CHAPTER XX

Evaluation of the Terminal Area Precision Scheduling and Spacing System for Near-Term NAS Application

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ABSTRACT

NASA has developed a capability for terminal area precision scheduling and spacing (TAPSS) to provide higher capacity and more efficiently manage arrivals during peak demand periods. This advanced technology is NASA's vision for the NextGen terminal metering capability. A set of human-in-the-loop experiments was conducted to evaluate the performance of the TAPSS system for near-term implementation. The experiments evaluated the TAPSS system under the current terminal routing infrastructure to validate operational feasibility. A second goal of the study was to measure the benefit of the Center and TRACON advisory tools to help prioritize the requirements for controller radar display enhancements. Simulation results indicate that using the TAPSS system provides benefits under current operations, supporting a 10% increase in airport throughput. Enhancements to Center decision support tools had limited impact on improving the efficiency of terminal operations, but did provide more fuel-efficient advisories to achieve scheduling conformance within 20 seconds. The TRACON controller decision support tools were found to provide the most benefit, by improving the precision in schedule conformance to within 20 seconds, reducing the number of arrivals having lateral path deviations by 50% and lowering subjective controller workload. Overall, the TAPSS system was found to successfully develop an achievable terminal arrival metering plan that was sustainable under heavy traffic demand levels and reduce the complexity of terminal operations when coupled with the use of the terminal controller advisory tools.

Keywords: terminal metering, arrival scheduling, controller decision support tools, air traffic control automation

1 INTRODUCTION

The nation's future air transportation system, known as the Next Generation Air Transportation System (or NextGen), is being designed to handle the predicted increases in traffic volume and to improve the capacity, efficiency and safety of the National Airspace System (NAS). NextGen goals include expanding the capacity of high-demand airports, while maintaining the efficiency of arriving aircraft.[1] Arrivals into high-density airports experience significant inefficiencies resulting from use of Miles-in-Trail procedures, step-down descents, and excess vectoring close to the airport. Use of these current procedures contributes to reducing airport capacity, increasing controller workload, increasing arrival delay, as well as increasing fuel burn, emissions and noise.[2]

NASA has developed a capability for terminal area precision scheduling and spacing (TAPSS) to increase the use of fuel-efficient arrival procedures during periods of traffic congestion at high-density airports. The TAPSS system is a 4-D trajectory-based strategic and tactical air traffic control (ATC) decision support tool (DST) for arrival management. In this concept as originally developed,[3] arrival aircraft are assigned optimized Area Navigation (RNAV) Standard Terminal Arrival Routes (STAR) prior to top-of-descent (TOD) with routing defined to a specific runway. The Precision Scheduler in the TAPSS system then computes an efficient schedule for these aircraft that facilitates continuous descent operations through the routing topology from TOD to landing. To meet this schedule, controllers are given a set of advisory tools to precisely control aircraft.

The TAPSS system was tested in a series of human-in-the-loop (HITL) simulations during the Fall of 2010 to evaluate the integrated performance of the precision scheduler and control tools. Results show a reduction in the complexity of terminal area operations, which in turn helps increase airport throughput without negatively impacting the environment. The performance of the TAPSS system over current operations was found to achieve up to a 10% increase in airport throughput with reduced controller workload.[3,4] The TAPSS advisory tools also resulted in aircraft maintaining continuous descent operations longer and with better scheduling conformance, under heavy traffic demand levels.[5] These previous HITL simulations explored the benefits of using the TAPSS system, with experiment assumptions made such that the operations concept could be deployable in 5-10 years. The TAPSS system, however, could provide benefits in the near-term (i.e., 3-5 years.)

This paper will focus on the results from a study performed in 2011 that evaluates the performance of the TAPSS system for near-term NAS application. The main research objective is to assess the TAPSS system under terminal routing infrastructure that more closely resembles current practices. The secondary objective of the study is to determine the incremental benefits gained when using the advisory control tools versus simpler control advisories. For comparison, metrics used to evaluate performance will be the same as previous HITL experiments. The paper is organized as follows: The next section describes the TAPSS operational concept and system. Section 3 details the experimental setup of the human-in-the-loop simulations. Results from the simulations are then discussed in section 4, which first discusses the evaluation of the TAPSS system under current procedures and then examines the benefit of each controller advisory tool. Section 5 concludes with a summary of key findings and plans for further research.

