DEVELOPMENT AND EVALUATION OF THE TERMINAL PRECISION SCHEDULING AND SPACING SYSTEM FOR OFF-NOMINAL CONDITION OPERATIONS

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Abstract

NASA has developed a capability for terminal area precision scheduling and spacing (TAPSS) to increase airport throughput and the use of fuel-efficient arrival procedures during periods of peak traffic congestion at high-throughput airports. This advanced technology represents NASA's current concept for the NextGen terminal metering desired capability. A series of high-fidelity human-in-the-loop simulation experiments were conducted to evaluate the performance of the TAPSS system during off-nominal conditions, specifically aircraft executing missed-approach and go-around procedures after transitioning to the final approach fix during an attempted landing. Each simulation run contained 2-4 missed approaches during a highly congested 60-minute period. The TAPSS system was adapted to arrival operations for the Los Angeles International airport (LAX). It was also enhanced to support automated missed-approach processing and procedures. The experiments evaluated the utility of the missed approach enhanced automation features by comparing system performance and controller workload with and without the enhancements. The simulated traffic throughput exceeded that of the current LAX operations with two runways in instrument meteorological conditions (IMC) by 10%. The results showed that when using the enhanced automation, the controllers could maintain the higher throughput levels with more consistent and predictable routing in the final operations but with increased vectoring and off-route aircraft in the feeder positions. Controller workload results indicated a preference for the automation enhancement especially as the numbers of missed approaches increased from 2 to 4 during the 60-minute evaluation period.

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 reduced airport capacity, increased controller workload, increased arrival delay, as well as increased 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 fully connected to the Instrument Landing System (ILS) approach procedures 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 2010 and 2011 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 in the complete NextGen future, with a fully implemented performance-based navigation infrastructure in the next 5-10 years, as well as the current procedures indicating viability in the next few years [6].

However, to ensure the viability of the TAPSS system, it needs to be evaluated for, and possibly enhanced to support, off-nominal operations in the terminal area. The previous HITL simulations had the controllers and pilots operating in a voice paradigm, with some level of off-nominal events, such as missed or incorrectly implemented clearances. These required corrective actions by the controller/pilot team. The breadth of possible off-nominal conditions is too large to be fully simulated in HITL. Thus, a series of HITL experiments were conducted focused on missed-approach operations in a highly saturated, periods in which the arrival demand exceeds the capacity, terminal environment. Missed-approaches greatly disrupt ATC arrival and landing operations especially during saturated conditions, as a missed approach is effectively two landings: one that is missed and another that has to be urgently implemented. Thus, during saturated conditions the controllers have to create a new landing slot where one currently does not exist. This usually involves a significant level of vectoring and extra controller-to-pilot clearances for not only the aircraft executing the missed-approach but also all the other aircraft in the immediate spatial and temporal vicinity. Research conducted by NASA developed significant insight into the interaction of automation, procedures and human-directed planning and to overcome the challenges of off-nominal operations [7,8]. These insights provided guidance to develop fully automated enhancements to reduce the amount of human planning and coordination of this previous research.

This paper will focus on results from a study performed in 2011 that evaluated viability of the TAPSS automated missed-approach enhancements. The research objective was to assess the TAPSS system during missed approach operations both with and without the automation enhancements. This paper is organized as follows: the next section describes the basic TAPSS operational concept including the missed approach automation enhancements. This is then followed by the details of the experimental methods and conduct, simulation results and discussion followed by summary and concluding remarks.

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) an enhanced FAA Time-Based-Flow Management (TBFM) technology known as the Traffic Management Advisor (TMA) with time-based precision scheduling features [3,9-10] and 2) the controller trajectory-based 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. These scheduler outputs are determined using high-fidelity modeling of aircraft four-dimensional trajectories from cruise to landing transitioning the various routing merges and applying aircraft sequence wake-vortex or radar separation constraints at appropriate merge, or the landing runway threshold, locations. 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 [11-13]. 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 [14-16]. Flight crews fly VNAV (Vertical NAVigation) descents along the RNAV approach and follow any controller clearances.

