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

Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System

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Abstract--This paper describes the design, development and results from a high fidelity human-in-the-loop simulation of an integrated set of trajectory-based automation tools providing precision scheduling, sequencing and controller merging and spacing functions. These integrated functions are combined into a system called the Terminal Area Precision Scheduling and Spacing (TAPSS) system. It is a strategic and tactical planning tool that provides Traffic Management Coordinators, En Route and Terminal Radar Approach Control air traffic controllers the ability to efficiently optimize the arrival capacity of a demand-impacted airport while simultaneously enabling fuel-efficient descent procedures. The TAPSS system consists of four-dimensional trajectory prediction, arrival runway balancing, aircraft separation constraint-based scheduling, traffic flow visualization and trajectory-based advisories to assist controllers in efficient metering, sequencing and spacing. The TAPSS system was evaluated and compared to today's ATC operation through extensive series of human-in-the loop simulations for arrival flows into the Los Angeles International Airport. The test conditions included the variation of aircraft demand from a baseline of today's capacity constrained periods through 5%, 10% and 20% increases. Performance data were collected for engineering and human factor analysis and compared with similar operations both with and without the TAPSS system. The engineering data indicate operations with the TAPSS show up to a 10% increase in airport throughput during capacity constrained periods while maintaining fuel-efficient aircraft descent profiles from cruise to landing.

Keywords-Air Traffic Management; arrival metering; trajectory management; scheduling; human-in-the-loop simulation; NextGen

1. INTRODUCTION

The efficient scheduling and control of aircraft from cruise to touchdown during congested periods is a highly complex problem. Both current procedures and deployed arrival scheduling tools often compromise the ability of aircraft to fly efficiently using continuous descents for airport throughput performance [1 & 2]. Significant research has been conducted both in the United States and Europe to develop trajectory management tools enabling aircraft to simultaneously execute efficient descents while maintaining throughput using current arrival scheduling capabilities [3,4,5 & 6]. This research has added controller advisory tools to work in concert with current arrival scheduling tools like the FAA's Traffic Management Advisor (TMA) or the European Arrival Manager (AMAN). These research systems are limited to either en-route or terminal airspace only application. Limited research has been conducted to fully integrate trajectory and scheduling tools from cruise to landing.

The growth of commercial air travel within the United States has put a severe strain on the nation's air traffic capacity. The US Government established the Joint Planning and Development Office (JPDO) to solve this problem and develop the Next Generation Air Transportation System (NextGen) [7]. Similarly, the European Community has developed a concept under the banner of the Single European Sky ATM Research [8]. Outlined in the NextGen concept documents is a high-level description of an Air Traffic Management capability called Trajectory-Based Operations (TBO) supporting high-density arrival/departure operations.

The JPDO conducted a high-level benefit analysis of TBO and has found significant capacity related benefits for this concept [9]. NASA has developed a detailed expansion of TBO in several aspects, including a functional architecture, technologies, procedures and capabilities that could enable these high-density operations [10]. Key capabilities described in this concept are precision scheduling along routes and merging and spacing controller automation functions. Although these capabilities have yet to reach their full potential, the theoretical advantage of a precision scheduling and control system for managing constrained resources is well understood. Reference [11] describes how the ATC arrival problem could take advantage of precision scheduling systems. Reference [12] describes a stochastic modeling approach for evaluating the capacity benefits of scheduling accuracy. Reference [13] extends this stochastic modeling to evaluate the effect of arrival uncertainty, minimum separation while varying the effect of aircraft excess separation buffers, and delay distribution between controller teams on airport throughput and controller intervention. This work provided scheduling design insight into the effect of arrival uncertainty on the application of scheduling control at the entrance to the terminal airspace (meter-fixes) and runway thresholds.

The purpose of this paper is to propose an enhancement to TMA and to demonstrate in simulation, that by making use of the improved routing and navigational performance capabilities being introduced by the FAA, the enhanced

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TMA and controller advisory tools can be integrated into a system that is capable of meeting increased demand while supporting continuous descent approaches. This paper will present a brief description of this Terminal Area Precision Scheduling and Spacing (TAPSS) system concept and technologies, followed by a description of a simulation evaluation conducted to both tune the system and evaluate its benefits. Results from the evaluations are discussed and the paper ends with some concluding remarks about the future development of this tool.

2. TAPSS SYSTEM DESCRIPTION

The TAPSS system is a trajectory-based strategic and tactical planning and control tool that consists of trajectory prediction, constraint scheduling and runway balancing, controller advisories and flow visualization. The trajectory prediction, constraint scheduling and runway balancing is built on the existing TMA. The controller spacing and metering advisories are built upon the research of the Controller Managed Spacing (CMS) and Efficient Descent (EDA) Advisor technologies [3&5]. A simple conceptual and functional diagram for an operational implementation is shown in Figure 1. On the left side is the air traffic control operational system from which the TAPSS would receive aircraft track data, flight plans and various controller entries. These data are passed to the system interface for distribution to the trajectory prediction, constraint scheduling and runway balancing, controller advisory and visualization processes. Atmospheric data (winds, temperature and pressures aloft) would also be interfaced to the prediction, advisory and visualization software.

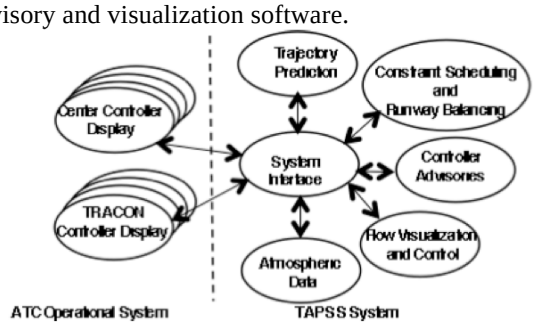

Figure 1. TAPSS simplified functional diagram.