2 TERMINAL AREA PRECISION SCHEDULING AND SPACING SYSTEM OPERATIONAL CONCEPT

The TAPSS system is used for integrated arrival management between the Air Route Traffic Control Center (Center) and Terminal Radar Approach Control (TRACON) airspace. The TAPSS system consists of two major capabilities: 1) the time-based Precision Scheduler[6-7] and 2) the controller advisory tools. Arrivals are managed by the TAPSS system starting in Center airspace approximately 200 nmi from the airport. The Precision Scheduler provides the arrival sequence, scheduled times of arrival (STAs), runway assignments, and delay. Center controllers use this information to assign each arrival its RNAV STAR ending at its assigned runway. They are given an advisory tool, the Efficient Descent Advisor (EDA), to provide speed and path-stretch advisories to meet the meter fix STAs.[8-10] TRACON controllers are also given a set of advisory tools, called the Controller Managed Spacing (CMS) tools, which provide slot marker circles, speed advisories, early/late indicators, and timelines to meet STAs to meter points in the terminal area.[11-13] Flight crews fly VNAV (Vertical NAVigation) descents along the RNAV approach and follow any controller clearances.

3 EXPERIMENT DESIGN

3.1 Simulation Environment

The HITL simulations were conducted during the Fall of 2011 at NASA Ames Research Center using the Multi-Aircraft Control System (MACS) simulation platform.[14-15] MACS provides high-fidelity display emulations for air traffic controllers/managers as well as user interfaces and displays for confederate pilots, experiment managers, analysts, and observers. MACS also has flight deck capabilities that simulate current-day flight technologies that allow controllers to issue ATC clearances. The Center and TRACON controllers worked with operational emulations of radar displays. The Aeronautical Datalink and Radar Simulator (ADRS) served as a communication hub to provide the networking infrastructure that allowed the necessary information to be transferred between the precision scheduler and controller advisory tools.

3.2 Airspace

Los Angeles International Airport (LAX) arrivals were modeled using the West flow runway configuration with runways 24R and 25L runway under Instrument Meteorological Conditions (IMC). Figure 1 illustrates the STARs modeled in the simulation. The RIIVR and SEAVU STARs are used by Westbound traffic, accounting for more than 50% of the arrival traffic. These arrivals may be assigned to either 24R or 25L as determined by the Precision Scheduler runway balancing algorithms. Approximately a third of the traffic arrives on the KIMMO and SADDE STARs and only use runway 24R. The rest of the arrivals from the South are always assigned runway 25L. Arrivals into LAX currently have an aircraft mix of approximately 85% jets.

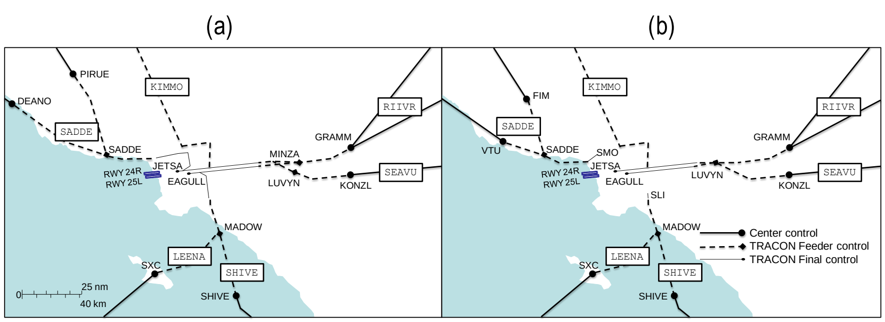

Figure 1. Simulation airspace depicting (a) previous and (b) modified arrival routes.