Missed Approach Enhanced Operational Concept

As discussed in ref. [3] a primary objective of the TAPSS technologies is to keep aircraft on their preferred routing through the terminal airspace. The technologies support the controllers in the use of speed control to achieve this objective while minimizing vectoring through the terminal airspace from entrance to landing. To achieve these objectives while maintaining both airport throughput and aircraft separation rules, the scheduler element of TAPSS uses a balance of scheduled separation buffers and speed-based delay distribution. Thus, during normal TAPSS operations there is minimal if any vectoring in the terminal airspace though speed based clearances are routinely used to maintain schedule conformance and throughput performance. During off-nominal operations, such as, missed-approaches there is intended to be enough schedule buffer and vectoring degrees of freedom to operate safely. This leads to a primary assumption for the missed-approach concept of operations (con-ops): the current airspace design and operations within the terminal should be able to operate with the added missed approach disruption and return to nominal operations without external help from the ARTCC. It is recognized that this assumption will necessarily break down as the number and frequency of the missed approaches increases. This assumption applies to both missed-approach con-ops; that is with and without enhanced automation.

Missed-Approach Con-ops Without Enhanced TAPSS Automation

The TAPSS un-aided con-ops defines a method that is very similar to the current-day handling of missed-approaches within today's terminal airspace. In our simulations all missed-approaches were initiated by the pilot after the aircraft was cleared for approach. The pilot, informed the tower controller, a confederate in our simulations, that the aircraft was executing the missed-approach procedure. The missed-approach procedure for the aircraft was to fly runway heading and climb until 3000 ft mean sea-level (MSL) and the fly to a missed-approach navigation waypoint that was either 15 deg left or right of the runway heading depending on the landing runway. The tower confederate controller handed the aircraft off to the correct feeder sector. The feeder sector then controlled and vectored the aircraft into the arrival sequence, handed the aircraft off to the final controller for sequencing and eventual landing. During this period the TAPSS automation continued to operate as if there was not a missed-approach. The controller's duties were to safely fit the aircraft into the arrival stream by creating an appropriately sized gap. During this period of disruption the controllers often vectored several aircraft to create the required gap.

Automation Aided Missed-Approach Con-Ops

The automation-aided missed-approach con-ops begins with a procedure that is similar to the un-aided scenario with the missed-approach initiated in the flight-deck. Additionally there is a defined missed approach procedure known to both the aircraft and the TAPSS automation that includes routing to re-intercept the arrival procedures along with both defined speed and altitude profiles. The initial routing for this procedure is very similar to the un-aided procedure but extends beyond the missed-approach waypoint back to the runway. Once the aircraft is handed off to the feeder sector he/she inputs, with a keyboard entry, that a particular aircraft is executing a missed-approach procedure and needs to be re-inserted into the arrival flow for landing. The TAPSS automation then reschedules all aircraft within the terminal and those not yet frozen in the ARTCC with this new aircraft included in the schedule. All effected TAPSS terminal automation symbology is updated with the new schedule as a single discrete update. This then re-schedules, using the same modified first-come-first-served algorithm described in the references, a series of properly sized gaps in the arrival streams to fit the aircraft executing the missed-approach back into the stream. Once this update is initiated the controllers then use the TAPSS guidance to manage the aircraft and depending on the situation may have to resort to vectoring until the missed-approach disturbance is mitigated. The scheduler also uses a reduced buffer size, from the nominal 0.3 nm to 0.1 nm for the missed approach affected aircraft within the terminal area. This minimized the overall schedule disruption with a possible cost of overall system safety.

Experimental Design

The TAPSS scheduling, controller trajectory advisories and missed-approach con-ops were evaluated using the Multi-Aircraft Control System (MACS) HITL simulation capability [17-18]. 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 to arrival operations to Los Angeles International Airport (LAX). The evaluation focused on the ability and the performance of the controller teams to safely control the traffic to the STAs at the meter-fix, merge-points and runways in the presence of missed-approach operations. The NASA Ames N210 ATC simulation laboratory was arranged with three ZLA Center arrival sectors handing off to three SoCal TRACON feeder positions, which then handed off traffic to two final positions. Once the final controller cleared the aircraft for approach at the final approach fix, the aircraft was handed off to the confederate tower controller. Figure 1 is a picture of the laboratory configuration 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 enhanced FAA TBFM 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 controller trajectory-based advisories both the TRACON feeder and final positions displayed timeline information associated with the merge-points and runways.