The trajectory prediction generates estimated times of arrival (ETA) for all aircraft to the scheduling control points: metering fixes, terminal merge points and all eligible runways. The ETA data and ATC constraints are used to generate the scheduled time of arrivals (STA) for all aircraft to these same reference points. The ETA, STA data and other information of interest are displayed in various formats on the original TMA type display. The controller trajectory and speed advisory function processes the ETA and STA along with aircraft specific and atmospheric data to produce sequence, speed and trajectory advisories. Operationally, ETA, STA, sequence, speed and trajectory advisories would be transmitted to the operational ATC computers in the Air Route Traffic Control Center ("Center") and the Terminal Radar Approach CONtrol (TRACON) facilities for presentation on appropriate controller radar displays.

2.1 Trajectory Prediction

Precision time and trajectory prediction algorithms are the foundation for the TAPSS system. Trajectory prediction algorithms provide precise estimates of the future path of all aircraft known as 4D trajectories (position (x,y,z) and time). This, coupled with the precision control enabled by the controller advisories, is the basis for the TAPSS. The foundation for the prediction processes are a set of algorithms developed for aircraft flight management systems (FMS) of modern commercial aircraft. The trajectory prediction is separated into two modules: the route analyzer (RA) and trajectory synthesis (TS) [15&16]. Based upon user generated and site specific adaptation routing logic and heuristics, the RA generates a two-dimensional path from the aircraft's current position to all eligible runways at its final destination. This two-dimensional path is coupled by the TS with the aircraft's current energy state and atmospheric data to calculate a flyable fuel-optimal four-dimensional trajectory using aircraft specific mathematical performance models. ETAs are extracted from this trajectory for specific points of interest. The TS trajectories include all modes of flight including ascent, cruise, procedural-based level-offs and descent.

TAPSS requires typical routings to be known from cruise to landing, and to contain supplemental waypoints known as meter-fixes (Center) and merge-points (TRACON). This routing can be flexible, yet requires a defined period of time to be used by the aircraft for the TAPSS scheduling and control processes. The defined period allows both the scheduling algorithms and the trajectory-based advisories to be consistently executed by the Center and TRACON controller teams. This time period is called the freeze horizon and is typically on the order of 20 to 40 minutes from landing. The routes in the Center airspace are usually found in an expanded flight plan. A meter-fix is a transition waypoint between the Center and TRACON airspace (Figure 2) and begins the routing to the runways in the TRACON. These routings are typically defined procedurally in today's ATC system, based on airport configuration and are simple constructs in the current TMA.

These TAPSS required precision routings are becoming more and more defined in the Nation's advancement towards NextGen, known as Area Navigation (RNAV) approaches. For some operations where the aircraft is expected to maintain lateral containment to the routes, they are known as Required Navigation Performance (RNAV/RNP) approaches. TAPSS depends on the definition of these RNAV or RNAV/RNP approach procedures with limited flexibility. The scheduling and runway balancing algorithms at the freeze horizon will select the routing options, all the way to the runway. Figure

2 shows an example of multiple RNAV approaches for a hypothetical two-runway configuration with a classic four corner-post TRACON operation. The primary routes are shown as a solid line with secondary routes shown as dashed lines. The TRACON route, in blue, is an example of a selected secondary route to the runway starting at the meter-fix and is connected with the fixed routes in the Center airspace.

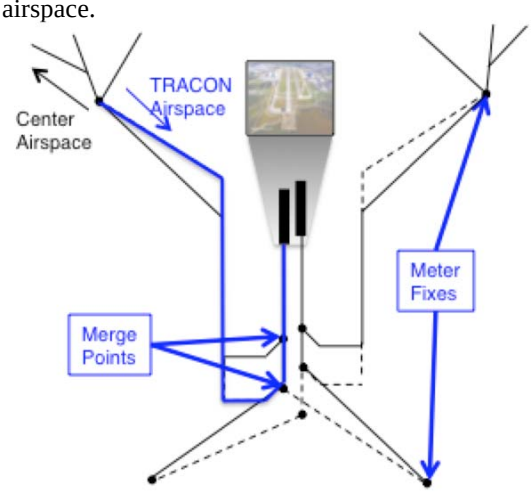

Figure 2. TAPSS Flexible TRACON Routing.

The TAPSS system requires both a planned nominal speed and a slow speed to develop a delay distribution function used by the scheduling algorithm. In order to develop trajectories that are compatible with aircraft flight management system trajectories, these speeds are defined as calibrated airspeeds. Table 1 provides typical values from top-of-descent to landing for jets and turboprops. These speeds can also be aircraft specific which is critical for landing speeds.

Table 1 lists flight profile segments with example speed ranges (Nominal/Slow); top-of-descent (TOD) to flight level 10,000 ft (FL100), FL100 to 20 NM (nautical miles) from runway threshold (THD), FL50 to 12 nm from THD, speed at the outer marker and landing speed. The ETAs based on the (Nominal/Slow) speeds for each aircraft to each eligible runway are recalculated with each positional track update from the operational ATC system. The grouping of these ETAs using the nominal speeds represents the arrival "demand" for any reference point used in the scheduling algorithms (meter-fixes, merge-points and runway).

Table 1. Typical Airspeed Along Routes For Jets and Turboprops.