The simulation airspace is segregated into two main areas of control: Los Angeles Center (ZLA) and Southern California (SoCal) TRACON. Figure 1 shows the portion of the arrival route each of these areas was responsible for, along with their associated metering points. The ZLA controllers were responsible for managing each LAX arrival starting approximately 70 miles before its TOD and ending at its entry into terminal airspace located near the meter fixes. For simulation purposes, several of these sectors were combined so that three Center controllers were responsible for the Northwestern (i.e., DEANO and PIRUE), Eastern (i.e., GRAMM and KONZL) and Southern (i.e., SXC and SHIVE) STARs. Likewise, three TRACON Feeder controllers handled the next section of the route from the

Northwestern (SADDE), Eastern (MINZA and LUVYN) and Southern (MADOW) arrival flows. The TRACON Feeder controller managing the Southern flows also controlled aircraft on the KIMMO STAR. The last aircraft hand-off is given to one of the two TRACON Final Controllers managing final spacing to LAX runways 24R and 25L respectively.

HITL simulations were conducted using a modified version of the terminal routing infrastructure to better model current operations. The previous route design is shown in Figure 1a, and Figure 1b illustrates the following changes:

- *The SADDE STAR starts at VTU and FIM.* The Center controller responsible for the SADDE arrivals previously used DEANO and PIRUE as the meter fixes into the terminal area. The TRACON boundary was relocated to its actual location closer to LAX, where FIM and VTU are the meter fixes.
- *The SADDE STAR ends at SMO, then arrivals are given heading 070 and the expected runway. The SHIVE and LEENA STARS ends at SLI, then arrivals are given heading 320 and the expected runway.* Previous simulations operated under the assumption that all arrival routes had complete RNAV routing directly transitioning to a Standard Instrument Approach Procedure (SIAP), which defines a series of predetermined maneuvers for the orderly transfer of an aircraft under IMC from the beginning of the initial approach to a landing. However, many published RNAV routes end with a specified heading near the TRACON boundary. Aircraft are then instructed to expect vectors onto the final approach.
- *Arrivals on the GRAMM and SEAVU STARs merge at LUVYN.* Past studies assumed independently operating runways, 24R and 25L. That is, arrivals on the RIIVR and SEAVU STARs were able to fly ‘side-by-side’ when landing on separate runways. Actual operational procedures prohibit such procedures and require these arrivals to be staggered by at least the wake separation minima until the final “capture box.” LUVYN was used as a metering point for the GRAMM and SEAVU arrival flows. Thus, having the GRAMM and SEAVU arrivals merge at LUVYN allowed the Precision Scheduler to incorporate the necessary spacing.

3.3 Scenario

The simulation scenarios were based on current LAX traffic characteristics with approximately 60 minutes of traffic starting outside the Center boundary. Current airport arrival demand ranged from 55-72 aircraft per hour. Two scenarios were created, one with current LAX arrival-demand levels and the second with baseline arrival demand increasing 10%. For each level of demand, two variations of the scenarios were created with different call signs and start times.

3.4 Test Conditions

To investigate whether using the TAPSS system could be beneficial for the current airspace structure, simulations were conducted using the modified routes that closely match today's current LAX arrival operations and compared with those using the original routing from past simulations. These test conditions are labeled 'Mixed RNAV' (i.e., Case 2) and 'Full RNAV' (i.e., Case 1) respectively. To evaluate the benefit of the controller advisory tools in the 'Mixed RNAV' condition, simulations were run with different tools available for use and labeled 'All/Partial/No Tools' (i.e. Case 2-5.) accordingly. All test cases ran with scenarios having the baseline demand level and the traffic demand increased by 10%. The experimental matrix is presented in Table 1.

Table 1. Experiment matrix.

Each case ran with two scenarios with demand levels: 1) Baseline and 2) Baseline +10%.

		Tools Available				
		Center	*TRACON*			
	RNAV	EDA	Timelines	Early/Late Indicator	Slot Marker	Speed Advisory
CASE 1: All Tools	Full	✓	✓	✓	✓	✓
CASE 2: All Tools	Mixed	✓	✓	✓	✓	✓
CASE 3: TRACON All Tools	Mixed		✓	✓	✓	✓
CASE 4: TRACON Partial Tools	Mixed		✓	✓		
CASE 5: No Tools	Mixed					

3.5 Controller and Pilot Procedures

Eight controllers participated simultaneously to cover all positions and had experience using the TAPSS system from prior HITL simulations. All participants were recently retired (within the previous 2 years) from either SoCal TRACON or Los Angeles Center and had an average of 20 years of ATC experience.

