

# EFFECTS OF SCHEDULING AND SPACING TOOLS ON CONTROLLERS' PERFORMANCE AND PERCEPTIONS OF THEIR WORKLOAD

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## Abstract

A human-in-the-loop simulation of an integrated set of time-based automation tools that provided precision scheduling, sequencing and ground-based merging and spacing functions was run in the fall of 2010. These functions were combined into the Terminal Area Precision Scheduling and Spacing (TAPSS) system. TAPSS consists of a scheduler and two suites of advisory tools, one for the Air Route Traffic Control Center (ARTCC, or Center) and one for Terminal Radar Approach Control (TRACON) operations. Both suites are designed to achieve maximum throughput and controllability of traffic. The subject airspace was the terminal area around Los Angeles airport (LAX) and the en route space immediately beyond. Scenario traffic was based on the demand from today's heavy arrival periods, and traffic levels were simulated that matched these or added five, ten or twenty percent to this amount. Eight retired, highly experienced controllers worked two final, three feeder and three en-route positions to deliver traffic to the two outboard arrival runways at LAX (24R and 25L). Although the main research question was whether controllers could safely control the traffic, their level of performance was also of interest and how the advanced tools facilitated or hindered their tasks. The results show that the TAPSS tools enabled higher airport throughput and a larger number of continuous descent operations from cruise to touchdown for the jet aircraft in the scenarios. This contrasts sharply with the "current day" operations in which the Center controllers utilize step-down descents to meter the aircraft. Reported workload levels were lower in the "TAPSS tools" condition than in the "current-day" condition and the TAPSS operations earned cautiously acceptable ratings, indicating the prototype tools have value.

The goals of the next generation air transportation system in the United States (NextGen) [1] include maintaining a high level of throughput at airports and improving the efficiency of traffic management in dense terminal areas. The efficient scheduling and control of aircraft from cruise to touchdown during congested periods is a highly complex problem due to many factors including mixed equipage, constrained maneuvering space and inherent system uncertainties [2]. Ongoing research both in the USA (NextGen) [3, 4] and Europe (Single European Sky Air Traffic Management Research) [5, 6] aims to develop trajectory management tools enabling aircraft to execute efficient descents, while simultaneously maintaining throughput that will use (close to) current system capabilities.

NASA is investigating a concept for high-density arrival operations [2]. Two of its key elements are *i)* precision scheduling along routes and *ii)* merging and spacing control functions. Currently, uncertainty in runway arrival estimation, and therefore also control, limits the utility of air traffic control (ATC) scheduling but the theoretical advantage of a precision scheduling and control system for managing these constrained resources is well understood [2, 7].

An extension to the Center/TRACON Automation System (CTAS) [8] technologies currently under development is the Terminal Area Precision Scheduling and Spacing (TAPSS) system [9], which leverages the increase in prediction accuracy of emerging trajectory management tools such as Area Navigation (RNAV) and trajectory-based operations (TBO). TAPSS is a trajectory-based strategic and tactical planning and control tool capable of trajectory prediction, constraint scheduling and runway balancing, controller advisories and flow visualization. TAPSS enables a simultaneous execution of efficient descent procedures along

precision RNAV approach routes as a way to achieve high runway throughput.

The sections following in this paper briefly describe the TAPSS, a human-in-the-loop (HITL) simulation to test the prototype system, and some selected results.

## **The Terminal Area Precision Scheduling and Spacing System**

The TAPSS system is founded on precision time- and trajectory-prediction algorithms that provide precise estimates of the future time-parameterized path (4D trajectory) of every aircraft in the traffic sample. Trajectory prediction is carried out by two separate modules: the route analyzer (RA) and trajectory synthesis (TS) [10, 11]. Based upon user-generated and site-specific adaptation routing logic and heuristics, the RA generates a two-dimensional path from an aircraft's current position to each eligible runway at the aircraft's final destination. The TS couples this two-dimensional path with the aircraft's current energy state and atmospheric data to calculate a fuel-optimal four-dimensional trajectory using aircraft-specific mathematical performance models. Estimated times of arrival (ETAs) for specific points are extracted from this trajectory. This, coupled with tools to assist controllers to manage traffic to these schedules, is the basis for the TAPSS.

Scheduling is accomplished as a multi-step process:

1. An initial schedule is generated to each of the meter fixes.
2. The aircraft sequence is determined based upon the earliest ETA to the meter fix and the scheduling algorithm does this using a modified functional logic of the first-come-first-served (FCFS) principle.
3. The first aircraft in the sequence is scheduled at its earliest ETA.
4. The next aircraft in sequence is scheduled to its earliest ETA or the time necessary to ensure in-trail separation constraints are met. The in-trail separation constraints can be specified as any value at or above the minimum separation standard of five nautical miles (nmi) for similar aircraft types crossing the same meter fix to the same airport destination. Thus, an initial

separation-based schedule is established for all meter fixes. The FCFS algorithm logic is coupled with a runway-balancing algorithm that uses available runway capacity information and the Center/TRACON (Terminal Radar Control) delay distribution function (DDF) to generate the aircraft-specific Scheduled Times of Arrival (STA). Thus, schedules are created simultaneously for all three types of control points – the Center meter-fixes, runway thresholds and terminal merge-points – and are conflict-free at these points.

5. Ensure threshold separation at the runway. The threshold separation requirements are the FAA's wake vortex standards based on aircraft weight class. The scheduling algorithm selects the first aircraft from each of the initial meter fix schedules. An "order of consideration" (OOC) is generated from this aircraft group by using the ETAs to the runway threshold. The aircraft with the earliest runway ETA is selected as the first aircraft of the OOC and scheduled to the threshold using the meter fix to runway transition time. Now the next aircraft from that meter fix is added to the OOC for possible selection. It is scheduled using its meter-fix STA, transition time, and the specified threshold separation requirements.
6. Once the second and subsequent aircraft have been scheduled to the runway, whether there is a threshold separation delay can be ascertained. Separation delay is necessary whenever the STA of a trailing aircraft is modified to maintain separation standards and indicates that the runway "capacity" [12] has been exceeded. If this delay is greater than the Center/TRACON DDF, then the aircraft STAs to the meter fixes are modified by an amount exceeding the DDF. This causes modification to aircraft in-trail separation and revises the meter fix schedule. The process is repeated until all aircraft are scheduled.