Route-leg	TOD to FL 100	FL 100 to 20 NM from THD	FL 50 to 12 NM from THD	Outer Marker	Landing
Jet	280/250	250/210	220/200	180/170	140/120
Turbo	230/210	220/200	220/180	170/160	130/110

2.2 Constraint Scheduling and Runway Balancing

The constraint scheduling and runway balancing logic and algorithms necessary for the diverse operational requirements of ATC are beyond the scope of this paper and will be covered briefly and where the logic is extended beyond the original TMA. A thorough description of the TMA scheduling logic can be found in [17]. The basic functional logic for the scheduling algorithm is a modified first-come-first-served (FCFS) algorithm. The scheduling constraints used to modify the FCFS schedule are the factors associated with the separation safety requirements specified by FAA regulations. The FCFS algorithm logic is coupled with a runway balancing algorithm that uses available runway capacity and the Center/TRACON delay distribution function (DDF) to create the aircraft specific STA. The scheduling algorithms create conflict-free schedules simultaneously at the Center meter-fixes, runways threshold and terminal merge-points.

2.2.1 Meter Fix Constraints

Scheduling is accomplished in a multi-step process. First is the generation of an initial schedule to each of the meter fixes. The sequence is determined based upon the earliest ETA to the meter fix. The first aircraft in the sequence is scheduled at its earliest ETA. The next aircraft in sequence is then 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 greater than or equal to the minimum separation standards of 5 NM for similar aircraft types crossing the same meter fix to the same airport destination. Thus, an initial meter fix separation based schedule is established for all fixes.

2.2.2 Runway Constraints

Scheduling to ensure required runway threshold separation is met is the next major step. Threshold separation requirements are the FAA wake-vortex standards based on aircraft weight class. Controllers may increase these values due to weather or other significant events for extra separation buffers. 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. It is scheduled to the threshold using the meter fix STA, the meter fix to runway transition time and the threshold separation requirements. The next aircraft from that meter fix is added to the order of consideration for possible selection. It is scheduled using its meter fix STA, nominal transition time from the meter-fix to the runway and the specified threshold separation requirements. Once the second and subsequent aircraft are scheduled, threshold separation delay is known. Separation delay is necessary any time intervention is required to modify the approach of a trailing aircraft to maintain separation standards. This intervention is required when runway "capacity" has been exceeded. If this delay is greater than the Center/TRACON DDF, then the amount greater than the DDF is fed back to the meter fix STA. This modified meter fix STA causes modification to the aircraft's

in-trail separation based meter fix schedule. The process is repeated until all aircraft are scheduled and no more separation-based modifications are required.

2.2.3 Center/TRACON Delay Distribution Function

The Center/TRACON DDF is calculated using the nominal and slow ETAs discussed earlier. The DDF effectively sets the amount of delay that can be efficiently and economically absorbed within the TRACON airspace when runway demand exceeds capacity. An overall design consideration for TAPSS is that the delay within the TRACON airspace be absorbed by using only speed control, thus limiting vectoring as a routine delay technique within the TRACON airspace. This design feature limits the inefficient low-altitude fuel burn associated with extensive low-altitude vectoring for delay queuing at a runway's final approach fix used by current scheduling tools [1]. This is enabled by the expected higher precision of delivery afforded by the controller trajectory and speed advisory tools. Another effect of limiting vectoring is that the average aircraft arrival speeds are higher, thus enabling an increase in overall runway throughput, further discussed in the results section. The typical total Center/TRACON DDF is 1 to 2 minutes.

2.2.4 Merge-point Constraints

Simultaneous to the meter-fix and runway constraint scheduling processes, the TRACON merge-points are checked to ensure that separation constraints are not violated. Since aircraft are in-trail at the merge-points they have to follow the same minimum wake vortex based separation constraints that are required at the runway. Due to variations in aircraft speeds on the routes there is no guarantee that even though runway separation is not violated, separation at the merge-points will be acceptable. Thus, separation evaluation is required at merge-points. This evaluation is accomplished by translating the runway STAs back to the merge-points using the difference between the nominal ETA values at the merge-point and runway. At the merge-point, the separation between aircraft is determined by using the aircraft 4D trajectories, type, and their scheduled sequence along with separation requirements. Much like with the runway constraint scheduling, if the translated STAs between two aircraft exceed the DDF time available from the merge-point to the runway or a previous merge-point, then there is not enough DDF time available. Thus the STA is modified and excess delay is pushed upstream to the previous merge-point or meter-fix. This process is repeated until all aircraft have been scheduled without violating separation constraints at any merge-point.

2.2.4 Runway Allocation

The runway allocation algorithm of the scheduling process is event driven. The events are 1) initial aircraft knowledge as determined by TAPSS receipt of an estimated or departed flight plan, 2) a stable radar track-based ETA, 3) freezing of the schedule prior to transmission to the controllers' radar display. For these events the total system delay associated with the particular aircraft scheduled to its current runway is compared with the total system delay if the aircraft was allocated to an alternate runway. The comparison includes any delay incurred in the TRACON due to a longer meter fix to runway routing. The runway allocation algorithms are controlled by heuristics that provide weighting coefficients for runway changes. These heuristics are captured in adaptation parameters that are a function of airport configuration, local procedures and aircraft type. The parameters are eligible runways (categorized as primary, secondary, or tertiary) along with the amount of system delay savings necessary to allocate to an alternate runway as determined by delay and weighting coefficients. By simply modifying the coefficients, one could easily include airline specific runway preferences. The coefficients can also be used to favor TRACON routes to reduce airspace complexity.

2.3 Controller Advisories

The TAPSS system leverages trajectory-based controller advisory systems to enable the precision necessary to simultaneously achieve the STAs at the meter-fix, merge-points and runway. TAPSS incorporates two separate advisory tools, one for the Center and one for TRACON operations, to achieve the controllability required for the TAPSS.

