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Controller-Managed Spacing – A Human-In-The-Loop Simulation of Terminal-Area Operations

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A human-in-the-loop simulation investigated how well terminal-area air traffic controllers could manage arrival traffic flying optimized profile descents on RNAV/RNP routes, while maintaining high throughput under varying environmental conditions. Scenarios were investigated with and without advisory tools and improved displays, and also examined how well controllers could cope with off-nominal situations such as ties at merge points. The role of an arrival management planner responsible for issuing path changes to aircraft upon entry to the terminal area was also investigated. The results show that in the tools condition, controllers kept aircraft on their routes while maintaining similar throughput levels to the no-tools condition. Route deviations occurred in the no-tools condition. While the absence of advanced tools resulted in slightly higher workload, the average controller workload ratings were low for both the no-tools and tools conditions. With the currently implemented advisory tools and displays, participant controllers in both conditions were able to absorb approximately one minute of delay with speed adjustments alone. This work is part of ongoing research on operations in super-density terminal airspace.

I. Introduction

The Super Density Operations (SDO) element of the NASA Airspace Systems Program is developing concepts for Next Generation Transportation System (NextGen) terminal-area operations in heavily constrained and complex airspace surrounding major airports.[1] One area of SDO research focuses on future concepts for controlling aircraft flying Optimized Profile Descents (OPDs) on Area Navigation/Required Navigation Performance (RNAV/RNP) routes. By avoiding extended level segments and keeping aircraft higher during approach, OPDs can reduce fuel consumption, emissions, and noise.[2] SDO concepts also seek benefits in the form of improved controller situational awareness, reduced aircraft flying time and distance, and improved predictability. Research has been carried out reporting that even partial OPDs result in some fuel and emission savings.[3] However, for these benefits to be realized, aircraft need to remain on their routes. This means a shift in the current control practices in the terminal area away from vectoring strategies.[4] The key concept for OPDs is highly accurate trajectory predictions of various aircraft that allow precise control by the terminal radar approach control (TRACON, or terminal area) controllers. However, frequent conflicts at merge points of arrival streams that require active controller intervention,

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trajectory prediction and aircraft performance uncertainties as well as off-nominal conditions are the main constraints for implementing OPDs today. Figure 1 shows typical air traffic control patterns at LAX when aircraft don't fly OPDs. Each track extension usually results in flying at low altititudes and excess fuel, noise and emissions. Furthermore, the presence of those uncertainties increases the risk of reducing runway throughput.[5] This is yet another reason that OPDs have not been implemented widely.

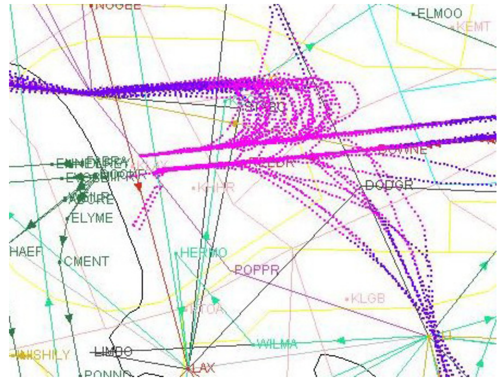

Figure 1. Current-day traffic patterns at LAX, showing a heavy use of vectoring.

NextGen research seeks to achieve increased structure in the TRACON, improvements in precision scheduling as well as the development of enhanced sequencing, merging and spacing capabilities. This implies a need for the development of advanced decision support tools and displays, with which controllers would be able to precisely control aircraft executing OPDs in a super-density environment using a minimum of clearances. For example, limiting the control to speed clearances only will help to maintain OPDs to the runways. Delivering aircraft closer to their Scheduled Time of Arrival (STA), with less excess spacing will also help to increase throughput levels.

In this study, a set of advanced TRACON controller aids was tested, with the aim of increasing controller situational awareness and enabling controllers to provide a more precise arrival traffic feed to the final control sector, and a properly spaced flow to the runway. Rather than testing each tool individually, the study investigated whether the tools can be effectively be integrated into the terminal-area controller workstation, and how well the different tools function in concert. The research also investigated whether advanced tools and enhanced displays would help controllers to cope with off-nominal situations. In addition, the research investigated the effect of an arrival management planner position on the control problem. In case of significant differences between the Estimated Time of Arrival (ETA) and STA of the aircraft upon TRACON entry, this controller was tasked to reduce these differences to levels manageable by the feeder controllers.

II. Background

Advanced controller aids for the terminal area have long been a subject of research. In 1989, NASA Langley reported on research on the traffic intelligence for the management of efficient runway scheduling (TIMER) concept.[6] TIMER aimed to structure the arrival stream prior to the terminal area using en route metering, and inside the terminal area to use time-based sequencing and spacing along fuel-efficient cruise and profile descents. The goal was to build a runway schedule, together with computer-generated controller aids, to improve delivery precision.

The Final Approach Spacing Tool (FAST) was a Center/TRACON Automation System (CTAS) decision support tool for terminal area air traffic controllers. It uses trajectory predictions to compute and display heading and speed advisories designed to sequence and space arrival aircraft to runways assigned via heuristic selection based on delay savings and workload benefits. An evaluation of a passive version of FAST ('P-FAST') that adjusted runway assignments and arrival sequences continuously in response to controller decisions showed benefits in terms of increasing airport arrival rates and runway utilization, and relatively high controller acceptance of the system overall.[7]

MITRE has researched several methods to solve merge problems in the terminal area.[8] Under FAA sponsorship, MITRE developed the Relative Position Indicator (RPI), a near-term future application that leverages RNAV and RNP procedures to improve predictability of merging arrival operations in the terminal area. The RPI algorithms calculate the distance of aircraft to a merge point along an RNAV or RNP procedure and convey this information via an indicator on the controller workstation. This information helps to further fine tune the spacing of aircraft at merge points.[9]

A study conducted at NASA Ames using the Atlanta TRACON airspace environment in 2008 preceded the study reported in this paper. This initial simulation evaluated the use of slot markers depicted graphically on controller displays, as well as runway timelines. Slot marker circles indicated where an aircraft would be if it were to fly the nominal arrival route through the forecast wind field while meeting all published restrictions, and predicted to be on time for its runway STA. Data were analyzed to determine the spacing error at the outer marker as well as the offset in distance between aircraft position and the respective slot marker position. The results indicated that when the slot markers were enabled the spacing violations and excess spacing was not reduced significantly. The results discussing the distance from the aircraft to the slot marker position versus altitude revealed that between 5,000 ft and 2,000 ft, there were no significant differences between the tools and no-tools condition.[10]