### **Center/TRACON Delay Distribution Function**

As indicated above, the purpose of the DDF is to set the amount of delay that can be efficiently and economically absorbed within the TRACON airspace when runway demand exceeds capacity. The amount of delay is typically one to two minutes. An overall design consideration for TAPSS was that the delay

within the TRACON airspace be absorbed by using speed control only, thus limiting vectoring (lateral maneuvering) as a routine delay technique. Limiting vectoring also limits the low-altitude fuel inefficiency that is associated with extensive vectoring when queuing at a runway's final approach fix that results from current operations [13]. And reducing queuing has the effect that average arrival speeds are higher thus enabling an increase in overall runway throughput. All this is enabled by the expected higher precision of delivery afforded by the trajectory and speed advisory tools for controllers.

### TAPSS Controller Tools

The effects of moving to a precision scheduling system on controller functions are large. When working within TAPSS, the controller has to manage aircraft to keep them within tight time tolerances and, once the aircraft are on a Standard Terminal Arrival Route (STAR), s/he has to accomplish this primarily by speed control, using vectoring as a last resort. To assist controllers with meeting these additional requirements of controlling to tighter parameters, TAPSS incorporated two separate suites of advisory tools, one for the Center and one for TRACON operations.

#### Center Controller Advisories

The trajectory-based advisory tools used in the Center operations are based on the Efficient Descent Advisor (EDA) currently being developed for the 3-Dimensional Path Arrival Management (3D-PAM) program [3]. The EDA develops conflict-free speed and routing controller advisories to accurately and efficiently meet the meter-fix STAs. Figure 1 shows an example of an EDA advisory displayed for an aircraft in Center airspace. The advisory offers both a speed control (in cruise and in descent) and path-



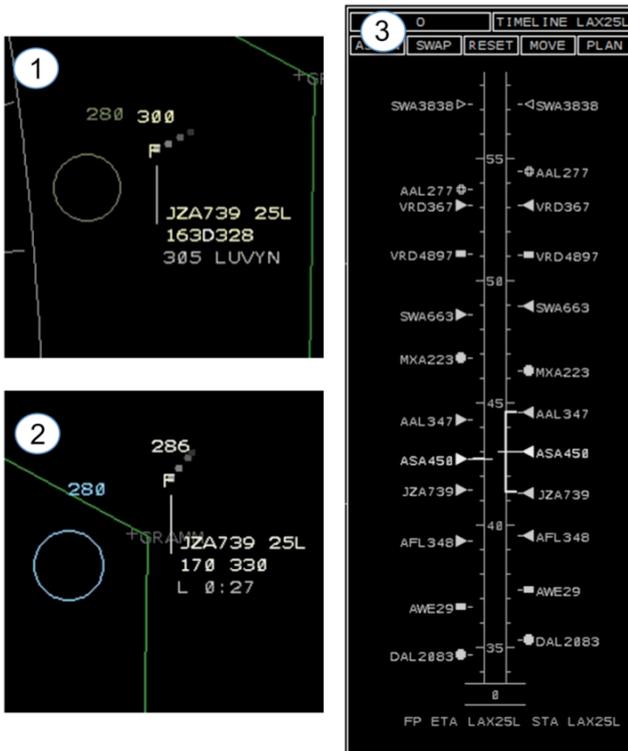
Figure 1. Example of a Center Advisory

stretch components to the resolution. Execution of such advisory components has been shown to achieve the desired delay for an aircraft to meet its meter-fix STA. The presence of an EDA advisory is indicated to the controller in a note that appears by the flight data block (FDB) of the aircraft. The details of the advisory are in an EDA window that is displayed on the controller's scope and the "target time" – the delay countdown value – is displayed in the data tag. Controllers were asked to use a procedure that issued speed and descent clearances first, so the pilot could set the vertical navigation (VNAV) panel on his/her flight management system (FMS). Routing clearances followed, along with the new "expected runway" advisory, which is required by TAPSS. These clearances provided the pilot with a profile descent that allowed him/her to set up the transition and the approach for the TAPSS issued runway. All three of the advisories in Figure 1 would have been issued after the schedule froze, approximately 20 minutes from the meter fix, which is about ten minutes from the aircraft's initial descent from cruise.

#### TRACON Controller Advisories

The TRACON controller advisory tools are based on the Controller Managed Spacing (CMS) concept [4, 14]. The suite of three tools displays information that is intended to assist the controller to issue speed resolutions to aircraft. The advisories are shown in Figure 2. Two advisories were presented, one a speed advisory displayed on the third line in the flight data block (Figure 2-1) and the other a trajectory slot marker (Figure 2-2). The speed advisory suggests an airspeed to a downstream navigation waypoint that, if followed, would deliver the aircraft to the next merge point at the STA for that leg of the arrival.

The trajectory slot marker is a type of ghosting display that presents time-based schedule information spatially on the traffic display. It indicates where an aircraft would be if it were to fly the nominal RNAV arrival route, meeting all published restrictions, and arriving on time at its STA for its next merge-point. In this study, the slot marker radius was defined to be the distance equal to 7.5s of flying time at the current nominal speed (approximately 0.25 nmi at final approach speeds). Therefore, the slot marker size decreased as the charted speed decreased. Dwelling on a FDB or an aircraft target on the timeline highlighted the aircraft's slot marker (Figure 2-2).