2.3.1 Center Controller Advisories

The trajectory-based advisory tools used in the Center operations are based on the capability developed by NASA known as the Efficient Descent Advisor (EDA) and further refined by a combined NASA, FAA and Boeing Co. team called the 3-Dimensional Path Arrival Management (3D-PAM) system [3]. Both the EDA and its near-term 3D-PAM derivative develop conflict free speed and routing controller advisories to accurately and efficiently meet TMA STAs, and thus extensible to the TAPSS system.

Figure 3 shows an example advisory display of the EDA information for an aircraft being controlled to a meter-fix STA. Displayed are speed advisories for a cruise mach of 0.76 (•C/M .76) and a descent speed of 250 knots (•D/250). Also included is a path-stretch advisory (@LBL,AMWAY125051, AMWAY) providing a delay vector for the aircraft UAL123 to turn at LBL to the fix-radial distance from AMWAY of 125 degrees at 51 miles and then turn directly to AMWAY. Execution of these advisories will achieve the desired delay for an aircraft to meet the meter-fix STA.

The operational concept is for the controller to issue the speed and descent clearances via voice for the pilot to set the vertical navigation panel on the FMS. This is followed by the routing clearance with the new auxiliary waypoint added to the route and the runway advisory, which is required by TAPSS. These clearances provide the pilot with a profile descent enabling fuel-efficient descents and allow pilots the opportunity to set up the transition and approach

procedures for the TAPSS scheduled runway. All three advisories will be issued after the TAPSS system freezes the schedule, approximately 20 minutes from the meter-fix or about 10 minutes from the aircraft's initial descent from cruise. This has the added benefit to enable the pilot to program the FMS while in cruise without the time pressures of the TRACON airspace. While TAPSS is controlling the operation, only speed and limited heading clearances should be necessary for the rest of the flight.

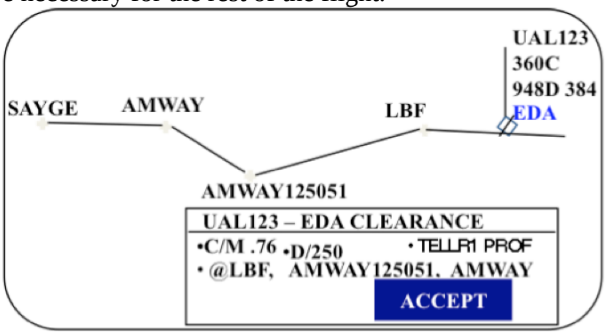

Figure 3. Center Controller Advisory

2.3.2 TRACON Controller Advisories

The TRACON controller advisory tools are based on another capability developed by NASA known as the Controller Managed Spacing (CMS) concept [5]. The advisories are shown in Figure 4 superimposed on a TRACON controller's radar display. Two advisories are presented, one a speed advisory displayed on the third line in the flight data block and the other a trajectory slot marker.

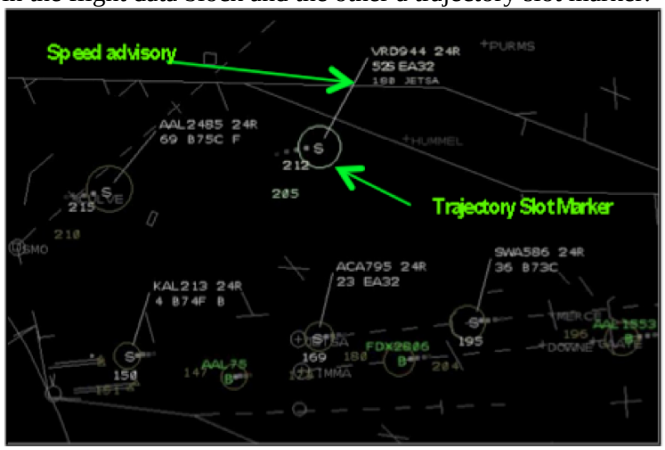

Figure 4. TRACON Controller Advisories

The speed advisory, shown as 180JETSA, is provided to the controller to give a speed clearance of 180 knots airspeed to the navigation waypoint JETSA. JETSA is the merge-point on the final just prior to the outer marker. The trajectory slot marker shows the desired location for the aircraft along its assigned RNAV approach route. In this figure the aircraft track symbol "s" is situated in the center of the trajectory slot marker. The current airspeed is derived from the radar tracker based ground speed and the winds aloft from the atmospheric data. The current airspeed of the aircraft is 212 knots and the current speed of the trajectory slot marker is 205 as displayed in the figure. Thus the speed advisory is providing an indication for the aircraft to slow down to 180 knots to maintain the aircraft symbol within the trajectory slot reference.

The rules governing the movement of the trajectory slot marker and speed advisories are provided in reference [5]. This references use the runway STA as the control reference point for calculation of both the speed and trajectory slot advisories. For the TAPSS system, this reference was modified to use merge-point STA as the control values driving the advisories.

3.0 TAPSS EVALUATION DESCRIPTION

During 2010 the TAPSS system was evaluated in a series of high fidelity Human-In-The-Loop (HITL) simulations conducted in one of the Air Traffic Control laboratories at NASA's Ames Research Center. Two sets of experiments were conducted, each of a two week duration. The objectives of the first simulation period were to establish controller acceptable TAPSS parameters for the DDF and scheduled spacing buffers. The second experiment period evaluated the TAPSS system performance relative to the current day ATC operations using the TMA.