III. Experimental Design

The present controller-in-the-loop simulation was conducted in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center, using the Multi Aircraft Control System (MACS) software. MACS provides an environment for rapid prototyping, human-in-the-loop (HITL) air traffic simulations, and evaluation of the current and future air/ground operations.[11]

A. Airspace

Simulated aircraft were assumed to be flight management system (FMS)- and Automatic Dependent Surveillance-Broadcast out (ADS-B out) -equipped, and capable of receiving trajectory-based clearances via data link communication. The aircraft flew OPDs on merging RNAV routes to runway 24R of the Los Angeles International Airport (KLAX). Traffic was distributed over the RIIVR2, SEAVU2, OLDEE1, SADDE7 and KIMMO2 Standard Terminal Arrival Routes (STARS) to runway 24R. The traffic distribution and traffic mix on these routes were based on current-day traffic loads. The RNAV routes were designed based on existing STARS and approaches using the Trajectory-Based Route Analysis and Control (TRAC) tool.[12] Several speed and altitude restrictions were implemented that are shown in Fig. 2. The routes followed an approximate descent angle of 2.4°.

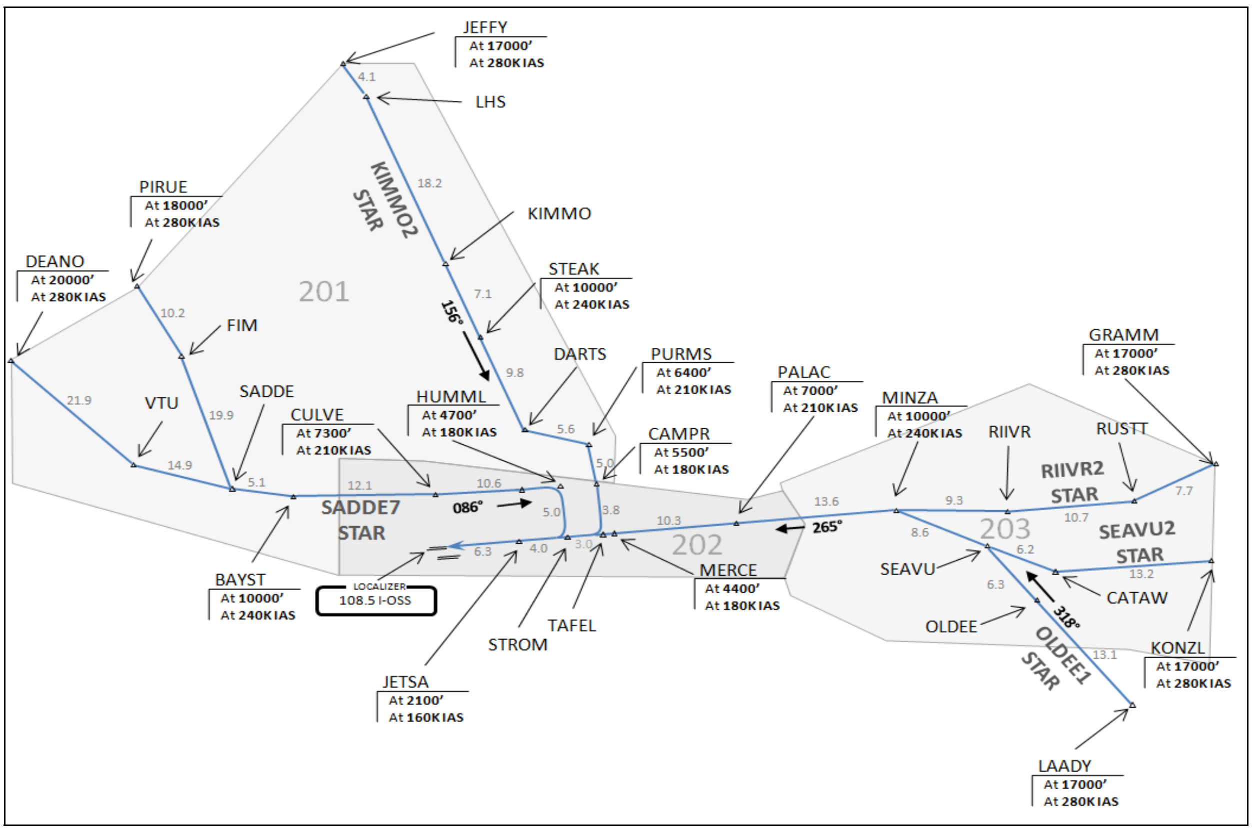

Figure 2. Simulated LAX airspace.

This allowed for speed control along the OPD's. Figure 2 shows a map of the simulated airspace displaying the sector boundaries, the STARs, waypoints, altitude and speed restrictions, as well as route leg distances. The simulation airspace was comprised of two feeder sectors, ZUMA and FEEDER (simulation sector numbers 201 and 203), and a final sector, STADIUM (sector 202). The sector boundaries were based on the currently operative sectors except sector 201, which was enlarged in order to include the KIMMO2 STAR. This resulted in some unexpected effects that are discussed later in the results section of this paper.

B. Conditions

Independent variables were wind forecast error, traffic scenario, and decision support tool (DST) availability.

1. Winds

Winds were always a headwind aligned with the landing runway. Two wind-forecast-error conditions were simulated. In one, referred to as the 'minus-bias' wind condition, the forecast winds were 10 kts less than the actual winds at altitudes below 20000 feet (Fig. 2). In the other, referred to as the 'plus-bias' wind condition, the forecast winds were 10 kts stronger than the actual winds.

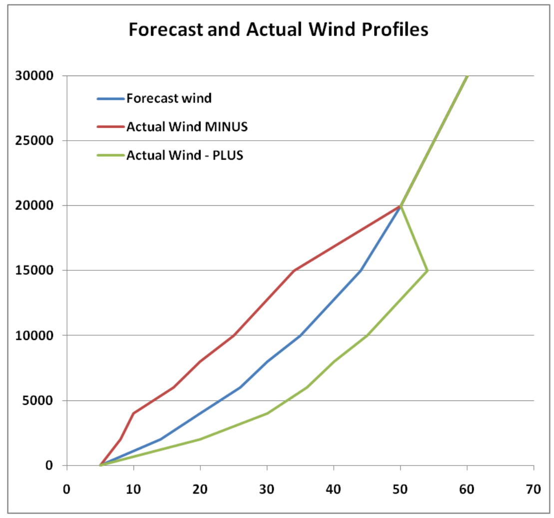

Figure 3. Actual and forecasted wind profiles.

