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Arrival Scheduling with Shortcut Path Options and Mixed Aircraft Performance

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Abstract— Previous work introduced the concept of using tactical shortcut options to improve schedule conformance in terminal airspace. When a scheduling point is congested, aircraft are scheduled to longer nominal paths, holding shortcut path options in reserve for tactical use if an aircraft is late, thereby improving the schedule conformance, reducing the required scheduling buffer, and increasing throughput. When the scheduling point is less congested, aircraft may be scheduled to the shorter path with original larger scheduling buffers. Previous work focused on a single generic merge point serving aircraft with uniform arrival precision. This paper extends the previous concept to enhance the performance of time-based arrival management and consider mixed aircraft performance. Aircraft equipped to achieve a high degree of schedule conformance may be scheduled to the shorter path under the same conditions that a less equipped aircraft would be scheduled to the longer path, giving the equipped aircraft an advantage that can be seamlessly integrated into the scheduler. The arrival scheduler with shortcut path options for mixed aircraft performance is applied to a model of first-come-first-served terminal metering at Los Angeles International Airport. Whereas clear system benefits were found for tactical shortcut routing and higher percentages of equipped aircraft, very little advantage could be seen for equipped over unequipped aircraft that could be used to incentivize early equipage.

Keywords— *scheduling and spacing; arrival management; mixed equipage operations*

I. INTRODUCTION

With today's congested airports, a considerable amount of research has focused on increasing airport throughput. The throughput of a single arrival runway is ultimately constrained by how tightly flights can be spaced as they complete the final approach. Whereas wake separation requirements dictate a minimum allowable spacing for safety, the achieved spacing is nominally a half to one mile greater to account for imprecision associated with aircraft merging and wind uncertainties [1]. The current practice of vectoring to properly space merging flows is highly flexible, but demands a high degree of controller attention, and produces relatively varied spacing results.

Time-based arrival management concepts such as the 4D Cooperative ARrival MAnager (4D-CARMA) from German Aerospace Center (DLR) [2-4] and FAA's Trajectory Based Flow Management (TBFM) [5-7] make use of improved estimated-time-of-arrival (ETA) afforded by fixed routing,

such as Area Navigation (RNAV) and Required Navigation Performance (RNP), and wind forecasts to develop precise arrival schedules. The question of spacing precision then becomes one of schedule conformance. The more precisely flights can be controlled to meet their scheduled times of arrival, the tighter flights may be scheduled. To this end, these time-based arrival managers employ controller decision support tools to help meet a schedule. Higher schedule conformance can be achieved by controlling aircraft to their scheduled time of arrival with speed control rather than vectoring [8]. The increased schedule conformance allows reduced scheduling buffers and increased throughput.

However, speed control alone offers a limited range of flexibility to respond to disturbances. For example, maximum speed restrictions make time recovery for late arrivals difficult in terminal airspace. A more feasible path-based method of time recovery could increase schedule conformance, allowing the precision schedulers to reduce their buffers and increase throughput even further. Whereas path-based control in the terminal area is not a new concept, when coupled with scheduling, flights are usually scheduled to the shortest paths, reserving longer paths for exception handling [7,9]. However, an investigation offering standard path stretch and shortcut path options to controllers to recover from highly disruptive off-nominal events, found that the shortcuts were among the most often used [10].

Previous research explored tactical use of shortcut path options to allow time recovery for late arrivals with promising results [11]. However, the study focused on a single generic scheduling point and assumed all aircraft had similar arrival precision at the scheduling point. This paper extends previous research by applying the concept of tactical shortcut path options to enhance TBFM arrival schedule conformance and thereby gain system throughput and delay benefits without increasing controller workload. Tactical shortcuts are integrated into a model of TBFM multi-point arrival scheduling at Los Angeles International Airport. TBFM development has placed considerable effort on integrating high precision procedures for equipped aircraft [17] to not only reap additional system benefits, but to incentivize equipage. Mixed aircraft scheduling conformance performance is considered in this study to explore what if any advantage tactical shortcuts can give to high arrival time precision aircraft. The next section

summarizes the tactical shortcuts concept explored in previous research and the main findings.

II. BACKGROUND

A flight's schedule consists of scheduled times of arrival (STAs) at coordination points (e.g. meter fixes, merge points, runway thresholds) along a fixed nominal route. The STAs of sequential flights at a given coordination point are spaced to achieve at minimum the required separation between the flights plus an additional scheduling buffer to account for flight arrival time uncertainty. A suitable scheduling buffer can be calculated for a given arrival uncertainty and desired maximum likelihood of a separation violation requiring controller intervention.

The tactical shortcuts concept assumes that at some point prior to the coordination point, late flights have the opportunity to take a shortcut path option and recover time. Previous research found that shortcuts designed to recover ~ 1.5 times the standard deviation of the flight arrival time uncertainty, could allow flights to be scheduled with smaller buffers without increasing the likelihood of separation violation [11]. This equated to 11% increase in throughput during high traffic demand periods. During low traffic periods, more benefit was found in scheduling flights directly to the shortcut path with the original larger buffers if there was sufficient slack in the schedule. Essentially, the schedule strategically assigned a nominal or a shortcut path-based on how well the schedule could accommodate the respective buffer size requirements.

Because required buffer size also depends on aircraft schedule conformance precision, a similar method may be used to account for mixed aircraft performance. Aircraft equipped to meet a schedule with a higher degree of precision require less buffer and so may be scheduled directly to the shortcut path under the same conditions that would schedule a less equipped aircraft requiring larger buffers to the longer nominal route.