3.1 Simulation Environment

The TAPSS scheduling and trajectory advisories were evaluated using the Multi-Aircraft Control System (MACS) HITL simulation capability [18]. MACS was adapted to simulate major arrival elements of the Los Angeles Air Route Traffic Control Center (ZLA Center) and the Southern California (SoCal) TRACON. The evaluation focused on the ability and the performance of the controller teams to safely control the traffic to the STAs at the various locations (i.e., meter-fix, merge-points and runways). The ATC simulation laboratory was arranged with three ZLA Center arrival sectors handing off to three SoCal TRACON feeder positions, who handed off traffic to two final positions. Figure 5 is a picture of that arrangement with the three Center positions, shown center-top, the three TRACON feeder positions on the right and the two final positions facing out on the far left. In the upper center of the picture is a large monitor showing the TMA timeline display configured with two runway and six meter-fix timelines from left to right displaying both aircraft ETAs and STAs to the respective reference points.

The operation simulated arrivals into the Los Angeles International Airport (LAX) in a West two-runway configuration, landing on runways 24R and 25L under Instrument Meteorological Conditions (IMC). The ZLA Center TMA metering operations were modified such that the six TAPSS meter-fixes could be controlled by the three controller positions. These controllers also took the simulated aircraft from en-route cruise at the Center boundary to handoff at SoCal TRACON. The three TRACON feeder positions were configured fairly close to today's operation with the addition of the merge-point

metering trajectory control capability discussed earlier. In addition to the trajectory-based advisories both the TRACON feeder and final positions had timeline information displayed associated with the merge-points and runways.

Eight controllers participated simultaneously to cover all positions. All participants were recently retired (within the previous 2 years) from either SoCal TRACON or ZLA Center and had over 100 years of combined ATC experience.

Figure 5. ATC Laboratory Configuration

3.2 Simulation Scenarios

The simulation scenarios were based on the JPDO 2004 baseline traffic scenarios used in their portfolio analyses [9]. This scenario was evaluated to find a three-hour period of the highest demand of continuous arrival traffic for LAX. One such period was between 6:30 and 9:30 pm local time. The arrival demand on the airport was found to vary between 50 to 66 aircraft/hour during this period. The directional distribution of the traffic had 57% of the aircraft arriving from the East, 38% arriving from the West (oceanic) and Northwest and about 5% arriving from the Southwest (oceanic) and South. Aircraft type distribution of the traffic had 20% heavy jets, 12% Boeing 757s, 53% large and regional jets and 15% turboprops. Specific aircraft demand scenarios were generated using these parameters to create simulation runs of approximately 100 min. in duration. Variation in the scenarios included the increase in demand by 5%, 10% and 20% in proportion for both direction and aircraft type.

3.3 RNAV Approaches to LAX

To simulate some of the near-term NextGen operations, continuously descending RNAV approach routes from Center airspace to touchdown were generated. The routes generally follow the flow of existing traffic. SoCal TRACON airspace already contains some existing routes with the continuously descending feature from the East known as Optimized Descent Profiles (ODP) [19] and "Tailored" arrivals from the Southeast oceanic direction. A continuously descending RNAV approach from the West and Northwest was created using the Mitre TARGETS route evaluation [5]. These routing profiles are shown in Figure 6 with the meter-fixes (labeled black), merge-points (labeled blue) and runways (24R & 25L) pointed out.

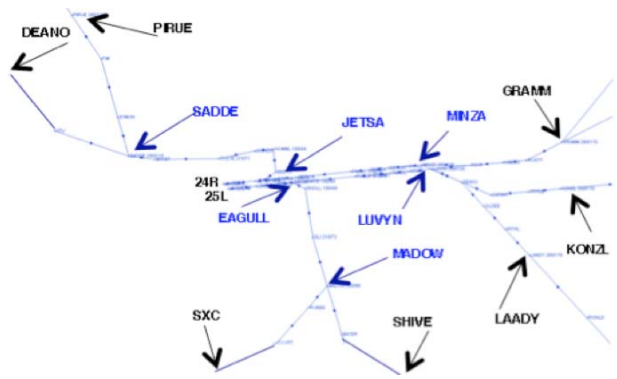

Figure 6. LAX Simulated RNAV Approaches

3.4 Experimental Test Conditions

As discussed previously two separate evaluations were conducted during two different periods.

3.4.1 Evaluation Period 1

Table 2 shows the experimental test conditions for the first evaluation period. The objectives of this period were to tune the DDF and scheduling separation buffers. Scheduling separation buffers are the separation values used by the scheduling processes that exceed the minimum wake vortex separation standards. The values ranged from 0 to 0.5 NM while keeping the DDF value as a constant. Then tests were conducted holding the excess separation buffer at a constant of 0.4 NM while the DDF was varied using; no delay (by setting the slow speeds to the same value as the nominal speed in Table 1), full delay (by using the "full" difference between the nominal and slow speeds in Table 1) and "partial" (by using 70% of the difference between the nominal and slow speeds from Table 1).

Table 2. Experimental Conditions for Period 1

Buffer	0	0.3	0.4	0.5
DDF	No Delay	Full	Partial	

A complete discussion of the theoretical effect of the DDF and the separation buffers can be found in [12 & 13]. The conditions selected for evaluation were derived from the consideration of the Monte-Carlo modeling results discussed in reference [13].

3.4.2 Evaluation Period 2

Table 3 shows the experimental test conditions for the second evaluation period. Here, the separation buffers and DDF were set to the most controller acceptable values found in the first evaluation period of 0.4 NM and "partial" DDF respectively. Experimental variations in demand from the baseline scenario and 5%, 10% and 20% increases were explored. The simulations were run using either all the TAPSS tools or just utilizing the TMA and current ATC radar controller capabilities. The 20% demand increase could not be evaluated for the TMA since the condition required 30+ minutes of holding and was considered both

unmanageable and unrealistic by the ZLA Center controllers.