2. Scenarios

Three different scenarios were used in the simulation runs. Scenarios A and B (see Table 1) were used as nominal scenarios, and did not have specific traffic conflicts built in. A third scenario, in which four merge conflicts were built into the traffic, was used as off-nominal scenario. If uncontrolled, the aircraft involved in the conflicts would arrive at the waypoints STROM, TAFEL, SADDE or MINZA at the same time. In addition, during trials with the off-nominal scenario, the controllers were asked to delay aircraft in order to build a gap in the arrival stream as would be required to accommodate, for example, a departure or terminal-area en route aircraft. The gap was built towards the end of the sequence, and was not at the same position in each off-nominal run. Table 1 shows the number of flights, type mix, and traffic distribution on the routes. All scenarios were constructed under the assumption that aircraft had been delivered to the TRACON entry points by en route control with no more than a +/-40 s nominal spacing error. However, due to the wind forecast errors, there were instances where aircraft entering the TRACON had ETAs up to 2 mins earlier than their STA in scenario B, and up to 3.5 mins in scenario A. The aircraft schedule used standard wake spacing distances (shown in Table 2) and included an additional 15 s buffer. When taking into account the approach speeds of the simulated aircraft, this buffer added approximately 0.5 nmi at the runway. The scheduling logic of the simulation software was also configured to allow an aircraft's STA to be scheduled up to 15 s earlier than its ETA.

Table 1. Scenario statistics showing the number of aircraft, type mix and traffic distribution on the STARs.

	Scenario A	Scenario B	Off-nom. Scenario
Number of a/c:	23	25	26
Type mix [%]: (B757 / Heavy / Large)	4 / 12 / 84	4 / 12 / 84	4 / 11 / 85
Traffic distribution [%]: SADDE7 / RIIVR2 / SEAVU2 / OLDEE1 / KIMMO2	48 / 24 / 20 / 8 / 0	48 / 24 / 20 / 8 / 0	44 / 30 / 11 / 11 / 4

Table 2. Wake Spacing Matrix.

	Trail Small	Trail Large	Trail Heavy	Trail 757
Lead Small	3	3	3	3
Lead Large	4	3	3	3
Lead Heavy	6	5	4	4
Lead 757	5	4	4	4

3. Decision Suppot Tools

In the tools condition, controllers had runway schedule timelines configured for the waypoints CULVE and PALAC and for the LAX24R runway (Fig. 4). Slot markers were also available during the tools condition (Fig. 5). As described earlier, slot markers are circles that indicated where an aircraft would be if it were to fly the nominal RNAV arrival route through the forecast wind field while meeting all published restrictions, and predicted to be on time for its runway STA. This means that an aircraft in the center of its slot-marker circle should arrive on schedule and consequently be properly spaced behind its lead (providing the lead aircraft is also in the center of its slot marker). The slot marker's radius was defined as the distance equal to 10 s of flying time at the charted speed. Both the slot marker and the aircraft target symbol were accompanied with the display of their respective indicated airspeeds. A third DST available during the tool condition were speed advisories displayed in the Flight Data Block (FDB). Designed to get an aircraft back on schedule (i.e., to "catch" the slot marker), the speed advisories suggested a speed to maintain ‘until’ a downstream waypoint. The speed advisories were displayed to the controllers if an aircraft’s ETA differed from its STA by more than 10 s (Fig. 5), and only if correcting the ETA was actually possible by the outer marker (JETSA).

C. Controller Tasks

The planning and control problem for the controllers was to cope with arrival traffic that was ahead or behind schedule, resolve ties at merge points, and handle off-nominal events when required (e.g., building a gap in the arrival sequence), all while dealing with the errors between forecasted and actual winds. The controllers’ goal was to efficiently deliver aircraft on their routes to the final sector and on to the outer marker and runway with no wake spacing violations. In conditions with controller tools, if path corrections were necessary in order to meet the schedule, sector controllers were instructed to coordinate with the planner.

The role of the feeder controllers was to accept aircraft check-ins from the pseudo-pilots, issue a “descend-via” clearance along the RNAV/RNP routes, and try to deliver the flights as close as possible to their STAs by their sector’s exit point, while using mainly speed control, and issuing as few clearances as possible. In the tools condition they were expected to use the timelines, slot markers and speed advisories to help them accomplish this goal. If necessary, controllers were asked to coordinate with the planner when larger maneuvers were needed. On initial contact a typical clearance would be “XYZ123 cleared for descent via the RIIVR2 arrival“ (result: aircraft were cleared down to 7000ft). After initial contact common clearances would be: “XYZ123, maintain 240 knots,” or “XYZ123, maintain 240 knots until MINZA, then resume charted speeds.”

The final controller was tasked with further fine-tuning the feed received from the feeder controllers. During the simulation they were also able to issue clearances they normally use, such as turning aircraft early to intercept the final approach course. For this maneuver, due to a limitation in the pseudo-pilot interface, the aircraft were put on a heading and then cleared direct to the JETSA waypoint. Similarly, extending the down-wind segment required a heading clearance before the turn onto the base leg. Upon check-in a typical clearance would be: “XYZ123 cleared for ILS runway 24 right approach.” When the aircraft were handed off to the tower, the feeder controller would issue: “Maintain 160 kts to the marker (JETSA), contact tower on 118.1”.

Aircraft were also color-coded on the controller displays to distinguish the different arrival routes. To support the planner, two predefined delay waypoints per arrival route were highlighted using a color scheme that matched the color-coding of the aircraft arrival routes. The delay waypoints allowed for one and two minutes of delay (in Fig. 6 TRTLE and HITOP, respectively). The planner used a trial planning function to compute a delay route using a path stretch via one of the delay waypoints starting at the TRACON entry points. The planner was advised to leave about 30 s to 60 s of delay for the feeder controllers to absorb. The trial-planned route was sent via data communication to the aircraft. Additionally, by interacting with the timeline, the planner had the ability to re-sequence and to re-schedule the arrival stream. Figure 6 shows an active trial plan over the one-minute delay point (TRTLE) for the RIIVR STAR.

Table 3. Number of experimental trials for each treatment combination.

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

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

In the no-tools (baseline) condition the controllers did have two display enhancements available based on the aircraft equipage assumptions: the indicated airspeed was displayed beneath the aircraft’s target symbol and, by clicking on the callsign in the FDB, the filed route of the aircraft could be displayed. Figure 5 and Fig. 7 show the various tools available in the tools and no-tools conditions, respectively.

