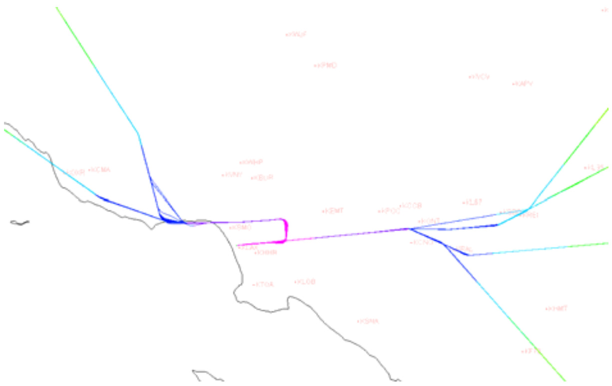

Fig. 6 Tracks for all aircraft in nominal tools conditions (color-coding represents altitude in 5,000 ft increments).

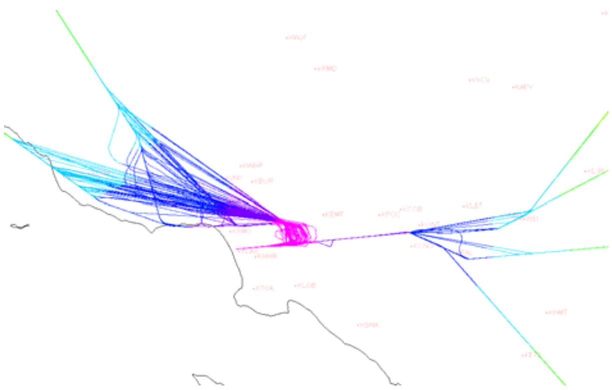

Fig. 7 Tracks for all aircraft in nominal scenarios without tools.

4.2 Spacing Conformance

Fig. 8 shows histograms (plotted as lines) for the required spacing errors observed at both the final approach fix (JETSA) and the runway (LAX24R) threshold for pairs of aircraft with and without DSTs, where errors are defined as the observed spacing less the wake vortex spacing required according to a standard 3/4/5 nautical mile spacing matrix.[1]

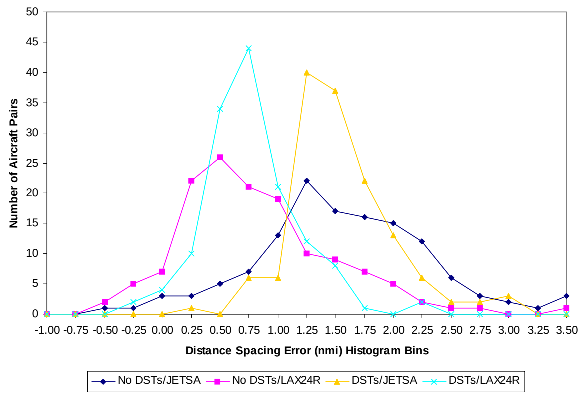

Fig. 8 Required wake vortex spacing errors measured at JETSA and LAX24R for nominal trials with and without tools.

These data show that with DSTs the Final controller was always able to achieve adequate spacing at JETSA, but the spacing sometimes deteriorated due to compression that occurred over the remainder of the approach (i.e., after the Final handed the aircraft off to the tower confederate). Figs. 9 and 10 show spacing error histograms at JETSA and LAX24R, respectively, for trials with and without DSTs in the two forecast wind errors. These plots depict similar performance measured at JETSA with DSTs in both wind conditions. All violations at LAX24R with DSTs occurred in 'Minus' wind conditions, in which aircraft had less headwind to aid deceleration along the final approach course than the automation predicted. Subjects learned how to achieve proper wake vortex spacing with the DSTs as the study progressed;

[1] Ordinate values represent the number of aircraft pairs in the bin with upper bound less than the abscissa value. For example, values plotted at 0 represent the number of pairs with spacing error greater than or equal to -0.25 nmi and less than 0 nmi (thus, values plotted at 0 or below are wake vortex spacing violations).

Fig. 11 shows that after the first trial with tools, only one violation occurred.

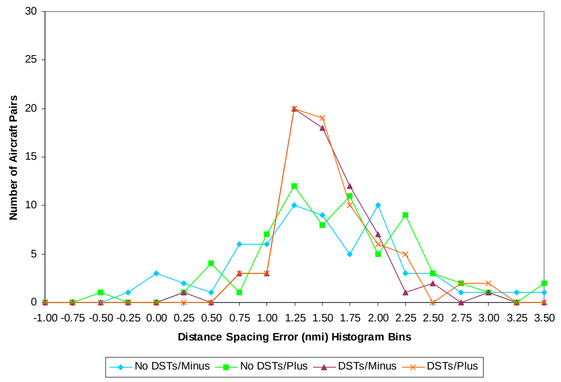

Fig. 9 Wake vortex spacing errors measured at JETSA for the different forecast wind errors.