Eight controllers participated and staffed all required positions. The controllers worked the same positons for each simulation run. 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 1. ATC Laboratory Configuration

Simulation Scenarios

The simulation scenarios were based on the Joint Planning and Development Office (JPDO) 2004 baseline traffic scenarios used in their portfolio analyses. This scenario was evaluated to find a three-hour period with 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. Because all aircraft in the simulation started in the ARTCC, each controller controlled aircraft during an approximate 60 minute period. Using the same distribution values the arrival demand was increased to levels expected in the NextGen timeframe increasing by 20% to 66 to 78 aircraft per hour. The scenarios also included 0, 1, or 2 missed-approaches per runway in each the simulation run. The missed approaches were nominally separated by 8-10 minutes, starting from a period when the airport was operating at high congestion

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 continuously descending routes from the East known as Optimized Profile Descents (OPD) and standard oceanic arrivals from the Southeast. Continuously descending RNAV approaches from the West and Northwest were created to simulate ODP procedures. These routing profiles are shown in Figure 6 with the meter-fixes (labeled black), merge-points (labeled blue) and runways (24R & 25L) pointed out.

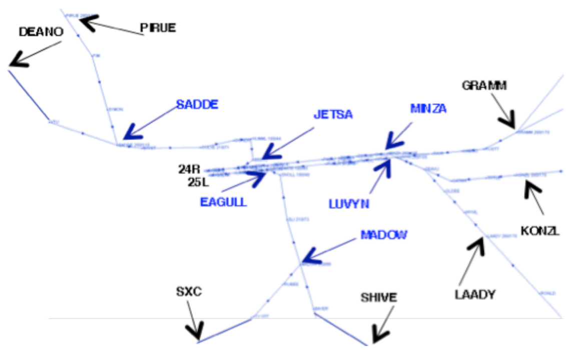

Figure 2. LAX Simulated RNAV Approaches

The missed-approach routing procedures used for the automation aided conditions are shown in Figure 3. In the simulations the only procedure available was a return to the original runway. The two procedures were similar in that they both had the navigational waypoint with RNAV turns back to the particular runway downwind, starting about 20 nm west of the airport. The automation was developed to allow the use of procedures to the alternate runways, though this feature was not used during the evaluations to limit the growth of independent experimental variables.

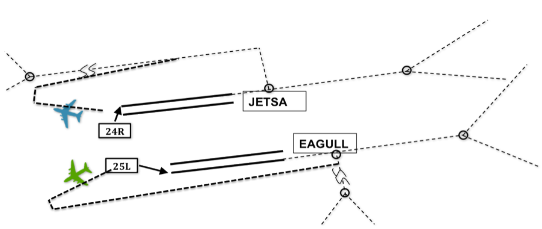

Figure 3. Missed-Approach RNAV Procedures

Experimental Conditions

An experiment was designed using the HITL simulations to evaluate the TAPSS system performance and controller workload in the presence of the missed-approach off-nominal condition. Table 1 shows the test conditions that were evaluated, including conditions in which the missed approaches were not conducted. A total of 13 data runs were included in the quantative analyses. Some of the runs contained situations where the pilots were able to follow the missed-approach procedures properly and and were deleted from the analyses. Thus the un-aided con-ops included analyses of a total of 17 missed-approaches and the aided con-ops inluded 14. As discussed before the number of missed-approach conditons evaluated included either one or two per runway during the 60 minute simulation run. Much of the experiment was dedicated to evaluating system performance with 2 missed-approaches per runway conditon. This was done to evaluate the con-ops and automation under the more challenging conditon of multipe missed-approaches to each runway. Each of these missed approaches were nominally separated by 8-10 minutes during the run, thus more runs were conducted with the higher 2-runway or a total of 4 missed-approach conditions. Both missed-approach con-ops were conducted with and without TAPSS missed-approach automation enhancements. For comparison purposes, two runs were conducted without a missed approach. The participant controllers were not told how many or which aircraft would perform missed-approaches during each simulation run and were only instructed as to the con-ops to be executed.