D. Simulation Schedule and Setup

The simulation was conducted over 4½ days, including six training runs and sixteen simulation runs. The inclusion of the off-nominal runs, given the time constraints, led to an uneven number of repetitions for the different conditions (Table 3). Each 60 minute simulation run was followed by a post-run questionnaire and a short break (with a longer break for lunch). The simulation was closed with a post-simulation questionnaire and a final debrief discussion.

Simulation data logs documenting various metrics such as task-load (e.g., pilot and controller entries), trajectory and flight state information, performance data, etc., were collected from every controller- and pseudo-pilot workstation. Using an ATWIT[13] based procedure, controllers were prompted every five minutes to input a rating of their current workload level using Workload Assessment Keypads (WAK) embedded in the MACS software. Voice communications between controllers and pilots were recorded using an emulation of the FAA's Voice Switching and Communication System (VSCS). Additionally, controller and pilot interface actions were recorded as screen capture videos.

The two feeder and the final positions were staffed with recently retired controllers, two of whom had worked at the Southern California TRACON facility (SCT). The tower controller and the en route "ghost" controller, responsible for the areas surrounding the test sectors, as well as the arrival management planner, were staffed with retired confederate controllers.

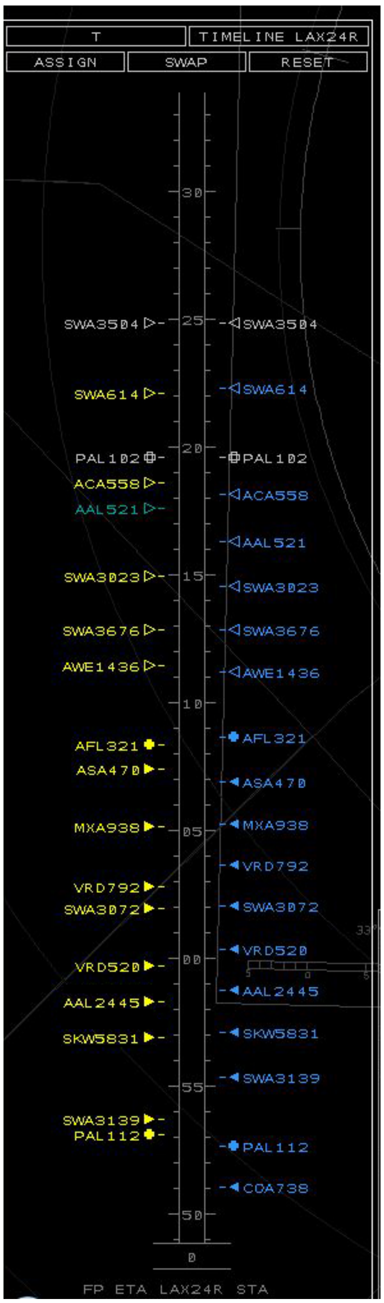

Figure 4. Timeline to LAX24R.

Figure 5. Slot markers, speed advisories and IAS indication in the tools condition.

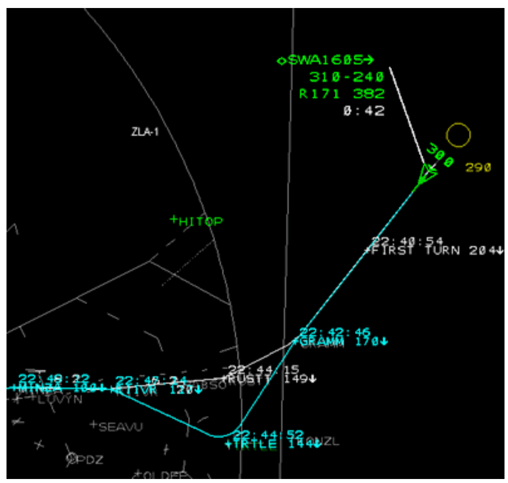

Figure 6. Trial plan of 1min delay route via TRTLE.

Figure 7. Planned route shown for an aircraft in the no-tools condition.

IV. Results

The results presented here discuss spacing accuracy, efficiency, route conformance, and controller workload measures.

A. Spacing Accuracy

A primary metric was the relative spacing between a lead aircraft at the time of runway threshold crossing and the trailing aircraft. This inter-arrival spacing data revealed that the accuracy of delivering the flights according to the standard spacing matrix (Table 2) did not significantly improve in the tools versus the no-tools condition. Figure 8 shows the histogram for the spacing distances at the runway of unique aircraft pairs for the wind error and tool-availability conditions. Inter-arrival spacing distances to the right of the zero-second-bin represent excess spacing, and the bins left of the zero-second bin represent spacing violations. Despite the 15 s buffer in the schedule, wake-vortex spacing violations still occurred for both the tools and no-tools conditions. Due to final approach trajectory prediction inaccuracies, aircraft meeting their STAs as of the outer marker crossing would sometimes begin to drift out of the slot marker circle, with wake spacing violations as possible result. The data in Fig. 8 illustrates that fewer violations occurred in the tools condition as opposed to the no-tools condition (n=5 and 20, respectively). This same trend can be seen in the plus-bias wind condition over the minus-bias wind condition (n= 9 and 16, respectively).

The results for the average inter-arrival spacing, for scenarios A and B, indicated that the tools had a positive impact on the inter-arrival spacing, compared to the no-tools condition (M=0.55 nmi and 0.64 nmi). For the off-nominal scenarios, the average inter-arrival spacing was larger in the tools condition (M=0.92 nmi and 0.86 nmi) (Fig. 9).

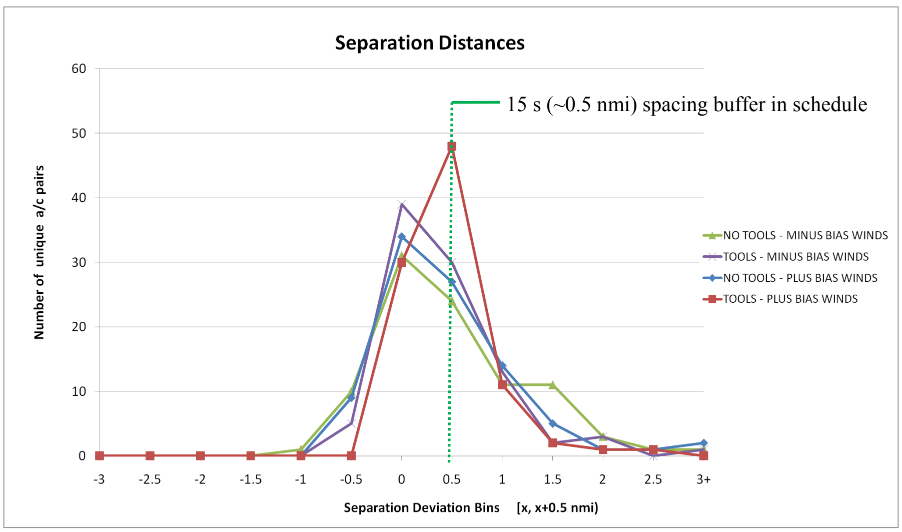

Figure 8. Actual Spacing between aircraft at runway threshold.