**Figure 2. Examples of TRACON Controller tools**

Timelines provided a graphical depiction of the relationship between the ETAs and STAs of aircraft crossing a specified location (Figure 2-3). The timelines enabled controllers to assess schedule conformance by comparing an aircraft’s ETA (on the left side) with its STA (on the right). If the ETA was ahead of the STA, the aircraft required delay. Conversely, if the ETA was behind the STA, the aircraft needed to be advanced.

## TAPSS Evaluation Methods

The TAPSS system is the first attempt to integrate EDA and CMS and was evaluated in a series of HITL simulation runs conducted in one of the ATC laboratories at NASA’s Ames Research Center. Two sets of experiments were conducted, each of a two-week duration. The objectives of the first experiment period were to establish controller-acceptable TAPSS parameters for the delay distribution function and scheduled spacing buffers, and are not covered in detail here. The second experiment period evaluated the TAPSS performance relative to current ATC operations, collecting data to assess the benefits of the TAPSS concept and operations. This study and some of its metrics are

described below. The focus of the second experiment period was the objective performance and subjective experience of expert controller-participants when they had TAPSS tools available as compared to when they had current-day tools, and how much the TAPSS tools assisted these participants to manage controlling traffic with scheduling constraints.

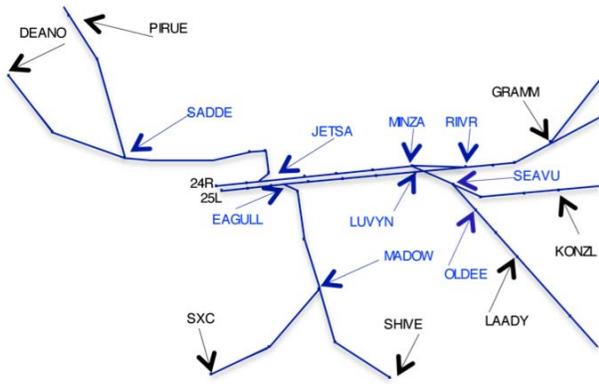
## Simulation Environment

The evaluation was conducted in a high-fidelity simulation built around the Multi-Aircraft Control System (MACS) simulation capability [15]. MACS provides an environment for rapid prototyping, human-in-the-loop air traffic simulations, and evaluation of current and future air/ground operations [16]. Simulated aircraft were assumed to be equipped with FMS and Automatic Dependent Surveillance-Broadcast-out. The MACS was used to simulate major arrival elements of the Los Angeles ARTCC (ZLA Center) and the Southern California (SoCal) TRACON around the Los Angeles International Airport (LAX). The TRACON controllers worked with an emulation of the Standard Terminal Area Replacement System [17] to which the TAPSS tools were added. The Center controllers worked with an emulation of the Display System Replacement [18] into which the TAPSS “Center” tools were integrated.

## Airspace and Route Structure

To simulate some NextGen operations, RNAV routes that enabled continuously descending approaches from Center airspace to touchdown were required. The routes that were built generally follow the flow of existing STARs and were designed using the Trajectory-Based Route Analysis and Control (TRAC) tool [19]. SoCal TRACON airspace already contains some routes with Optimal Profile Descents (OPDs) from the East [20] and Tailored Arrivals from the Southeast oceanic direction. RNAV routes suitable for continuous descent approaches were created for all routes [4]. They had a 2.4° descent angle that was sufficiently shallow to allow for speed control along the OPDs. These routes are shown in Figure 3 with the meter-fixes (black), merge-points (blue) and runways annotated.

The operation simulated the LAX arrivals in a West two-runway configuration, landing on runways 24R and 25L under Instrument Meteorological



**Figure 3. Simulated RNAV approaches to LAX**

Conditions (IMC) but with no winds. Traffic on the SADDE7 STAR was assigned to runway 24R; traffic on the OLDEE1, SHIVE1 and LEENA2 STARs to runway 25L. Traffic on the RIIVR2 and SEAVU2 STAR were allocated to both runways. The simulated ZLA Center TMA metering operations were modified such that the six TAPSS meter-fixes could be controlled by three Center controller positions, West, South, and East, which combined the 16 sectors that today work the airspace around the LAX TRACON. The controllers at these Center positions took the simulated aircraft from en-route cruise at the Center boundary to handoff at SoCal TRACON where they fed aircraft to three feeder sectors, Zuma, Feeder East, and Feeder South, and into two final sectors, Stadium and Downe. The TRACON sector boundaries were adapted slightly from the sectors that are in operation today but the layout of the sectors was fairly close to today's operation in a West configuration. The airport runs LAX traffic most often in a West configuration.

### Scenarios

Three base traffic scenarios were used in the simulation. These were taken from the Joint Planning and Development Office (JPDO) [21] baseline traffic scenarios. Each scenario covered a three-hour period that had high demand in the form of continuous arrivals. This arrival demand on the airport varied between 60 to 66 aircraft/hour and included both jet and turboprop traffic. Specific aircraft demand scenarios were generated using this arrival rate and reflecting the mix of type and direction of traffic to create simulation runs that were approximately 100 minutes long. To create conditions that simulated

future increased levels of traffic demand, these three scenarios had their demand values increased by 5%, 10% and 20%. Aircraft were added in the same proportions as they occurred in the baseline scenario to keep the same aircraft balance across the scenarios. This created a set of twelve scenarios. Thus, in the 120% traffic condition the arrival rate was 72 to 84 aircraft per hour, delivering 36 to 42 aircraft to each runway. Again, there were no winds included in the scenarios.

### Participants

Eight male controllers participated simultaneously to work all positions. All participants were recently retired (within the previous two years) from either SoCal TRACON or ZLA Center and had a mean of 28.5 years of ATC experience. The tower controller and the en-route "ghost" position, responsible for the areas surrounding the test sectors, were staffed with retired confederate controllers. Eleven pseudo-pilots, who managed the traffic and responded to controller instructions, were licensed pilots and students who were experienced in MACS operations.