The Center controller responsibilities included assigning the expected runway and STAR clearance prior to TOD for each aircraft in its sector, and ensuring that the aircraft met the STA at the meter fix. Pseudo pilots verified the STAR in the aircraft FMS display panel along with the appropriate runway. The Center controllers then either followed the EDA advisories (when available in Case 1 and 2) or used their own techniques to control aircraft to meet the meter fix STA using the delay countdown timer displayed next to the aircraft symbol shown in seconds. Next, the TRACON Feeder controllers received the aircraft from the Center controller and controlled to the meter points within their sector referencing the advisory tools available. Lastly, the Feeder controllers handed off the aircraft to the appropriate TRACON Final controller responsible for proper spacing to the runway. In the 'Mixed RNAV' case, the arrivals on the SADDE STAR were given to 24R Final controller on a set heading. It was the responsibility of the 24R Final controller to determine when to turn the aircraft from its downwind leg onto final. Controllers were encouraged to use vectoring as a last resort, utilizing speed control foremost to manage the arrival traffic.

4 RESULTS

The full use of the TAPSS system (i.e., the ‘All Tools’ case) is evaluated under the current routing infrastructure by comparing the scenarios using the modified routes (i.e., Case 1: ‘Mixed RNAV’) and the original routes (i.e., Case 2: ‘Full RNAV’). The Center and TRACON advisory tools are evaluated next under the ‘Mixed RNAV’ cases, by measuring the system performance in the absence of using a subset of the tools (i.e. Case 2-5.). For illustration purposes, the scope of this paper shows results for one scenario with its baseline demand level increased by 10%. These results are representative of the data trends observed in both variations of the scenarios used in the simulation.

4.1 Mixed RNAV Procedures

The lateral paths of all jets in the scenario are shown in Figure 2. Figures 2a and 2b show the results when using the original routes (i.e., Case 1: ‘Full RNAV-All Tools’) and the modified routes (i.e., Case 2: ‘Mixed RNAV-All Tools’) respectively. The terminal area is magnified in Figures 2c and 2d for the Full and Mixed RNAV cases.

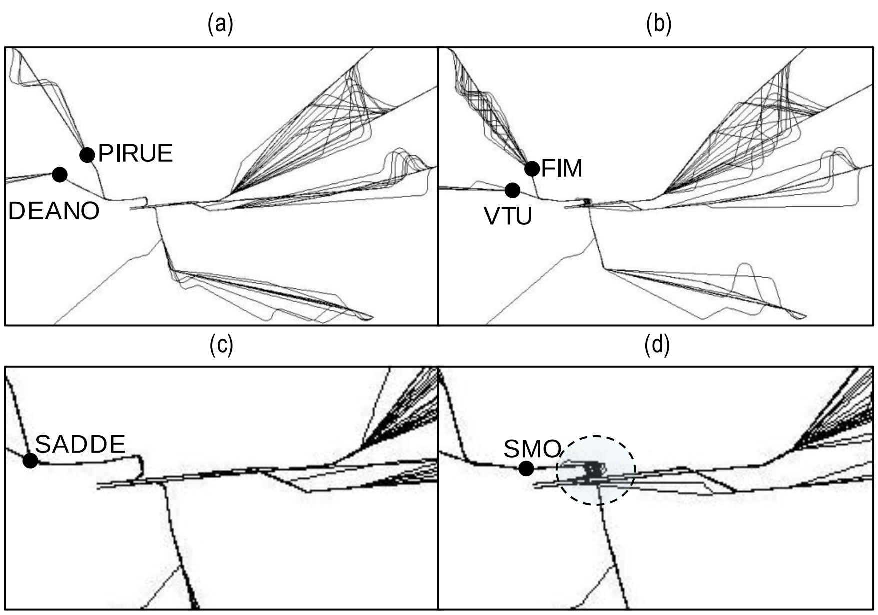

Figure 2. Lateral tracks for (a) Full and (b) Mixed RNAV-All Tools condition and corresponding magnified terminal area in (c) and (d).