Table 3. Experimental Conditions for Period 2

Demand	Baseline	5%	10%	20%
TAPSS tools	Yes	Yes	Yes	Yes
TMA	Yes	Yes	Yes	unable

In both experimental periods each experimental condition was repeated at least twice. Prior to the experiment, sufficient training runs were conducted to provide expertise with both the simulation environment and TAPSS tools. The demand scenarios for these training runs were modified sufficiently to minimize the overtraining effect on the actual experiment scenarios. The controllers were requested to follow the TAPSS advisories unless they felt separation would be compromised at which point they were allowed to use any technique to ensure separation was maintained.

4.0 RESULTS AND DISCUSSION

4.1 Evaluation Period 1

The primary purpose of the first evaluation period was to find controller acceptable values for the DDF and the scheduled separation buffer. Performance data were collected but more reliance was given to expert observation and post simulation controller/pilot debriefings to find the best operating points of the TAPSS system. Observation of the distances at which aircraft were slowed to minimum performance speeds and the location and duration of vectoring within the TRACON airspace were key indicators.

4.1.1 Scheduled Separation Buffers

The scheduled separation buffers, discussed earlier, were varied from 0 to 0.5 NM. When the separation buffer was set to 0 NM extensive TRACON vectoring as well as jet aircraft being slowed to about 180 knots was observed 20 to 30 NM from the outer marker. This is an indication of both excessive controller workload close to the airport as well as highly inefficient operations for jet aircraft. In the 0.3 NM condition extensive vectoring was still observed in the base to final turn often extending the turn to final for 24R to about 25 miles. Slow speeds in this same area were also observed though not as slow as the previous condition. The simulation runs using the 0.4 NM value resulted in some vectoring observed around the base to final turn for short periods. The observed speeds indicated a high preponderance of aircraft flying their nominal speeds through the TRACON. Finally, the 0.5 NM condition demonstrated minimal if any vectoring and nominal aircraft speeds throughout the TRACON. But this condition also caused a much higher level of vectoring workload in the Center airspace for metering. This condition indicates that there is not enough pressure on the final, leading to potential slot loss if the upstream metering performance is not perfect.

Based on the post-simulation controller/pilot debrief discussions combined with associated observational data, the 0.4 NM separation buffer seemed to provide the best trade-off of Center/TRACON controller workload and TAPSS system performance. The 0.4 NM value was then used for the evaluation and selection of the Center/TRACON DDF.

4.1.2 Variation of Delay Distribution Function

The route based DDF was varied according to the speed values in Table 2. The observed effect on system performance with DDF set for no delay within the TRACON was excessive vectoring within the Center airspace with little if any vectoring within the TRACON airspace. Both Center and TRACON controllers felt that this was an inequitable distribution of workload between the two teams. Setting the DDF to full delay within the TRACON showed the opposite effect with minimal delay in the Center yet excessive vectoring and early slowing of aircraft in the TRACON airspace. The selected partial setting for the DDF value seemed to balance the workload and the TRACON controllers were able to maintain the average speeds closer to the nominal speed, thus enabling higher throughput.

4.2 TAPSS System Performance Evaluation

As discussed earlier, the TAPSS system performance was compared to simulation runs of the TMA current ATC operations in the LA airspace. Data collected during period 2 included quantitative system performance data as well as qualitative questionnaires after each run. A complete discussion of all the results is beyond the scope of this paper. The results and discussion for the rest of the paper will be based on the scenarios using the 10% demand increases. These results are representative of the other conditions thus providing general insight to the benefits of the TAPSS concepts and technologies.

Figure 7 shows an overall plan-view of the simulation tracks for the 10% demand increase condition that compares current ATC TMA metering operations with operations using the TAPSS tools. Both of these plots show the x-y tracks of about a 400X400 nautical mile (NM) square around the simulated LAX airport. The Figure 7(a) shows the current TMA operation and the Figure 7(b) shows the operation enhanced with the TAPSS tools and technologies. It can easily be seen that in the TMA condition an extensive amount of vectoring and holding is required. The final also varies more erratically for the current operation with distinct gaps in the flow. For the TAPSS tools the flow is more uniform as the volume increases.