### Controller Tasks

The controllers' task was to efficiently manage schedule conformance and deliver aircraft with proper spacing to the outer marker and runway. The controllers were asked to use the tools to avoid vectoring and manage the arrival traffic with speed instructions alone. The Center controller task was to accept aircraft radio check-ins from the pseudo-pilots, issue a "descend-via" clearance (e.g., descent via the RIIVR2 arrival) along the RNAV routes, and try to deliver the flights close to their STAs. The feeder controllers' task was to accept aircraft handoffs from the Center controllers, keep aircraft on the RNAV routes, and continue to deliver the flights as closely as possible to their STAs. The final controllers' task was to fine-tune the schedule conformance and ensure proper spacing at the runway. The controllers were also asked to follow the TAPSS advisories unless they felt required separation would be compromised at which point they could use any technique to ensure separation was maintained. Controllers were not given any specific instructions about how and when to use the tools, and they were free to organize their tasks as they chose. For thorough evaluations of the use of specific tools,

please refer to [22] for EDA and [14, 23] for CMS tools.

### Study Design

The independent variables of interest in this study were the availability of the TAPSS tools and the controller positions. A third independent variable that will not be discussed in the paper below, was demand from the baseline scenario through a 5%, 10% and 20% increase. Table 1 shows the main design matrix for the study. The two rows of the Table show the two main conditions: current day practices and the practices envisioned and simulated with TAPSS. A comparative study of the two is the objective of this paper. Current day practices utilized the TMA metering and current ATC radar controller capabilities, TAPSS conditions used all the TAPSS tools outlined above during the simulation. The separation buffers and DDF were set to the most controller-acceptable values established by the previous evaluation period of 0.4 nmi and “partial” DDF respectively. (The partial value of delay was defined as 70% of the difference between the typical nominal speed and the slow speed for jets and turboprops.) The conditions specified by each cell in Table 1 were repeated in separate runs at least twice.

**Table 1. Study 2 Design Matrix**

Demand	Baseline traffic	105% traffic	110% traffic	120% traffic
TAPSS tools	Yes	Yes	Yes	Yes
Current day	Yes	Yes	Yes	unable

The dependent variables of interest in this study were the effectiveness of the TAPSS tools and the way the participant-controllers used or did not use the tools to assist them, i.e., could controllers use the tools to meet the schedules at workload levels and in a way that was acceptable to them.

Prior to the experiment sufficient training runs were conducted for the participants to feel familiar with both the simulation environment and TAPSS tools. The 20% demand increase scenario could not be evaluated for the “current day” condition because the metering led to more than 30 minutes of holding

and was considered both unmanageable and unrealistic by the ZLA Center controllers.

### Data Collection

Each controller and pseudo-pilot workstation recorded a number of variables in data logs throughout every simulation run. Aircraft performance data, trajectory and flight state information as well as pilot and controller data entries were logged. Voice communications between controllers and pilots were recorded. Additionally, controller and pilot interface actions were recorded as screen capture videos.

Subjective data included observations, debriefs and questionnaire responses. Controllers completed questionnaires after each data-collection run, and a comprehensive post-simulation questionnaire prior to the final debrief session.

## Results and Discussion

A number of metrics were calculated from the objective and subjective data to compare the TAPSS system, specifically the effects of the controller tools, to current-day operations. Runway throughput increased on average by ten percent using the TAPSS tools relative to the current day operations [9]. This result sets the context for the comparison of the performance results below. For system performance, which is determined by a combination of controller actions and automation support, three metrics were selected: route conformance, schedule conformance and excess spacing at the runways. The effects of tools on participants’ perceived workload were selected as the fourth performance metric. Participants’ opinions of the way they interacted with the TAPSS tools and of the “controllability” of the system were reviewed to reflect on the four metrics above.

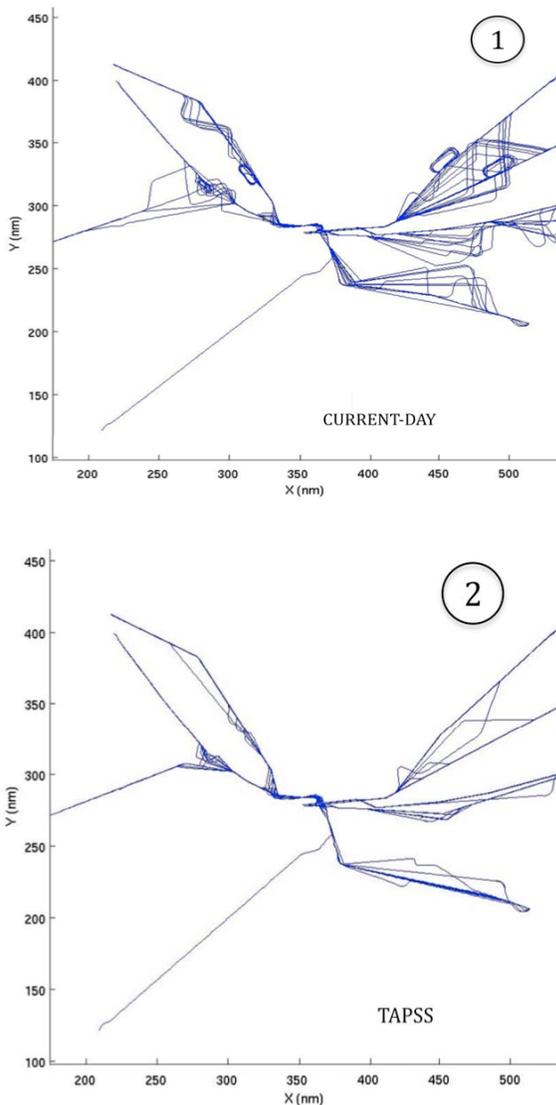
### System Performance

#### Route Conformance

In order to receive the benefits of OPDs, aircraft are required to conform to their routes with high precision. The benefits gained from TAPSS were strongly positively correlated with the accuracy of route conformance.