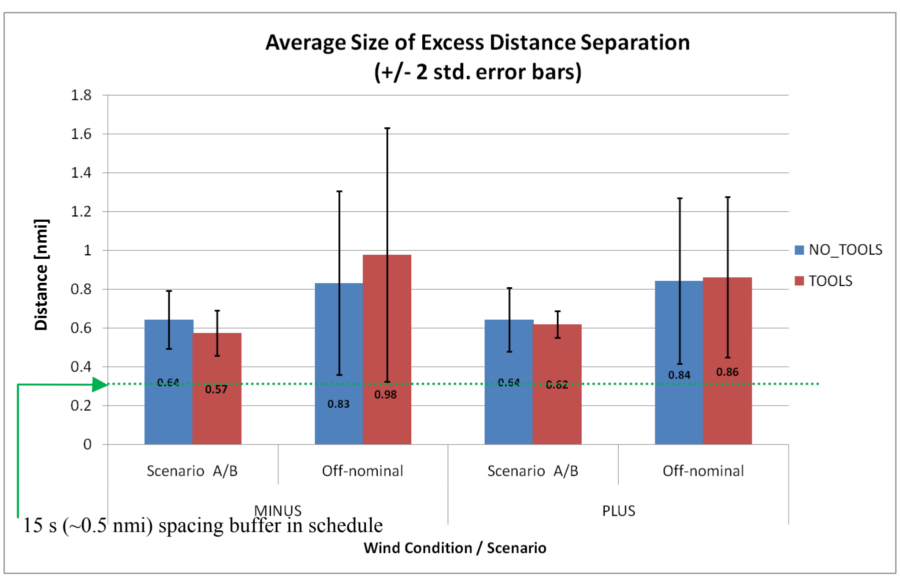

Figure 9. Average size of excess distance separation.

B. Efficiency

1. Throughput

Throughput is dependent on the order of aircraft weight classes in the arrival sequence and the scheduling criteria: using a 15 s buffer (0.5 nmi scheduling buffer) and allowing a maximum amount of time-advance in the schedule, the maximum theoretical throughput at the runway for the three scenarios in the two wind conditions is as follows in Table 4.

Table 4. Theoretical maximum throughput.

	Scenario A	Scenario B	Off-nom. Scenario
Minus-bias winds	34.34 ac/h	34.42 ac/h	34.39 ac/h
Plus-bias winds	32.92 ac/h	33.12 ac/h	33.76 ac/h

Table 5 shows the average throughput values for the different conditions and scenarios. Overall, no significant difference in throughput was achieved between the tools and no-tools conditions ($p < 0.05$). It is important to note that these values ignore the presence of wake-vortex spacing violations. Average throughput is larger in the tools condition opposed to the no-tools condition, for scenario A. Average throughput for scenario B is larger only in the tools / minus-bias wind condition. The opposite result was found for the off-nominal scenarios; average throughput was larger in the no-tools condition.

Table 5. Average actual runway throughput by scenario and wind condition.

Minus-bias winds	Scenario A	Scenario B	Off-nom. Scenario
Avg. throughput: no tools	33.38 ac/h	33.21 ac/h	32.88 ac/h
Avg. throughput: tools	33.9 ac/h	33.73 ac/h	31.89 ac/h

Plus-bias winds	Scenario A	Scenario B	Off-nom. Scenario
Avg. throughput: no tools	30.68 ac/h	33.16 ac/h	31.57 ac/h
Avg. throughput: tools	31.83 ac/h	32.17 ac/h	30.94 ac/h

2. Flight distance and flight time

As in previous simulations,[14] flight time and distance were used as surrogate metrics for fuel efficiency. Flight distance and flight time were analyzed using TRAC and were measured from the first plotted track point to the runway threshold crossing. Route lengths of the FMS route and the actual trajectory were also compared.

Note that the scheduler assigned STAs based on ETAs taking into account the actual winds at 1500 ft. Therefore, in the plus-bias wind conditions the spacing between consecutive STAs in the schedule was larger than in the minus-bias wind condition. Figure 10 shows the timelines for runs in the minus-bias (left timeline) and plus-bias (right timeline) wind condition. The figure indicates how the stronger tailwind component in the plus bias wind condition caused larger individual time spacing distances between consecutive aircraft and accumulated to an overall longer schedule. The aircraft ETAs tended to be earlier than the respective STA, especially towards the end of the arrival sequence (as shown in Fig. 10).

Due to the large size of sector 201, the controller used the available airspace and assigned many direct-to commands to cut aircraft short of the charted RNAV routes, especially in the no-tools condition. For example, Fig. 11 shows track plots with several flights sent directly to the waypoint HUMML (the tracks are color coded by altitude). The extensive shortcuts occasionally led to changes in the arrival sequence compared to the same scenario runs in the tools condition. Similar shortcuts were also observed in sector 203. Figure 12 and Fig. 13 show tracks from aircraft in the off-nominal scenario flying through sector 203, in both the no-tools and tools conditions. You can see that several direct-to clearances and delay vectors have been issued. Note that the delay vectors via pre-defined delay waypoints (HITOP and COREL) were issued by the planner, not by the feeder controller.