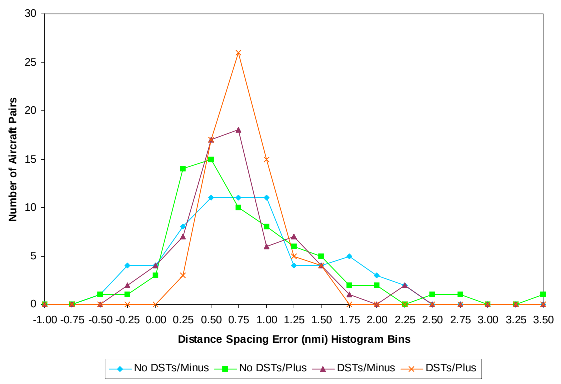

Fig. 10 Wake vortex spacing errors measured at LAX24R for the different forecast wind errors.

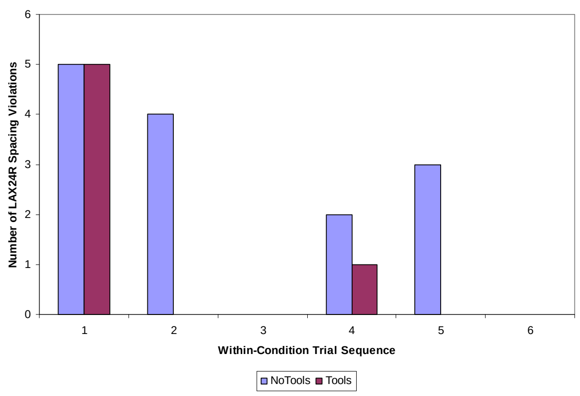

Fig. 11 LAX24R wake vortex spacing violations, by experimental trial order within the no-tools and tools conditions.

4.3 Schedule Conformance

Data were also analyzed to determine how well controllers achieved conformance to the runway arrival schedule. These data were collected in both DST and no-DST conditions, even though the slot markers and timelines were only visible to the controllers in the DST conditions. Fig. 12 shows schedule conformance with no DSTs, defined as an aircraft's estimated runway arrival time minus its scheduled arrival time (i.e., negative values indicate the aircraft is ahead of schedule) at three locations: entry to the Final sector, JETSA, and LAX24R. The plot is sorted by value within each data series for readability. Because of the large number of direct-to clearances issued by the 201 Feeder, Fig. 12 shows a large number of aircraft estimated to arrive earlier than scheduled.

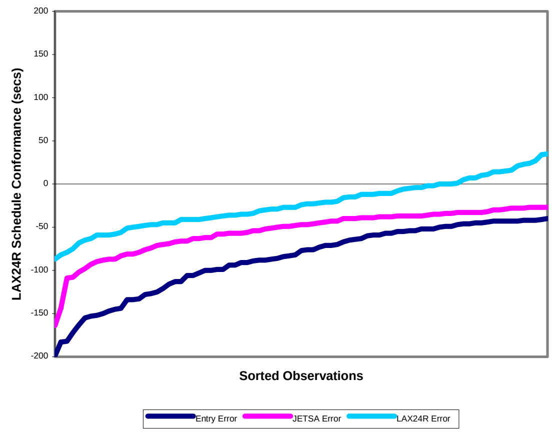

Fig. 12 LAX24R schedule conformance data recorded in the background during no-DST conditions.

Fig. 13 shows the schedule conformance with DSTs, using the same ordinate scale. Beyond the improved schedule conformance one might expect with the schedule-driven DSTs, these data show, first, that the Feeder controllers were able to use the slot markers and speed advisories to provide the Final controller with a reasonably well-conditioned flow. Second, the Final controller was also able to use the tools to further refine the schedule conformance at JETSA. However, the schedule conformance at LAX24R overall is worse than at JETSA, indicating that schedule conformance often deteriorated over the remainder of the

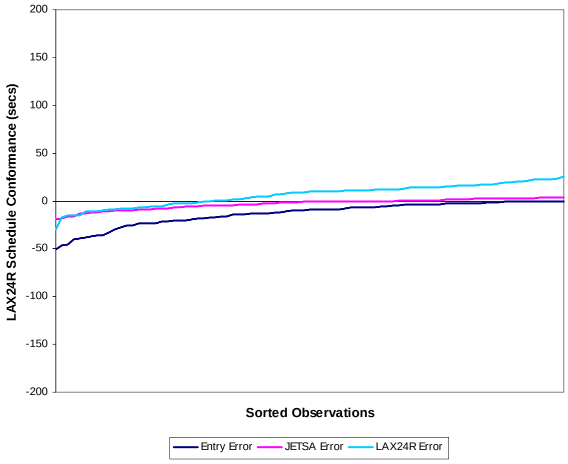

Fig. 13 LAX24R schedule conformance data recorded during DST conditions.

final approach due to final approach trajectory-prediction inaccuracies.