As an example, Figure 4 shows an overall plan-view of the simulation tracks comparing the TAPSS tools with the existing ATC capabilities for the 110%

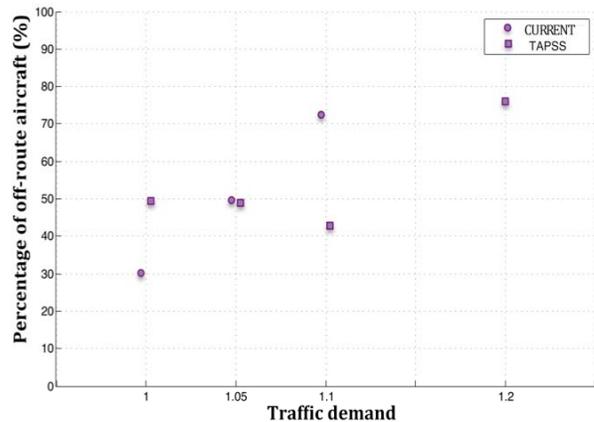
traffic condition. Both of these plots show the x-y tracks in a square area, of approximately  $400 \text{ nmi}^2$ , around the simulated LAX airport. Figure 4-1 shows the current capability and Figure 4-2 shows the operation enhanced with the TAPSS tools and technologies. In the current day condition an extensive amount of vectoring and holding is required for the operations with distinct gaps in the flow. The final also varies more erratically for the current operation as controllers managed traffic with vectoring.



**Figure 4. Simulated aircraft arrival tracks into LAX Airport, (1) with current-day tools, (2) with TAPSS tools**

Route conformance was characterized qualitatively using two metrics: percentage of traffic off-route and mean time off-route. The first metric is defined as the percentage of all aircraft that went off-route (i.e., deviated from the planned route by 2.5 nmi or farther) at any time during the simulated flight. (The 2.5nmi distance was chosen as the conformance value to be somewhat smaller than the FAA’s on-route definition of 4nmi when aircraft are flying routes between VORs that are less than 102nmi apart.) The second metric is defined as the mean time spent by an aircraft off-route (i.e., 2.5 nmi or farther from the planned route). The computed values of each metric plotted against traffic demand (for both current day and TAPSS operations) are shown in Figures 5 and 6.

Figure 5 shows in the current operations with the baseline demand there are a higher percentage of aircraft on-route than in the TAPSS conditions. This trend changes as the demand increases from 1.05x to the 1.1x demand condition. The metric is much more sensitive to variations in Center procedures. The Center procedures for the current operations at low delay levels were step down level-offs whereas the TAPSS used speed and route control to maintain the traffic on its optimized vertical descents. Thus, the small scheduled delays in the 1.0x current-day traffic conditions may appear to keep the aircraft “on-route”, but as traffic demand grows this result changes significantly to where in the 1.1x condition more than 80% of the current operations were off-route.



**Figure 5. Route conformance**

Figure 6 shows the second metric and shows trends similar to those of the first metric, with less time off-route in the 1.0x current day conditions and a significantly greater time as the level of traffic increases. As can be seen from both Figures 5 and 6, use of the TAPSS tools enabled the controllers to maintain the aircraft on-route more often and to return aircraft to the route more quickly when they had to be taken off-route at the higher demand levels.

Another key consideration in route conformance is the ability to maintain the aircraft on their proper vertical profile. A thorough analysis and the associated energy benefits of the TAPSS tools are discussed in [24]. The analyses show that use of the TAPSS tools enabled the controllers to reduce the amount of typical “level-offs” from cruise to touchdown by over 50%. This again provides context for understanding the impact on controller workload when TAPSS tools were available.

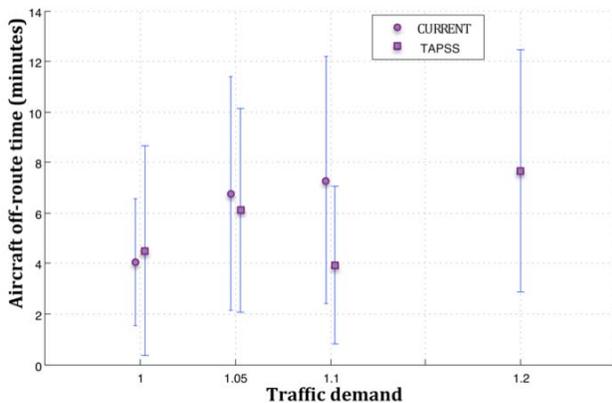


Figure 6. Mean time off-route

### Spacing at the Runways

Controllers were tasked with delivering aircraft to the runway threshold with at least the minimum required spacing between each pair of aircraft. This was not just the responsibility of the final controllers, as to achieve minimum spacing Final controllers needed to collaborate with the Feeder controllers to set up the overall aircraft spacing into a feasible range.

Shown in Table 2 are the mean and standard deviation of the excess inter-arrival spacing of aircraft pairs for the two tools conditions split by runway. The mean value was similar between the

Table 2. Mean excess spacing at the runway under the seven study conditions to the two LAX arrival runways (in Nautical miles)

Demand	Baseline	1.05x	1.1x	1.2x
	Mean & (SD)	Mean & (SD)	Mean & (SD)	Mean & (SD)
24R: TAPSS tools	1.75 (1.5)	1.5 (1.5)	1.1 (1.0)	0.6 (1.25)
24R: “current day”	2.2 (2.2)	2.2 (2.2)	0.9 (1.33)	Unable
25L: TAPSS tools	2.5 (2.75)	1.66 (2.33)	1.25 (2.25)	0.4 (2.0)
25L: “current day”	2.2 (3.7)	2.0 (3.2)	1.1 (2.2)	unable