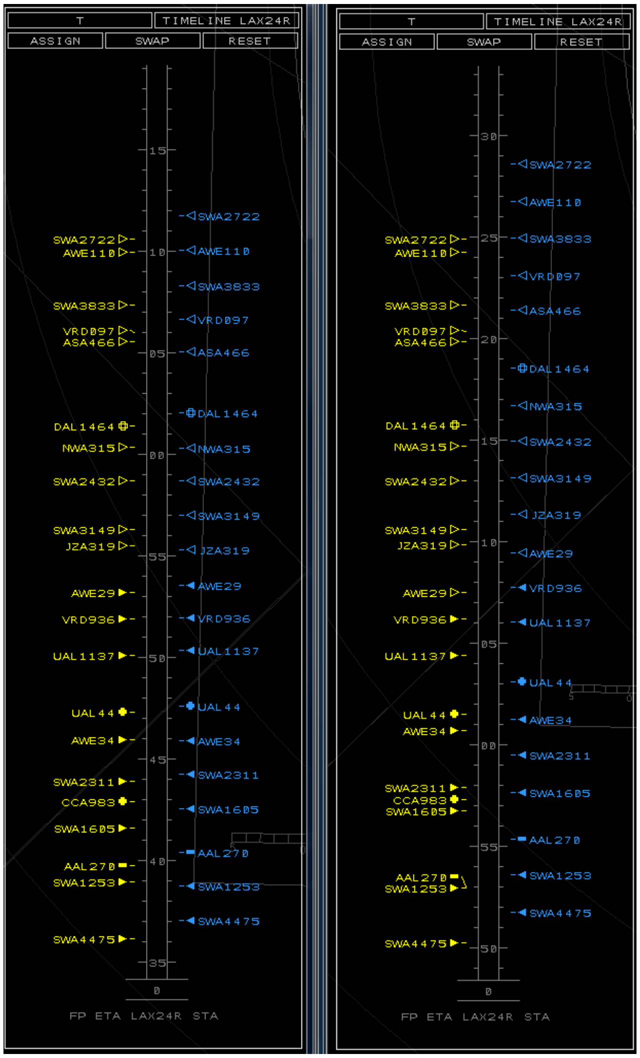

Figure 10. Timelines for runs in the minus-bias (left) and plus-bias (right) wind condition.

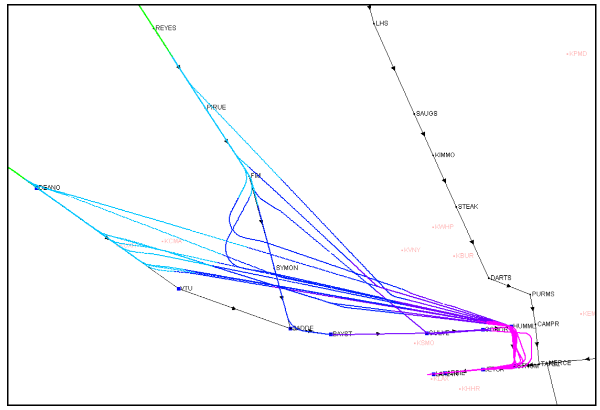

Figure 11. Tracks from aircraft that received direct-to clearances in sector 201.

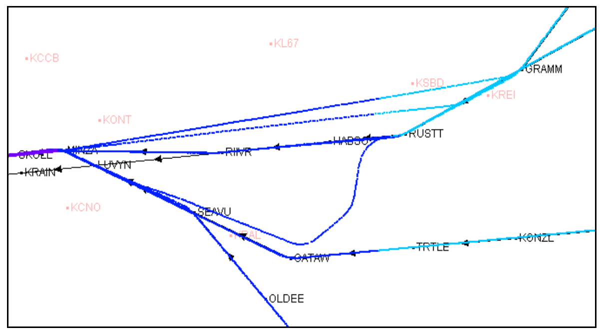

Figure 12. Tracks from aircraft that received direct-to clearances and delay vectors in sector 203 during a run in the no-tools condition.

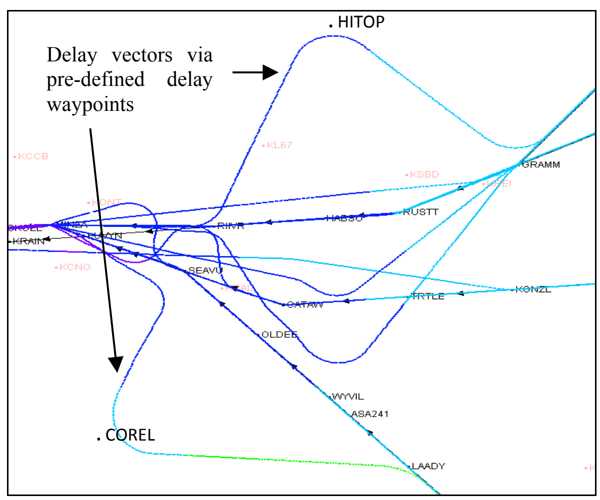

Figure 13. Tracks from aircraft that received direct-to clearances and delay vectors, also via predefined delay waypoints in sector 203, during an off-nominal run in the tools condition.

3. Deviations from RNAV arrival procedure

Figure 14 shows the average number of lateral deviations from the original FMS route (heading vectors, direct-to clearances, and delay vectors from the planner). The data is shown for the three scenarios, separated by the feeder sector that the flights went through. The data for sector 201 for the A and B scenarios show the frequent direct-to clearances issued by that controller in the no-tools condition. When counting only aircraft deviating off route in sector 201 that had not been issued a direct-to clearance to the waypoints CULVE or HUMML (the lower number in both of these columns in Fig. 14), the data shows that for either controller, on average, between zero and two aircraft were vectored off route in scenarios A and B. For the off-nominal scenarios, between one and 3.7 aircraft were vectored off route by either controller.

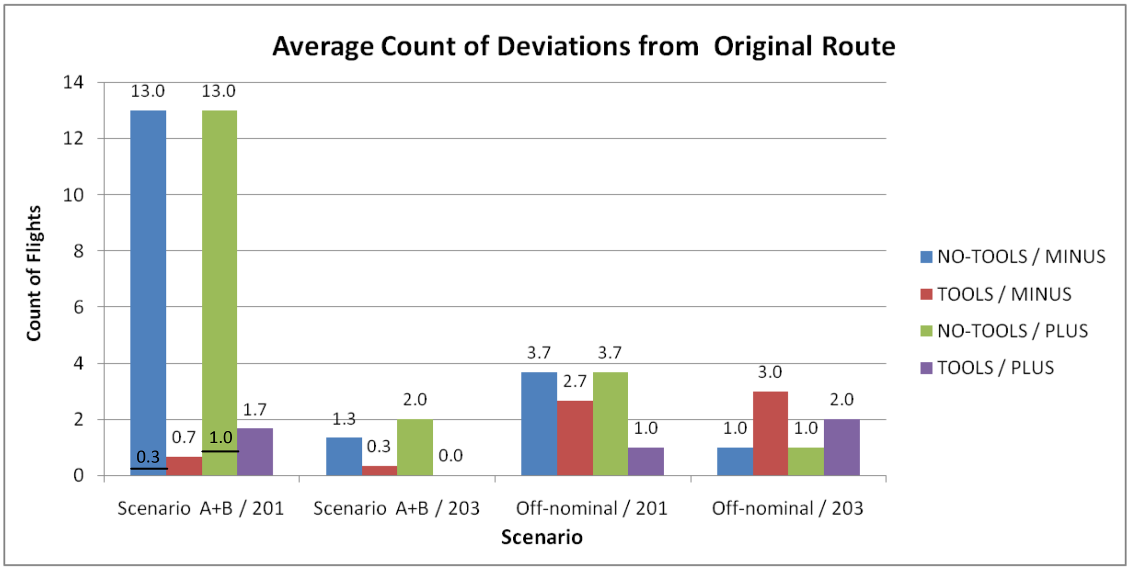

Figure 14. Average count of deviations from the FMS route.