Correlations of the *spacing* conformance data measured for the same aircraft at JETSA and at LAX24R (Fig. 14) confirm this result. Without the DSTs, the spacing errors exhibit some positive correlation (ρ = 0.57), suggesting that the Final controller was attempting to achieve the proper inter-arrival spacing before handing the aircraft off to the tower confederate. However, with DSTs the spacing errors are poorly correlated (ρ = 0.15), suggesting that attempting to establish aircraft in their slot-marker circles at JETSA produced different relative spacing at LAX24R, again due to final approach trajectory-prediction inaccuracies.

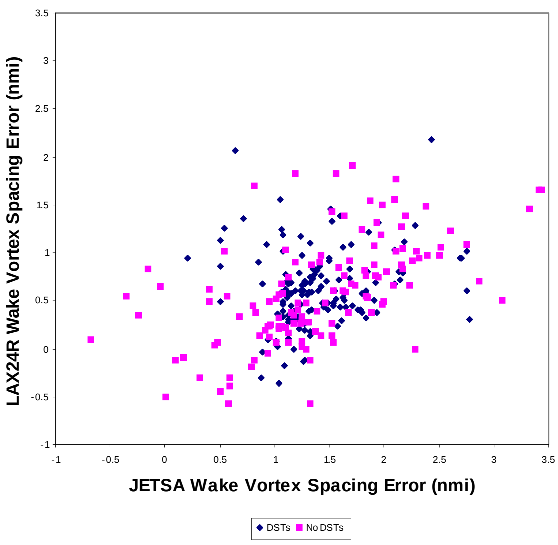

Fig. 14 JETSA vs. LAX24R wake vortex spacing error in DST and no-DST conditions.

4.4 Throughput

Despite the reduction in spacing variability observed with DSTs, average throughput did not differ significantly (α = 0.05) between trials with and without DSTs (ignoring wake vortex spacing violations). Average throughput also did not differ significantly from theoretical maximum values computed for each traffic scenario and wind condition.

4.5 Workload and DST Usability

Subjects used Workload Assessment Keypads to rate their workload at five minute intervals during each simulation trial; average workload ratings did not differ significantly in trials with and without DSTs. Controllers used all the DSTs and found them all usable with no additional workload contribution. Slot markers, speed advisories, and indicated airspeed displays were rated ‘very easy’ to use, although controllers suggested some means of displaying slot markers for multiple aircraft at once. Feeder controllers commented that they issued far fewer clearances in conditions with DSTs, and found the timelines very helpful in coordinating with each other. By contrast, without timelines the Feeder controllers simply ‘filled slots,’ coordinating verbally to the extent possible.

4.6 Off-Nominal Operations

The off-nominal trials were highly exploratory, but did demonstrate that an arrival planner could create large schedule gaps upon request by issuing path adjustments to absorb large delays. However, the slot markers for aircraft that received up-linked path adjustments continued moving along the nominal RNAV routes, limiting their usefulness to downstream controllers when the path changes were large. While the arrival planner was helpful for setting revised sequences and performing requested route adjustments, coordination was not always good, leading to mixed reviews.

5 Conclusion

A human-in-the-loop simulation of terminal-area operations with merging flows to a single runway indicated that prototype DSTs enabled controllers to keep aircraft on their assigned RNAV routes, and achieve good schedule conformance using advised speed clearances and schedule-driven slot markers. Schedule timelines aided coordination between Feeder controllers working merging traffic flows, simplifying the merge problem for the Final controller. Slot-markers also helped provide a well-conditioned flow to the Final controller. Controllers used the DSTs successfully without significantly increased workload or decreased throughput, and generally found them easy to use. The results also suggest that data-linked path adjustments may be useful for absorbing large delays.

Future simulations should attempt to improve the accuracy of trajectory predictions underpinning the DSTs, particularly in the final approach region, so that accurate schedule conformance translates consistently to accurate wake vortex spacing along the approach route. Additional DSTs that focus on spacing conformance should also be tested in conjunction with schedule-based DSTs. Under one such concept the Final controller would use schedule-based DSTs to merge aircraft on the final approach, then use relative spacing DSTs to establish inter-arrival spacing.

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