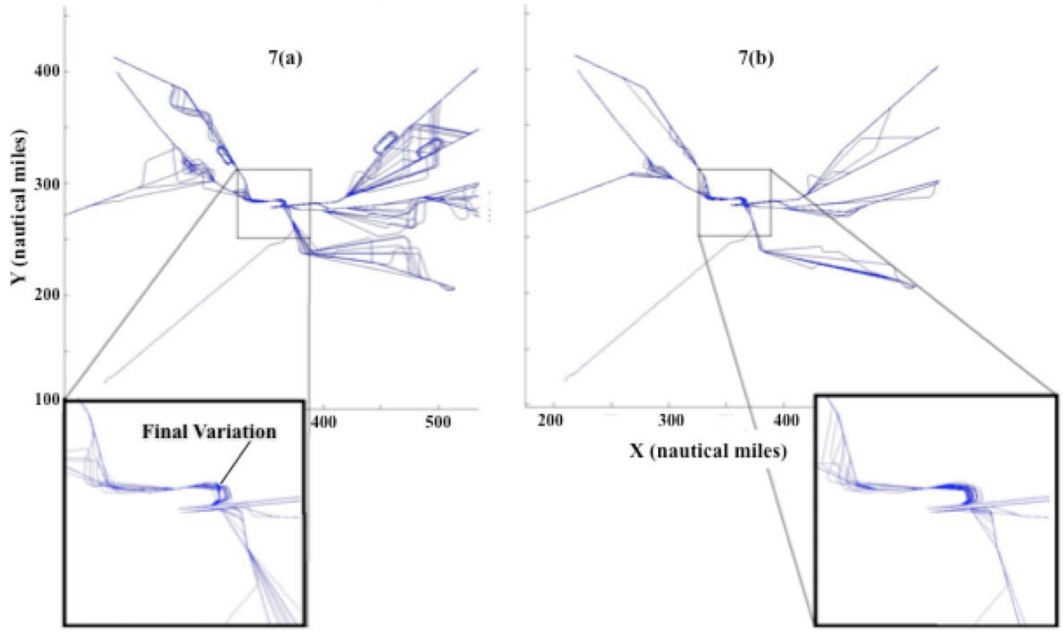

Figure 7 Simulated Aircraft Arrival Tracks into LAX Airport

Figures 8 and 9 compare current TMA operations and operations using TAPSS in terms of being able to support fuel-efficient descents. The plots show the aircraft descent profiles initiating at FL290 to FL390 and FL200 to FL210 for jets and turboprops respectively. The aircraft altitude is shown as a function of range to touchdown. As can be clearly seen, the TAPSS tools (Fig. 9) enables many more continuous descent operations from cruise to touchdown for the jet aircraft. This is contrasted sharply with the TMA operations (Fig. 8) in which the Center controllers required the use of step-down descents to meter the aircraft.

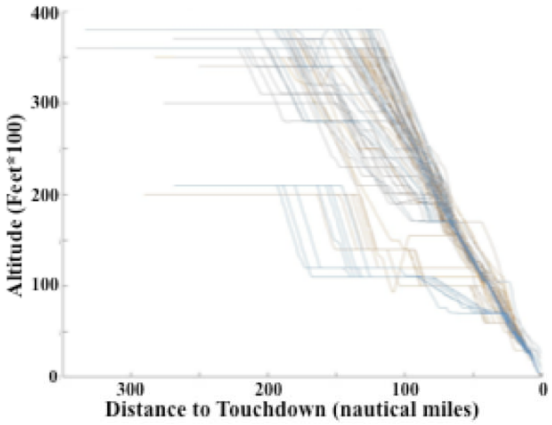

Figure 8. Descent Profiles Using TMA

Figure 10 plots the throughput for the 10% demand increase scenario. Throughput is referenced to aircraft landed per hour as a running average. The green line represents aircraft throughput if allowed to fly without intervention by controllers. This run also had hundreds of separation violations at the various merges and is shown only for reference purposes but would represent unconstrained demand on the airport. The peak throughput for this condition is 93.5 aircraft/hour. The red line is the run using the current TMA operations. This plot demonstrates the classic TMA front-loading technique with a peak throughput of 77.5 aircraft for an initial short duration and has an average overall throughput of 68 aircraft/hour during the capacity constrained period.

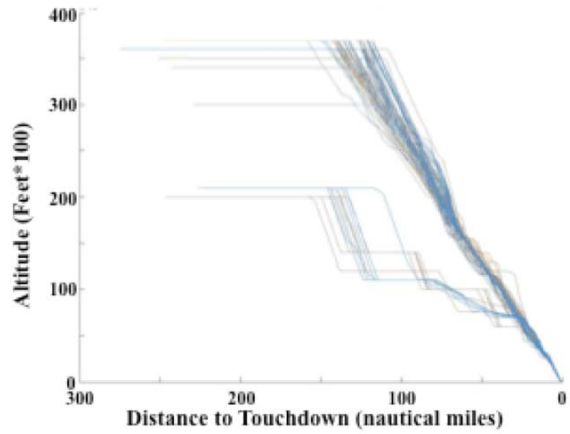

Figure 9. Descent Profiles using TAPSS

The blue line shows the TAPSS tools condition. As can be seen, the TAPSS tool has a higher average and peak throughput at times achieving 84 aircraft/hour with an average throughput of 75 aircraft/hour. Upon casual review it can appear that the current TMA does initially better with its front-loading effect, but the performance falls off to the 68-aircraft/hour TMA operations for LAX IFR conditions. The TAPSS results in less throughput initially but then maintains a higher throughput overall. This effect was

traced to the aircraft size distribution within the scenario. Early in the simulation there is a higher number of heavy aircraft and later a higher preponderance of large aircraft. Thus TAPSS is responding to the actual aircraft size distribution within the scenario better than the TMA system. On average the TAPSS provides a 10% increase in throughput under the same demand as compared to today's ATC operation using TMA. The key mechanism for this benefit seems to be two-fold. The first is the better systems response to aircraft size variations and their associated separation requirements. The second appears to be the higher controllability using the TAPSS technologies. Though not shown in these data, other analyses indicate that the average speeds on final are greater for the TAPSS system thus enabling higher effective landing throughput.