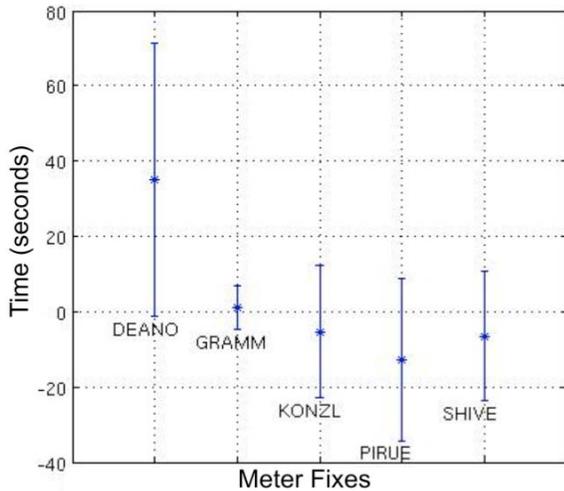
conditions with slightly less mean excess separation for the TAPSS tools, except for the 1.1x condition and 25L under the baseline traffic. But what is significant is the much higher variability, as indicated by the greater standard deviation, for all the current-day operations. There is close to a 30% greater variability in the current day compared to the TAPSS condition. This apparently more-controlled system is one of the reasons for the higher throughput under TAPSS that was discussed in [9].

### Schedule Conformance

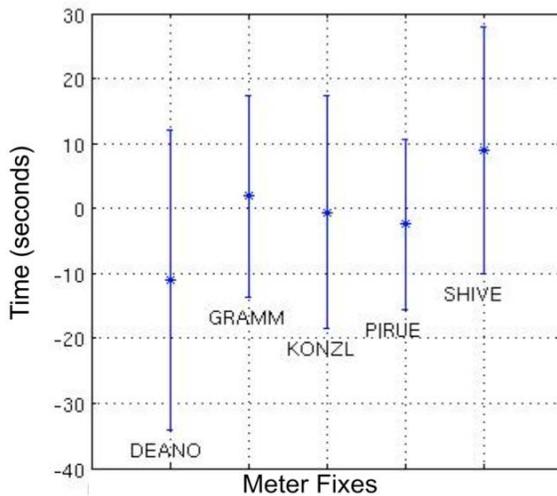
A third TAPSS goal was to assist controllers to control their aircraft such that they arrived at the runway on-schedule, known as “schedule conformance”. This metric was defined as an aircraft’s STA minus its actual meter-fix crossing time (negative values indicate the aircraft was behind schedule). Schedule conformance again indicates a combined effort from the controllers, because to achieve this goal the controller team must reduce the ETA-STA differences over the entire length of a flight through the Center and the TRACON.

Figures 7 and 8 show the schedule conformance for the Center controllers at the meter-fixes for the current-day operation and the TAPSS tools during the 1.1x condition as an example. The locations of these meter fixes are shown in black in Figure 3. The metering conformance is fairly similar between the

two conditions, although the difference in y-axis scale should be noted. Despite higher levels of error in the current-day condition, it can be seen in the figures that the controllers were able to meet the meter-fix conformance goals of  $\pm 30$  seconds for *both* current-day and TAPSS-tools conditions; although there is a slight improvement while using the TAPSS tools as the mean conformance falls within  $\pm 12$  seconds for each meter-fix.



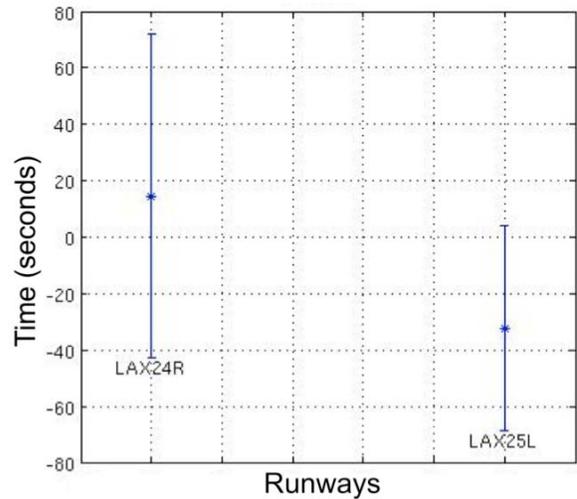
**Figure 7. Meter-fix schedule conformance for the 1.1x traffic condition using current-day operations**



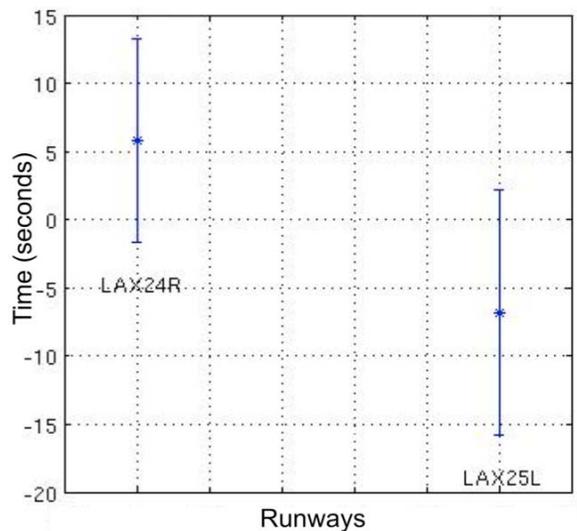
**Figure 8. Meter-fix schedule conformance for the 1.1x traffic condition using the TAPSS tools**

Figures 9 and 10 show the schedule conformance at the runway for both the current-day

and TAPSS-tools conditions for the 1.1x traffic condition. Figure 9 shows the current day operations performance with mean errors of 15 seconds early on runway 24R with approximately 60s as one standard deviation, and late by 35 seconds on runway 25L with 40s as one standard deviation. Figure 10 shows that with the TAPSS tools the Terminal controllers could easily meet the conformance goals of  $\pm 15$  seconds with a mean error that is within the resolution of the simulated ATC radar systems frequency.