Table 1. Experimental Simulation Runs

Missed-Approach Condition	Number of simulation runs	Un-aided con-ops	Aided con-ops
0/runway (baseline)	2	0	0
1/runway	4	4	3
2/runway	7	13	11

Results and Discussion

As discussed earlier the TAPSS missed-approach automation enhanced capability was compared against an unmodified version of the TAPSS system. Therefore the results and discussion in this section will compare and contrast primarily the differences between the two con-ops as a function of the number of missed-approaches. Also baseline results will be used to characterize the system performance in the presence of the missed-approach operations. The performance results provide insight into both quantitative system performance as well as controller workload evaluations.

TAPSS System Performance

Figure 4 shows a composite of the ground tracks of all the missed approaches conducted during the simulation runs. The solid blue lines are the missed approaches conducted using the TAPSS automation un-aided by the missed-approach processing. The orange dashed lines are the tracks of the aircraft using the automation aided con-ops and enhanced TAPSS technologies. The direction of the two landing runways 25R and 25L is shown for reference. The plot shows the extent of all the airspace used during these procedures which extends about 20 nmi north-south and about 40 nmi east-west. What is quickly observable in this plot is how the basic structure of the automation aided missed-approaches are much more regular and consistent. On the other hand many of the un-aided missed-approach operations show some tracks that are considerably shorter then the aided tracks especially to runway 25L which does not normally have a downwind segment due to basic airspace design. The tracks to 24R which are required to be sequenced and merged with a normal downwind segment are in many situations are extensively longer and even have an aircraft that executes a controller instructed go-around to maintain proper separation.

Figure 5 is a plot showing the statistical comparisons of the track miles actually flown for the missed-approach conditions for each type of missed-approach un-aided ("manual") and automation aided. The figure shows the maximum, minimum and median track miles flown as lines on the plot for the two different runways. Also displayed are box plots of the 25th and 75th percentile path lengths. The data shows that the missed-approaches that are automation aided, on average, have greater path distance, but with much less variability. Though the extra distance might be perceived as a negative, the authors caution that there was little attempt to optimize the missed-approach routes. Thus it is believed that shorter routing might have led to a less mean distance flown for the automation aided con-ops. The key point is the increased predictability of the automation-aided operations. Because these operations are happening at the height of extremely busy conditions, gaining predictability can be considered as an important overall benefit. The added consistency and predictability can also reduce controller mental workload and support automation in producing more robust predictions, thus creating more viable solutions.

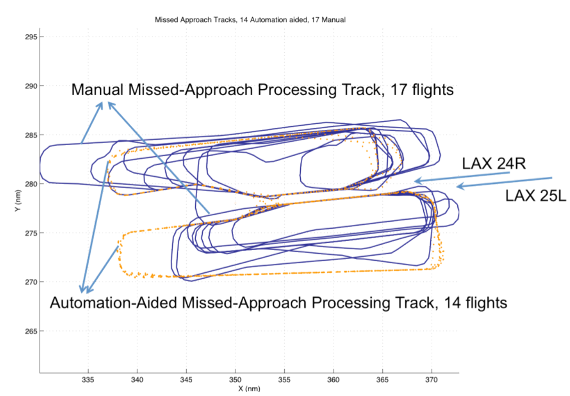

Figure 4. Missed-Approach Ground Tracks

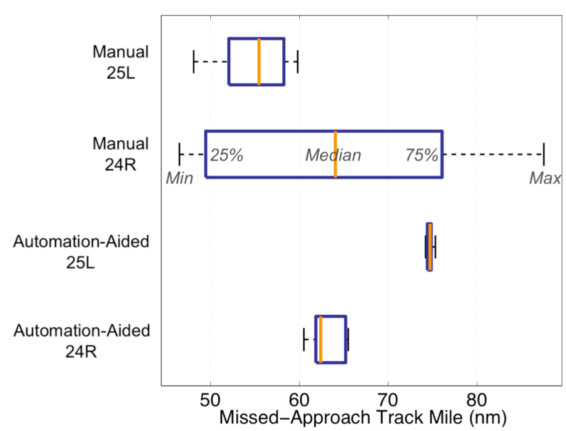

Figure 5. Missed-Approach Flown Track Miles

Figure 6 displays a basic system performance metric of average hourly throughput per each of the simulation runs. Shown is the average throughput during the period of the simulation starting with the first aircraft to land. This averaging is for simulation periods of approximately 60 minutes. There were shorter periods within the run in which landing throughput had a rate of 84 aircraft per-hour. The analyses was to determine if the missed-approaches in general, or the automation in particular had a detrimental effect on airport throughput. Each simulation achieved a similar average landing rate with the baseline shown in black, the un-aided (manual) shown in blue and the automation aided shown in orange. The data indicates that even in the presence of missed approaches the airport throughput can be maintained at a level similar to the baseline conditions for both con-ops. The airport average throughput rate ranges between 69 and 74 aircraft per hour in the simulations conducted. For reference, LAX routinely plans for a high of a 62 aircraft airport arrival throughput rate during IMC conditions in the west-flow runway configuration evaluated.