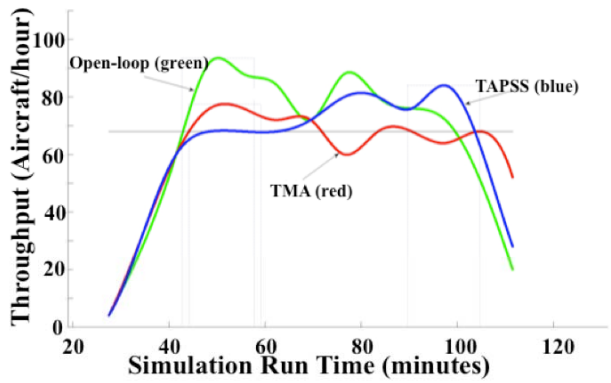

Figure 10. Airport Throughput Comparison

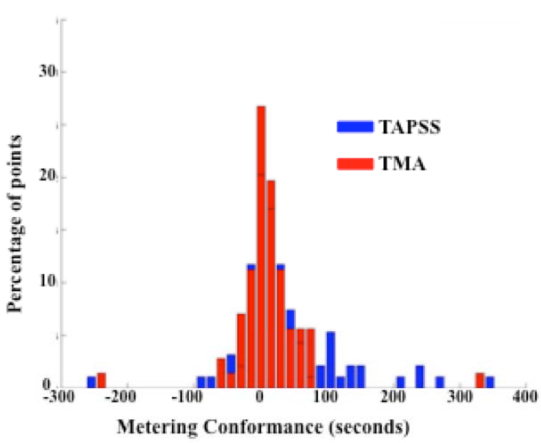

Figure 11. Conformance Histogram for DEANO

To better understand the higher controllability aspect of the TAPSS system Figures 11 and 12 show a comparison of typical controller schedule conformance histograms at a representative meter-fix and runway. Figure 11 shows the metering conformance (STA - actual meter-fix crossing time) for the DEANO meter-fix (northwest corner) for the two types of operation. The TMA operation is shown in red and the TAPSS operation shown in blue. Both operations show similar controller conformance performance. Mean error and 1-sigma standard deviation for the respective conditions are -2 ± 25 sec and -7 ± 30 sec. In contrast, Figure 12 demonstrates that when the TRACON controllers are using the TAPSS system, they are able to provide more precise delivery accuracy to the runway (24R). The histogram demonstrates a significant performance advantage for the TAPSS tools. The mean and standard deviation for the TAPSS tools are -15 ± 30 sec and -277 ± 95 sec for the TMA operation. This demonstrates the lack of runway precision in the TMA operations as well as significant landing opportunity loss due to most aircraft landing late.

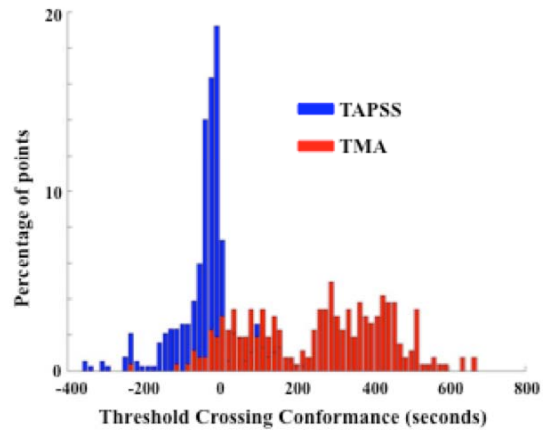

Figure 12. Conformance Histogram for 24R

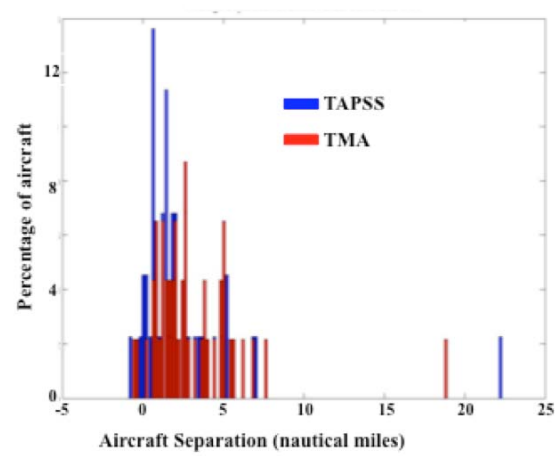

Figure 13. Aircraft 25L Separation at Outer Marker

Finally, some consideration needs to be given to overall safety of the system. Figure 13 shows the histogram of the separation performance relative to minimum separation required between landing pairs of aircraft at the outer maker. The figure shows the results for runway 25L. This was consistent for the other landing runways in the simulation, 24R. Controllers seem to achieve similar separation performance for both the current TMA and the TAPSS system operation. The TAPSS condition also had the separation peaked closer to the separation minimums indicating higher adherence to system separation goals. Both the runs show enough mean excess separation to account for compression on landing and are 1 NM for TAPSS and 2.5 for the TMA. Thus, for this limited look at

safety, TAPSS is at least as safe as the current baseline using separation violations as an indicator.

5.0 CONCLUDING REMARKS

The TAPSS, an advanced air traffic control decision support tool that integrates precision time and trajectory prediction, ATC constraint based scheduling and runway balancing, flow control visualization and controller trajectory-based advisories, has been developed and evaluated extensively in high fidelity human-in-the-loop simulations on the ZLA Center and SoCal TRACON. The tool generates speed and trajectory advisories that distribute delay efficiently between Center and TRACON operations. It was evaluated from today's level of operation to a 20% increase in airport demand. The tool was used to simultaneously achieve a 10% higher throughput when aircraft arrival demand exceeded runway capacity, and continuous descent fuel-efficient operations then capable in today's system.

This simulation and associated analyses show that the TAPSS system is a highly beneficial initial step in the development of a fully integrated trajectory-based automation that enables both greater airport throughput and fuel-efficient operations from cruise to touchdown for NextGen. Future plans call for the system to add capabilities to incorporate off-nominal conditions such as "go-around" and airport configuration changes during busy periods. Future scheduling enhancements of opportunistic time-advance and time recovery are being developed. Plans also include testing at higher levels of fidelity for both traffic conditions and actual FAA Center and TRACON controller equipment using TRACON routings closer to today's operations. This would accelerate the introduction into the National Airspace System meeting mid-term NextGen requirements for terminal metering

ACKNOWLEDGEMENT

The authors would like to acknowledge and thank the significant contributions of the controller subject matter experts whose insight and professionalism greatly enabled success of this effort: Tom Rudolph, Terry Comstock, Ted Blair, Charlie Burns, Neil Hightower, Scott Lewis, Roger Necochea, Dan Wood and Tom Wood.

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