Figures 2a and 2b indicate that arrivals are primarily vectored prior to the meter fixes, where the majority of the delay is absorbed at the Center level. There is noticeably more vectoring on Northwest arrival flows via SADDE in the Mixed RNAV case. Figure 2d also shows the ‘tromboning’ of the base leg in the Mixed RNAV case due to arrivals assigned a heading after SMO until further clearance. The throughput in both situations was found to be similar, where up to an 84 hourly arrival rate was sustained for an extended period. There are higher amounts of delay overall in the Mixed RNAV case, with larger differences in the Western arrival flows. The Mixed RNAV arrival flows via VTU and FIM have twice the amount of scheduled delays when compared to the Western flows via DEANO and PIRUE in the Full RNAV case.

The controllers were instructed to primarily use speed adjustments to absorb the scheduled delay. Excessive delay, however, may require path stretch maneuvers. Figure 3 shows the number of arrivals having flight path deviations that are more than 2.5 nm from their prescribed route in Center airspace and similarly, more than 1 nm deviation in the terminal area. Results indicate a greater number of off-route arrivals from the West (i.e. PIRUE/FIM), which is consistent with the amount of scheduled delay.

(a) (b)

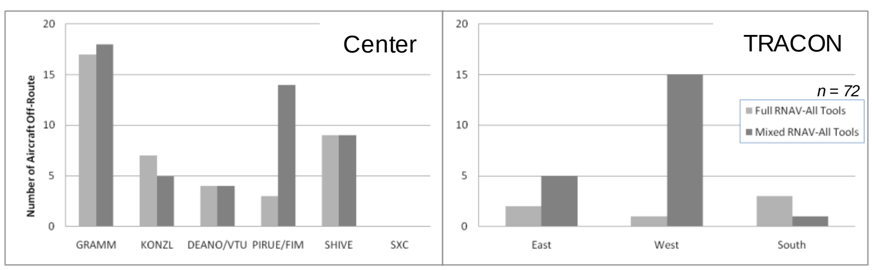

Figure 3. Number of aircraft off-route for Full and Mixed RNAV-All Tools test conditions in the (a) Center and (b) TRACON area.

The controller’s ability to absorb the amount of scheduled delay (i.e., conform to the STA) is measured by examining the difference between the actual time-of-arrival (ATA) and the STA for each aircraft. The schedule conformance in the Mixed RNAV case varies in precision performance when compared to the Full RNAV case. Differences were within ±15 seconds and within the scheduling buffer used by the TMA scheduler to account for uncertainties in the system.

Workload data were collected in post-run questionnaires using the rating portion of the NASA TLX.[16] Controllers rated their level of workload on a scale from 1 “very low” to 7 “very high.” The ratings were organized by the study condition and a mean was calculated for each

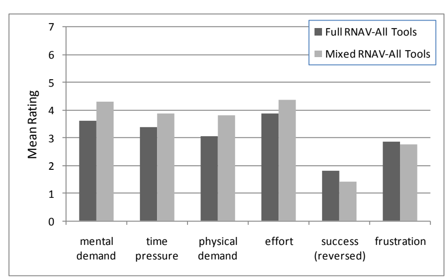

Figure 4. Mean ratings for TLX sub-scales in Full and Mixed RNAV-All Tools test conditions.

TLX subscale. The mean ratings for the Full and Mixed RNAV conditions are compared in Figure 4. The Mixed RNAV condition has the highest mean rating on every scale (success is reversed so the lower mean indicates higher success) except frustration. That is, participants rated the Mixed RNAV condition as having higher load on average but at the same time being more successful. However, the controller's average reported load is less than or close to 4, which is the midpoint of the scale, and so can be considered "manageable." These six pairs of ratings were compared using a Wilcoxon Signed rank test for non-parametric statistics. Participants' ratings on all the scales of the TLX were not significantly different between these two conditions.

The workload for the Final controllers was of particular interest. Their ratings were separated from the other controllers' ratings and compared. The comparison between the means of the Full and Mixed RNAV conditions is the same for the Final controllers as for the whole group of eight controllers. That is, the means for all the TLX subscales except frustration are higher, but not significantly higher, for the Mixed RNAV condition as seen in Figure 4. A point of interest is the differences between the 24R Final and the 25L Final controllers' ratings. The latter rated his/her workload lower under both conditions than the 24R Final. This could be a result of individual differences but also could indicate that the 24R Final was busier, possibly due to the complicated vectoring at the downwind turn to final from the SADDE and KIMMO arrivals. A second point of interest is the frustration scale, where both Finals consistently rated the Full RNAV condition as more frustrating than the Mixed RNAV condition. This could be due to controllers feeling more comfortable with practices that reflect current operations.