Figure 15 and Fig. 16 compare the route conformance in the final sector, especially at the base turn, for the tools and no-tools conditions. In the tools condition, the final controller was able to keep the aircraft more closely on their route, as compared to the no-tools condition. In the no-tools condition various base extensions were used which would possibly result in fuel inefficiencies. Often the aircraft were sent on a 160° heading followed by a 210° heading before the turn onto final. However, it is not clear exactly what caused the final controller to issue the base extensions. Further analysis on route conformance in sector 202, as a function of the feed of traffic from the two feeder sectors is required.

There was no significant difference in flight distance across conditions. This is likely due in large part to the use of the same FMS procedures in all conditions. Results showed that in all conditions the aircraft flew more than 90 percent of their flying time coupled to their FMS. Comparing average flight distance and average flying time for scenarios A and B, no significant differences were found. In the off-nominal scenarios the flight distances were longer in the tools condition (M=185.2 nmi / 182.6 nmi for tools / no-tools conditions). Similarly, the flight times were slightly larger in the tools condition (M=2075 s / 2047 s for the tools / no-tools conditions). Again, an in depth analysis of route conformance is required, broken-down for each sector, and that perhaps excludes the direct-to cases.

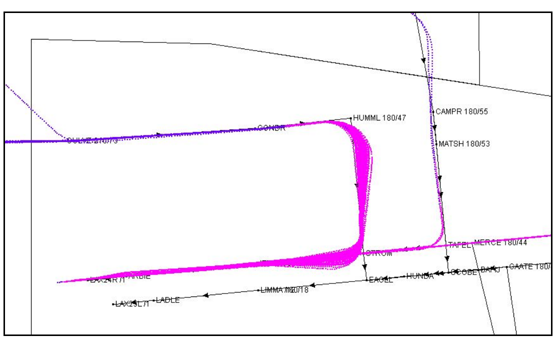

Figure 15. Base turn track plots for all aircraft of the runs in the tools condition.

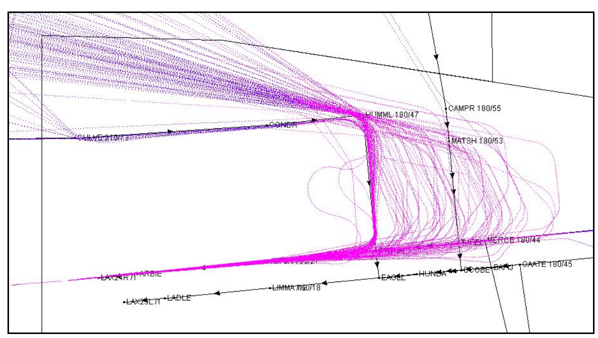

Figure 16. Base turn track plots for all aircraft of the runs in the no-tools condition.

Figure 17 shows the work of the planner in the off-nominal scenarios under the tools-condition: delay routes have been assigned in order to build a gap in the sequence. In the tools condition, the difference in lengths of the FMS route and the lengths of the actual trajectory is larger than in the no-tools condition. This is expected, because in the no-tools condition the planner was not available.

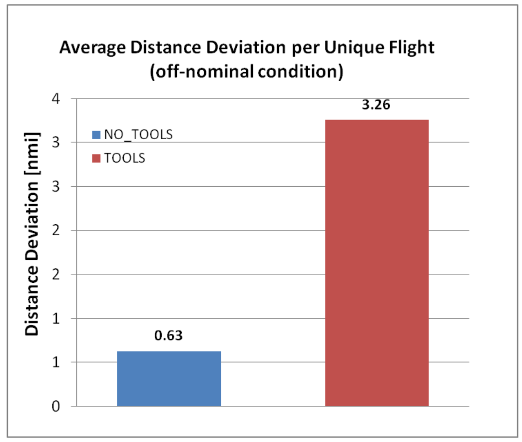

Figure 17. Average distance deviation (FMS vs. actual route) for runs in the off-nominal condition.

C. Workload

Real-time controller workload was measured using an ATWIT[13] based procedure. In our simulation controllers provided a workload rating on a scale of one to six every five minutes, with one representing very low workload and six representing very high workload. For all controllers, on an overall average, workload was perceived as "low" (M=2.14). Note that workload reported from the feeder controllers may be a result of low traffic loads in their sector due to operations to only one runway.

The data in Fig. 18 suggests that the tools did not have an effect on controller workload: the participant controllers gave similar workload ratings during the tools and no-tools conditions (M=2.18 / 2.11, respectively). Comparing the workload ratings of just the final controller between the tools and no-tools conditions maintained this trend: again no significant differences ($p < 0.05$) were found. As illustrated in Fig. 19, the data also suggests that the winds did not have an effect on controller workload: the participant controllers gave similar workload ratings during the minus-bias and plus-bias conditions (M=2.0 / 2.19, respectively).

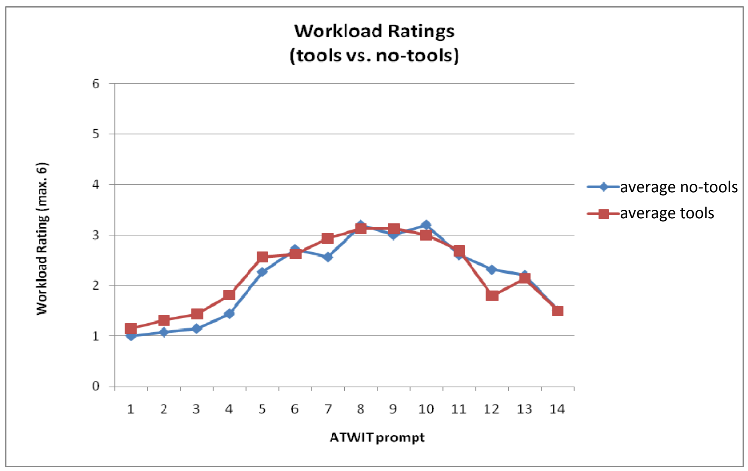

Figure 18. Average ATWIT workload ratings for the tools and no-tools conditions.