**Figure 9. Runway schedule conformance for the 1.1x traffic condition for current day traffic**



**Figure 10. Runway schedule conformance for the 1.1x traffic condition for TAPSS tools**

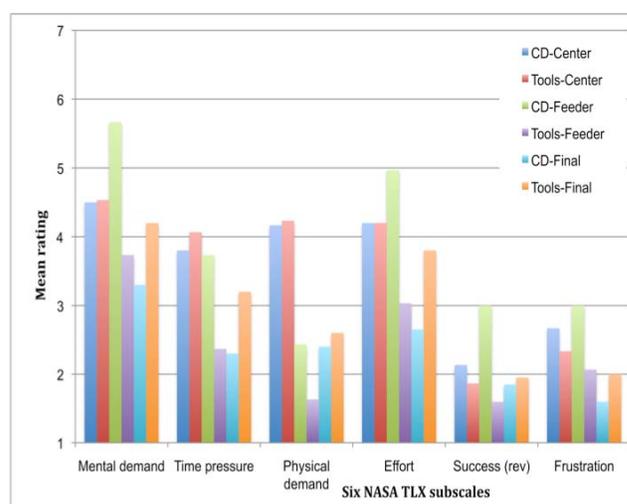
In sum, controllers could achieve the task – bringing aircraft to the meter-fixes close to their STAs – under both conditions. Without the TAPSS tools, however, the ability to provide the desired precision control within the TRACON could not be achieved. This newly achieved level of precision enabled both higher throughput and an increase in route conformance, such that aircraft could maintain RNAV approaches with OPD vertical performance in the high demand routine performance. Another gain from using TAPSS tools was that the ATM solutions were more precise as more aircraft were flown along their scheduled routes and, until the final sectors, they were also more accurate (ETAs were closer to STAs), as indicated by the schedule conformance. Final controllers found it more difficult under TAPSS conditions to absorb the remaining required schedule adjustments in the confines of their sectors and were able to run traffic more tightly in the current-day condition.

### Controller Workload

In addition to the metrics of task achievement, another measure was taken to assess whether the load on the controllers was reasonable while they were completing the study tasks. Controller workload was measured in post-run questionnaires using the NASA-TLX [25]. Controllers completed six scales (mental demand, time pressure, physical demand, effort, success and frustration) that comprise this rating scheme after each run, using a ranking that ran from very low workload (1) to very high workload (7).

When the TLX ratings were organized by tool condition the means for the TAPSS tools were lower for all six scales than the means for the current day tool conditions, suggesting participants found that using the TAPSS tools made the runs less demanding and less frustrating and also that they felt more successful (as this scale was reversed). For example, the mean mental demand rating was 4.15 for the TAPSS condition (SD=1.61) and was 4.64 (SD=1.76) for current-day conditions. When tested, using a Wilcoxon Signed rank test, the mental demand ratings were shown to be significantly different at the  $P < 0.01$  level ( $Z = 2.84$ ,  $df = 1$ ). The other five scales also showed significant differences between the two conditions in the same direction at the  $p < 0.05$  level or greater, indicating that controllers found the TAPSS tools helpful to reduce all aspects of workload.

As the TAPSS tools consist of two separate suites of tools (Center and TRACON), the workload ratings were sorted by participants' positions. The means for each TLX scale by tool type and controller position were calculated (see Figure 11). Splitting the ratings by controller position revealed that not only did controllers using different suites of tools change their workload ratings by varied amounts but that controllers in the two TRACON positions rated their workload differently when using the same suite of tools. Center controllers rated their workload similarly whether they had TAPSS tools or not. Feeder controllers rated their workload much lower when they had TAPSS tools, e.g., their mean mental



**Figure 11: Mean ratings on six NASA TLX subscales by tool-type and participant position**

demand rating dropped from 5.66 (“high”) when using current-day tools to 3.73 (“average”) when using TAPSS tools. However, Final controllers’ ratings *increased* on average when using TAPSS tools, for example, their mean mental demand rating increased from 3.3 (“some load”) when using current-day tools to 4.2 (“average”) when using the TAPSS tools. The differences between workload ratings under these two sets of conditions were tested using repeated measures ANOVAs. Using mental demand as an example once again, the results indicated that the mental demand reported after the two tools conditions was significantly different ( $F = 7.54$ ,  $df = 1$ ,  $p = .008$  using the Huynh-Feldt correction) and was modified by the controllers’ position ( $F = 15.11$ ,  $df = 2$ ,  $p = .000$ ). Post hoc tests

(Bonferroni) revealed that the Feeder and Final controllers rated their mental demand significantly differently ( $p=.022$ ) but Centers' ratings were not significantly different from either Feeders' or Finals' ratings ( $p>.05$ ). The physical demand and effort scales showed similar patterns of results while the success and frustration scales did not show an effect for controller position. The time pressure scale did not show an effect for tools but did show an interaction with the controllers' position ( $F=10.45$ ,  $df=2$ ,  $p=.000$ ). Post hoc tests (Bonferroni) for time pressure revealed that the Center controllers rated their time pressure significantly differently from the Feeders' and Finals' ratings ( $p=.024$  and  $p=.005$  respectively).