4.2 Center Advisory Tool

To evaluate the performance of EDA, three cases were run using using the TAPSS system without EDA (i.e., Case 3-5) and then compared with the Mixed RNAV-All Tools case (i.e., Case 2.) Figure 5 shows the average schedule conformance (i.e., ATA – STA) at the meter fix for each test condition. Controllers were able to meet the schedule more precisely without the use of EDA, with overall differences less than 15 seconds. The accuracy in EDA operations is limited to the corrective advisory tolerance, which was set to 20 seconds. The slight improvement in schedule conformance precision is possibly attributed to the delay countdown timer being displayed and updating in the resolution of seconds, thus allowing Center controllers to monitor performance in real-time.

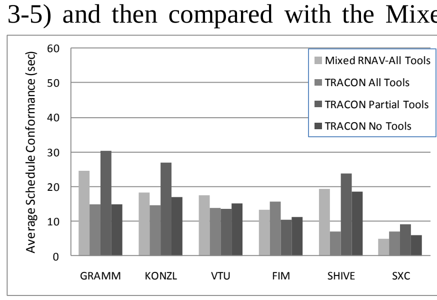

Figure 5. Average schedule conformance at each meter fix when using EDA (i.e., Mixed RNAV-All Tools) and without (i.e., all other test conditions).

When examining the number of flight path deviations that are more than 2.5 nm from their prescribed route in Center airspace, the use of EDA did increase the number slightly. This is due to the EDA tool advising path maneuvers taken at higher altitudes, which is calculated to be more fuel efficient. These path maneuvers at high altitudes will result in larger deviations because of higher ground speeds.

The average workload ratings given by Center controllers were calculated for each TLX subscale and compared in Figure 6. Center controllers reported the highest mean ratings on every scale in the Mixed RNAV-All Tools case, where they had the EDA tool available. That is, Center participants rated the condition where they had tools to use as having the highest load and feeling the least successful. However, when these ratings were compared using a Friedman two-way ANOVA for non-parametric statistics, there were no significant differences between them.

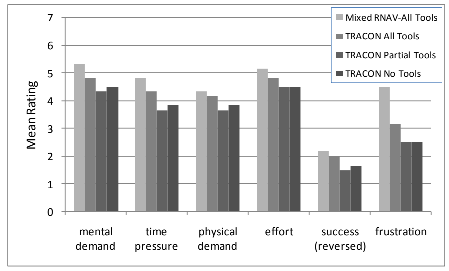

Figure 6. Mean ratings for TLX sub-scales for Center controllers.

The mean ratings that have the largest difference were given for the frustration query, where the mean for the Mixed RNAV-All Tools condition was 4.5 and the combined rating was 2.7 for the runs where EDA was not used. Participant comments suggested that when EDA was in use, they were not able to receive an advisory for delays less than 20 seconds due to the corrective advisory tolerance set to 20 seconds. Controllers were then frustrated that the delay countdown timer was not closer to zero, and they attempted to achieve better precision in cases where EDA was not in use.

4.3 TRACON Advisory Tools

The CMS tools were also examined similarly, by comparing the Mixed RNAV-TRACON All, Partial and No Tools conditions (i.e., Case 3-5). Figure 7 shows the average schedule conformance at the terminal meter points for each test condition. The average schedule conformance improves when the CMS tools were used. Better performance is seen when the entire set of CMS tools is in use versus a subset of tools.

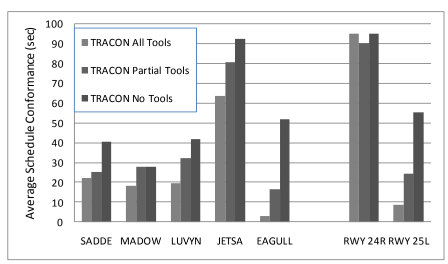

Figure 7. Average schedule conformance at each terminal metering point when using various subsets of the CMS tools.