As a complement to the real-time workload ratings, workload data was also collected in the post-run questionnaires through the NASA-TLX[15] (Fig. 20). Although controllers reported the highest ratings on the mental demand scale (M=2.77, medium-low), their overall NASA-TLX workload was low, with the mean of the combined mental and physical workload scales being 2.37 (low). An analysis of the NASA-TLX data compared across conditions found no significant differences, with one exception: the data in Fig. 20 shows a significant difference in the controllers' ratings of their mental workload between the tools and no-tools conditions ($t(46) = 2.626$, $p=0.012$). Controllers rated the no-tools condition as mentally more challenging (M=3.2) than the tools condition (M=2.33).

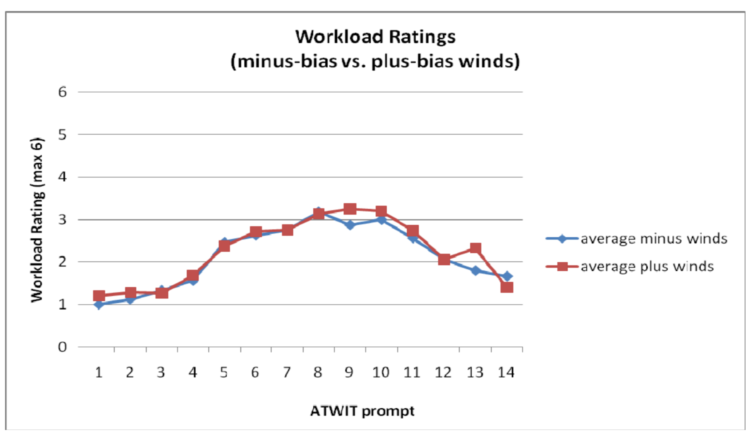

Figure 19. Average ATWIT workload ratings for the minus and plus-bias wind conditions.

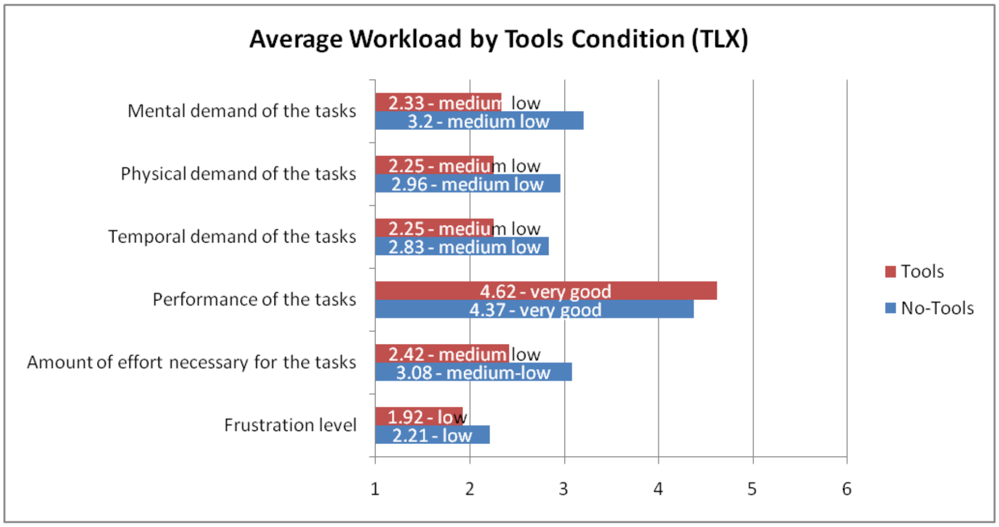

Figure 20. Average NASA-TLX workload ratings from post-run questionnaires, broken down by tools condition.

D. Discussion and Additional Observations

The simulation results were biased by two artifacts: the large size of sector 201, and the unexpectedly large ETA-STA differences due to wind forecast errors in the plus-bias wind condition. The large size of sector 201 gave the controller the opportunity to issue a large number of direct-to clearances. This affected the results for route conformance, flying time and flight distance. Using the current sector boundaries will prevent these effects in future simulations. The large differences between aircraft ETAs and STAs at simulation initialization and TRACON entry in the plus-bias winds condition increased the difficulty of the control problem. Larger spacings between consecutive aircraft STAs accumulated to produce a longer schedule. Therefore, the aircraft had to absorb more delay than in the minus-bias wind condition and the controllers had to issue larger control interventions in order to match the aircraft ETAs and STAs. The effects of the wind profiles on the schedule computations require further study.

The feeder controllers used the timelines, the slot markers, and the speed advisories as guidance to deliver a well-conditioned flow to the final sector. From observations during the simulation, it appeared that the timelines improved the situational awareness of the controller. Specifically, the controllers seemed to be able to quickly identify if the predicted spacing to the lead aircraft at the runway was too small, and if the aircraft ETA did not match the STA and therefore, control was required. No changes in the arrival sequence during the tools condition signifies that the controllers also might have used the timelines to gain a better awareness of the order the aircraft are scheduled to arrive. The slot makers were meant to give the controllers a spatial target to control to, and to help the final controllers merge aircraft and avoid excess spacing and wake spacing violations at the outer marker and runway. However, the speed profile used for the computation of the slot marker position differed slightly from the aircraft speed profile along the final approach, which caused aircraft that were on time to drift out of their slot marker circle. Improved trajectory predictions along the final approach would mitigate this problem.

Once these issues are addressed, results of future simulations can also give insight on how large an additional scheduling buffer should be. Controller performance and the usefulness of the improved decision support tools need to be investigated when the ETA-STA differences at TRACON entry are smaller or larger, and when other off-nominal conditions occur, such as a rescheduling event or a runway configuration change. Further improvements may be achievable through adjustments to the DSTs. For example, the speed advisories could be redesigned to enable controllers to reduce ETA-STA differences by the time they hand off aircraft.

V. Concluding Remarks

Results of the HITL simulation of merging terminal area arrival traffic show that, with display enhancements and decision support tools, controllers were able to keep aircraft on their routes. This finding indicates a progress towards the requirements for NextGen: the conformance of flights to RNAV/RNP routes (e.g., avoiding lateral vectoring) is essential for NextGen trajectory-based operations, as improved route conformance will enable OPDs which reduce fuel consumption, emissions, and noise, and because higher route conformance will reduce uncertainty and improve predictions.

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