### Acceptability of TAPSS Operations

Among the post-run questions were six that formed an acceptability scale, which followed the Controller Acceptance Rating Scale (CARS) developed by [26] as closely as possible. Although the first question ("were the separation assurance and metering operations safe?") was mandatory the following questions were conditional upon previous answers. Participants were asked to rate the acceptability of the metering and separation of the TAPSS operations once each day. Participant answers were compiled to form a scale from one to ten, with one indicating that the operation was not safe through to ten indicating the system was acceptable. Overall, participants rated that the TAPSS operations "require considerable compensation to maintain adequate performance" ( $M=6.5$ ,  $SD=3.07$ ). However, as with the workload ratings, controllers in different positions had distinct views of the operations. Figure 12 shows that TRACON controllers were generally positive about the TAPSS operation, rating it most often as requiring "Minimal controller compensation to reach desired performance" ( $N= 23$  of 39, 58%) and only saying it was "not safe" in three cases. Final controllers were slightly less positive about the operations than Feeders, as can be seen from their greater spread of ratings across the CARS levels (Figure 12). Center controllers, who worked the traffic first and worked with a different suite of tools, rated TAPSS operations less positively than TRACON controllers. A third of the time, Center controllers rated the operations as not safe in some way, although they gave the same proportion of

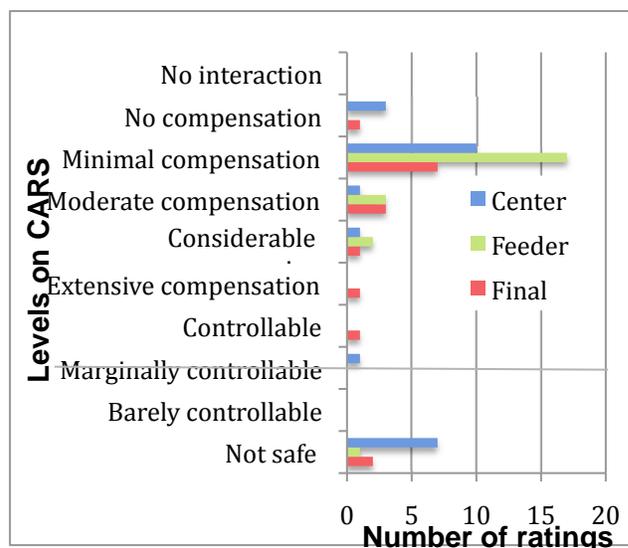


Figure 12: Count of participants' CARs for the TAPSS operation

highly positive ratings (in the top three CARS levels) as the TRACON controllers.

Participants' responses to other questions were reviewed to try to tease out some of the properties of the TAPSS tools that might contribute to their different operations' acceptance ratings (CARS, Figure 12). Three properties of the TAPSS operations were queried: tool quality, operational procedures, and the way the controller worked with the tools. TRACON controllers all said that the aircraft arrival sequence they received and the Aircraft STAs were "very high quality", whereas the Centers said that although their arrival sequence and aircraft STAs were "good quality" the EDA advisories were only "OK quality". The same trend is reflected in participants' answers to whether the procedures they worked with were acceptable. TRACON controllers reported the procedures they used were "acceptable" ( $M=4.4$ , out of a five point scale), but Center controllers reported their procedures were "OK" ( $M=3$ , out of 5). These opinions support the CARS findings above, possibly providing some explanation for why Center controllers rated the TAPSS operations as less acceptable overall: their advisories were not always good and the procedures they used could be improved. Their reasons for feeling their procedures needed improvement included consideration of the many additional elements that affect situations in the real world that were not included in this experimental setting: one of the

controllers commented that “there are 5 of the 10 busiest airports in the US located in the greater LA area. That other traffic *must* be considered. Also, there is a *huge* amount of restricted airspace that the military activates on a regular basis.”

Participants were also asked whether they had to change the way they worked to fit in with how the scheduler was organizing traffic. The majority of Center and Feeder participants said “no” they did not have to change the way they worked (64% and 75% respectively). However, Final controllers said they had to change the way they worked nearly as often (42% of the time) as they said they did not have to change the way they worked (46% of the time). This pattern of opinions does not support the CARS findings as much as it supports the workload findings (Figure 11), where Finals reported a higher workload when using the TAPSS tools. Maybe their workload increased because they were having to work differently to use the TAPSS tools, a possibility that has some support because Finals agreed that they changed the way they organized their tasks to fit in with the TAPSS tools. The key seems to be having to change the organization of tasks because Centers agreed their approach to their tasks changed but they said specifically they changed the way they prioritized their tasks not the way they organized them and their workload reports showed no significant differences.

## Conclusions

The study reported above was a first investigation of the performance of a precision scheduling, merging and spacing control concept (TAPSS), which introduced advanced trajectory-based tools to enable controllers to work within the required tight time frames predicted to arise in future airspace systems. Participating controllers were able to control traffic and bring a highly route-conformant stream of aircraft successfully to the runways with and without the assistance of TAPSS tools up to 110% traffic levels. Their solutions were more precise under TAPSS tools conditions and, until the final sectors, they were more accurate also, as evidenced by the schedule conformance metrics. However, Final controllers found it more difficult to absorb the remaining required schedule adjustments in the confines of their sectors and were sometimes able to run traffic more tightly in the current-day condition.

Center controllers used advised corrections and TRACON controllers used speed clearances alone, enabling aircraft to execute OPDs while remaining on their RNAV routes. Although Feeder controllers reported lower workload when they had TAPSS tools available, Final controllers reported higher workload under the same conditions, suggesting that having to reorganize the way they worked to use the tools increased the burden they felt. However they indicated that their operations were safe and controllable. Center controllers on average said they could maintain adequate performance in their portion of the system but a third of the time said they did not feel the operations would be safe if real-world constraints were taken into consideration, e.g., traffic from other airports.

Future plans include adding to the system’s capabilities to incorporate off-nominal conditions such as “missed approach” and airport configuration changes during busy periods. Future scheduling enhancements of opportunistic time-advance and time recovery are being developed. While the TAPSS-TRACON tools seem to exactly meet the needs of Feeder controllers they need to be modified to better meet the needs of the Final positions. Center tools seem to be the right type and are being improved under the 3D-PAM program [3]. Plans also include testing at higher levels of fidelity for traffic, environmental conditions and actual FAA Center and TRACON controller equipment, and using TRACON routings closer to today’s operations.

In sum, this simulation of scheduling and merging arrival traffic into and through a “future” terminal area showed that controllers, assisted by simple-to-use and informative decision support tools, were able to correct for initial schedule errors and deliver aircraft on-schedule. The tools showed great potential but need to be fine-tuned to meet the varying needs of controllers who perform different functions along the descents into and through a terminal area.

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