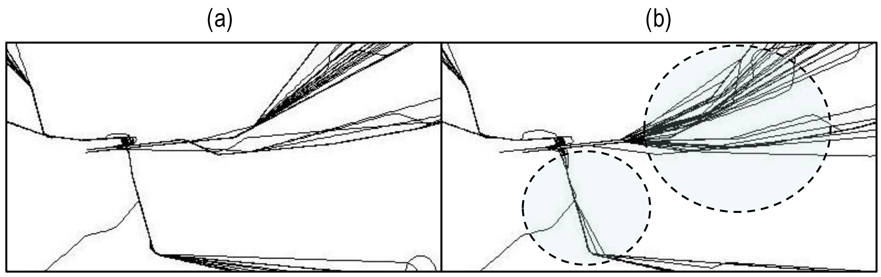

Figure 8. Lateral tracks in the terminal area for the TRACON (a) All Tools and (b) No Tools test conditions.

The lateral tracks in the terminal area for the TRACON All and No Tools case is shown in Figure 8. Although the TAPSS scheduler was used in all conditions, having performance monitoring tools reduces the variation in the lateral paths as highlighted in Figure 8. As a result, a more orderly flow is maintained in the terminal area, which facilitates high throughput to the runways.

Figure 9 shows the number of arrivals having flight path deviations that are more than 1 nm from their prescribed route in the terminal area. The No Tools condition has more arrivals off route, especially from the East side. This occurs less often when any of the CMS tools are in use.

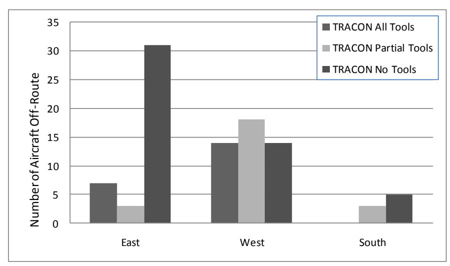

Figure 9. Number of arrivals having flight paths deviating more than 1 nm from prescribed route.

The workload analysis described in the previous section for the Center positions was repeated for the TRACON positions. The mean ratings for the TRACON controllers for the Mixed RNAV-TRACON All/Partial/No Tools conditions are compared in Figure 10. TRACON controllers reported their workload increased, on average, as the tools they had available decreased. Their highest mean workload ratings on all the TLX scales were for the No Tools condition and their lowest mean workload ratings were for the TRACON All Tools condition, where the Centers did not have tools but they did. These differences are not significant for the physical demand, success or frustration scales but are significant at the P<.05 level for the mental demand, time pressure and effort scales. As an example, the mental demand ratings showed significant differences ($F(3,9) = 8.51$, $p=.037$), and post hoc tests indicated that the No Tools condition was reported as imposing

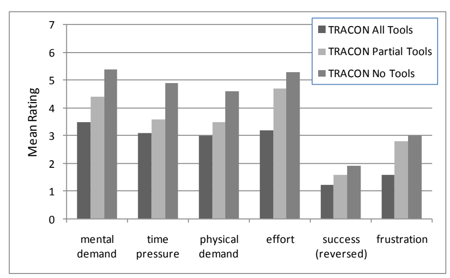

Figure 10. Mean ratings for TLX sub-scales for TRACON controllers.

greater mental demand than the TRACON All Tools condition. These differences among conditions may also account for the significant differences in the time pressure and the effort scales.

5 CONCLUSION

NASA developed a capability for terminal area precision scheduling and spacing (TAPSS), which was tested in a series of high-fidelity HITL simulations at NASA Ames Research Center. The HITL experiments evaluated the performance of the TAPSS system for near-term implementation by using the current-day routing infrastructure to validate the feasibility of the operational concept. The benefit of the controller advisory tools was also measured to help prioritize the requirements for controller radar display enhancements.

Simulation results indicate that using the TAPSS system provides benefits under current operations, supporting a 10% increase in airport throughput. The EDA tool had limited impact on improving the efficiency of terminal operations, but did provide more fuel-efficient advisories to achieve scheduling conformance within 20 seconds in the Center. The CMS tools were found to provide the most benefit, by improving the precision in schedule conformance to within 20 seconds, reducing the number of arrivals having lateral path deviations by 50% and lowering controller workload. Overall, the TAPSS system was found to develop an achievable arrival metering plan that was sustainable under heavy traffic demand levels, and to reduce the complexity of terminal operations when coupled with the use of the terminal controller advisory tools.

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