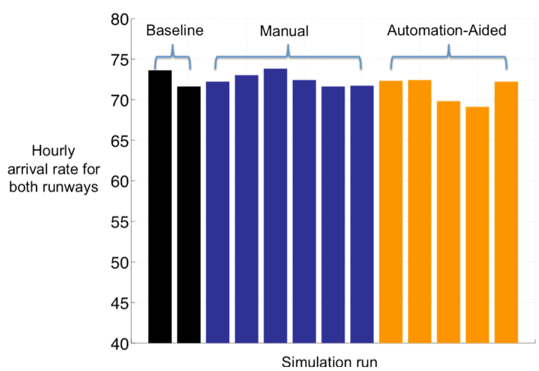

Figure 6. Airport Throughput Comparison

A very simplistic safety assessment metric was considered for the evaluation of the simulation data. These safety data examined separation violations within each run at runway threshold. A separation violation occurs when, two aircraft are closer than required wake-vortex separation, which depending on the type of leading aircraft can be 3, 4, 5 or 6 nm. Two key parameters of separation violations were considered, first the numbers of violations per hour and second the actual closest approach separation infraction distance. Figure 7 shows both these parameters for all runs. Shown in the figure are the hourly rate and the actual separation infraction distance. Though the simulation environment is considered mid to high fidelity it is not certified to test actual separation violations. Thus the data should only be considered useful in looking for trends and not absolute values. Solid blue arrows indicate the "safer" direction of the simple metrics of less numbers of violations and smaller violation distances. The data indicates that there is a higher frequency of separation violations and with greater violation distances for the un-aided missed approach simulations runs. This indicates that the missed-approach automation aided TAPSS has a potential for a greater level of safety then the un-aided system.

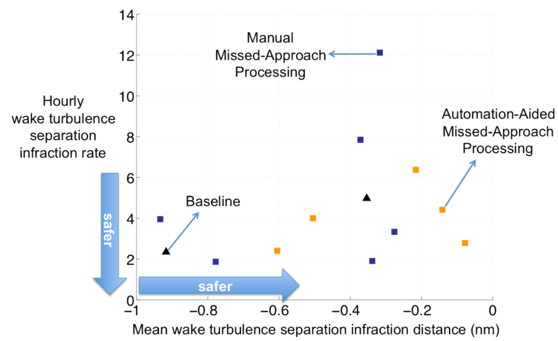

Figure 7. Safety Metric Comparison

TAPSS Controller Assessment

Workload data were collected in post-run questionnaires using the rating portion of the NASA TLX [19]. 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 TLX subscale. The mean ratings for the missed-approach manual and automation-assisted conditions are compared in Figure 8. The controllers were asked to consider only those periods in which missed approaches were being conducted. Taking the mean, participants thought they experienced "average" mental workload and time pressure. The success evaluation scale is in the opposite direction with high success indicated by a 1 and low by a 7. The mean value indicated that the controllers thought that they were successful in meeting their objectives. They expressed "some" frustration and they thought they were "highly" successful (which is true based on the objective results). Participants rarely used 7 to describe their workload, so the 22 occasions where the controllers said they had "very high" (7) mental load, time pressure, frustration and "very low" (1) success are notable. Six of these occasions were in the manual condition and 16 were in the automated condition. For all scales there is little difference in the means between the manual and automated condition. The means for the manual mental load and time pressure are slightly higher but are "average" for both conditions. The mean for manual success is slightly lower (so more positive) than the automated success mean but both are "high". The mean for manual frustration is slightly lower than for automated frustration, although this is the biggest difference between means of the four scales, but both reflect "some frustration". Thus, in general, although the differences are only slight, participants rated the demand on them as higher in the manual condition but felt, at the same time, that they were more successful and were more relaxed in the manual condition. This was discussed in subsequent post simulation debriefings and there was a consensus that the un-aided con-ops was very similar to their years of ATC experience with missed-approaches, therefore possibly more comfortable. It was also indicted that this could change as more experience is gained with the automation enhancements. The final controllers also observed that in some of the automated aided conditions they were not sure that there had been a missed approach. This observation means that the automation seamlessly integrated the aircraft back into the arrival flow from the final controller's perspective. This was considered a very positive observation.

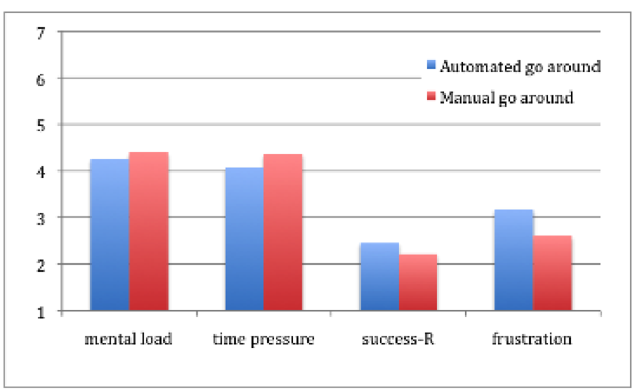

Figure 8. Controller Workload Ratings

Of the extensive results that were derived from the questionnaire the most significant results were in the types of clearances used to resolve the missed-approach operations. This data is from the self-reported questionnaire collected at the conclusion of each run. Unfortunately no quantitative data was collected to confirm or refute the reports. Figure 9 shows the type and extent of clearances used by the controllers. These include speed advisories, speed clearances, route changes, vectors, runway changes, climbs, early descents and level-offs. It is clear from these perception data that the manual go-around required significantly greater types of clearances to resolve the missed-approach off-nominal condition. These results were again, compared by the number of missed-approaches in each run. The controller participants felt that they issued more of every type of clearance in the 2-missed-approach per runway condition. On average they issued one or two types of clearance in the 1-missed-approach per runway simulations but issued up to seven different types in the 2-missed-approach conditions.

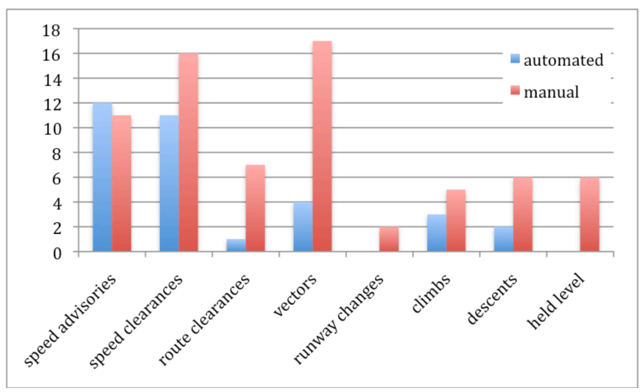

Figure 9. Controller Clearances for Missed-Approach Operations

Summary and Concluding Remarks

NASA has developed an enhanced capability for its terminal area precision scheduling and spacing (TAPSS) for operation during missed-approach off-nominal conditions. An extensive human-in-the-loop simulation was conducted to assess the viability of the automation-enhanced system in saturated landing conditions while conducting missed-approach operations. This first evaluation provided significant insight into both the design and operational concept of the missed-approach enhanced automation. Key findings are that when using the enhanced automation, the controllers could maintain the higher throughput levels afforded by TAPSS with a more consistent and predictable routing in the final operations during missed-approach operations. A general trend towards higher routing predictability and consistancy as well as a potential reduction in threshold separation violations was observed when using the missed-approach automation. The controller workload results indicated that the workload for both the automation enhanced and baseline automation was similar during the missed-approach operations. The controller questionnaire data also indicated that there was an increase in the numbers and types of clearances necessary when the TAPSS was unaided by the missed-approach enhancements, especially as the numbers of missed approaches increased from 2-4 during the 60-minute evaluation period. Further research is anticipated to more thoroughly evolve this enhancement supporting a more general class of off-nominal conditions.

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