One objective of this paper is to apply the tactical shortcuts concept to multi-point scheduling modeled after a real terminal airspace. For this purpose, shortcut path options were designed for arrival routing into Los Angeles International Airport (LAX). The resulting routing provides shortcut opportunities at up to two separate merge points along a single route from meter fix to runway.

Another objective of this paper is to explore what if any advantage this method of nominal vs. shortcut path scheduling can give to high arrival time precision aircraft that may incentivize advanced equipage.

III. METHOD

A. Scheduler Model

The arrival scheduler was modeled after TBFM's terminal metering functionality. This is a multi-point first-come-first-served constraint-modified scheduler [5]. Flights are assigned an arrival runway and STAs at multiple coordination points along a fixed route (e.g. the arrival meter fix, runway threshold, and any merge points in between). Flights are

scheduled on a first-come-first-served basis according to their earliest runway ETA with a planning horizon of ~ 40 minutes (~ 200 nm) from the runway. The scheduler considers constraints based on minimum required separation at coordination points, and feasible time-to-fly (TTF) ranges between coordination points.

The TBFM model in this work uses given TTF ranges between coordination points and time blocks at each point to generate feasible STA time windows at each point [12]. The TTF ranges fed to the model are based on predefined nominal and slow speed profiles for the given engine type along the given route. Time blocks are time conversions (based on nominal speed) of the distance-based separation requirements of previously scheduled flights plus a scheduling buffer. In previous research on tactical reconfiguration [13], the required separation distances used by the TBFM scheduling model were 5nm at all coordination points more than 40 nm from the airport, and 3nm at all points within 40 nm of the airport. Some differences are applied to that model for this work. First, more realistic TTFs are calculated based on step-down speed profiles and nominal and slow speed restrictions from route adaptation used in TBFM [14]. Second, in-trail wake vortex separation standards are enforced. Third, in this work, the scheduling buffer used to define the blocked times of previously scheduled flights are not time conversions of a constant distance buffer. The time-based buffers are dependent on flights' expected arrival time performance at the coordination point, and the availability of tactical shortcuts for the coordination point. Parametric analyses from the previous tactical shortcuts work [11] were used to generate buffer size functions of expected arrival time uncertainty standard deviation and scheduled path (nominal or shortcut) for each coordination point. The use of speed control within the shortcuts allows the minimum buffer (designed for optimal time recovery) to be used for a desired threshold percentage of flights estimated to require tactical controller intervention to avoid loss of separation. For a threshold of 10% controller intervention, the required scheduling buffers are 1.1σ and 1.8σ when a shortcut is and is not available, respectively, where σ represents the estimated delivery precision based on aircraft equipage [11]. A normal distribution with zero mean is assumed.

The scheduler considered two control modes within the TRACON. All flights were assumed to be RNAV equipped with a subset also equipped with flight-deck schedule conformance precision capability. Flight-deck Required Time of Arrival (RTA) delivery precision is estimated to be 4 sec [15]. Flight-deck interval Management (FIM) delivery precision is estimated to be 4.7 or 2.2 seconds if fast speed profiles are used [16]. For the purposes of this research, the RTA or FIM capable aircraft delivery precision is assumed to be $\sigma_{RTA}=4.5$ sec. All flights without flight-deck schedule conformance precision capability were controlled from the ground with the aid of ground-based automation tools. Controller Managed Spacing (CMS) ground-based automation tools have been shown to have a delivery precision of 5.2 seconds [8]. However, a recent evaluation suggests that CMS

delivery accuracy may be as low as 8-10 seconds¹ [17]. For the purposes of this research, the ground controlled aircraft delivery precision is assumed to be $\sigma_{CMS}=9$ sec. Thus flight-deck control was assumed to have twice the precision (half the standard deviation) as ground-based control. Table 1 shows the scheduling buffers used in this study based on aircraft equipage and tactical shortcut availability.

Table 1. Scheduling Buffer Size

		Tactical Shortcut Availability	
		Available	Not Available
Delivery Precision	RTA	$1.1\sigma_{RTA} = 4.9$ sec	$1.8\sigma_{RTA} = 8.1$ sec
	CMS	$1.1\sigma_{CMS} = 9.9$ sec	$1.8\sigma_{CMS} = 16.2$ sec

The analysis will compare metrics for ratios of mixed aircraft performance between RTA and CMS control modes ranging from 0 to 1 in 0.1 increments.

B. Traffic Scenarios

The tactical shortcuts concept was applied to LAX arrival scheduling due to the availability of LAX adaptation used in recent human-in-the-loop simulations of TBFM terminal metering [17]. Figure 1 shows the standard arrival routes from this LAX adaptation. Routes extend from meter fix to runway. The Northwest flows feed only runway 24R, the South flows feed only runway 25L, and the East flows feed both runways.

Traffic scenarios were generated in 15-minute increments to meet a desired aircraft per quarter hour set of meter-fix ETAs. Each flight was then randomly assigned a weight class, engine type, and arrival meter fix according to weighted distributions observed from July 2014 historical traffic. Figure 1 shows the baseline LAX arrival routing used along with observed traffic distributions to each meter fix. Observed arrival traffic was comprised of 94% jets and 6% turboprops. Pistons were not considered, as they comprised less than 0.1% of the traffic. Of the three Northwest meter fixes, only jets used

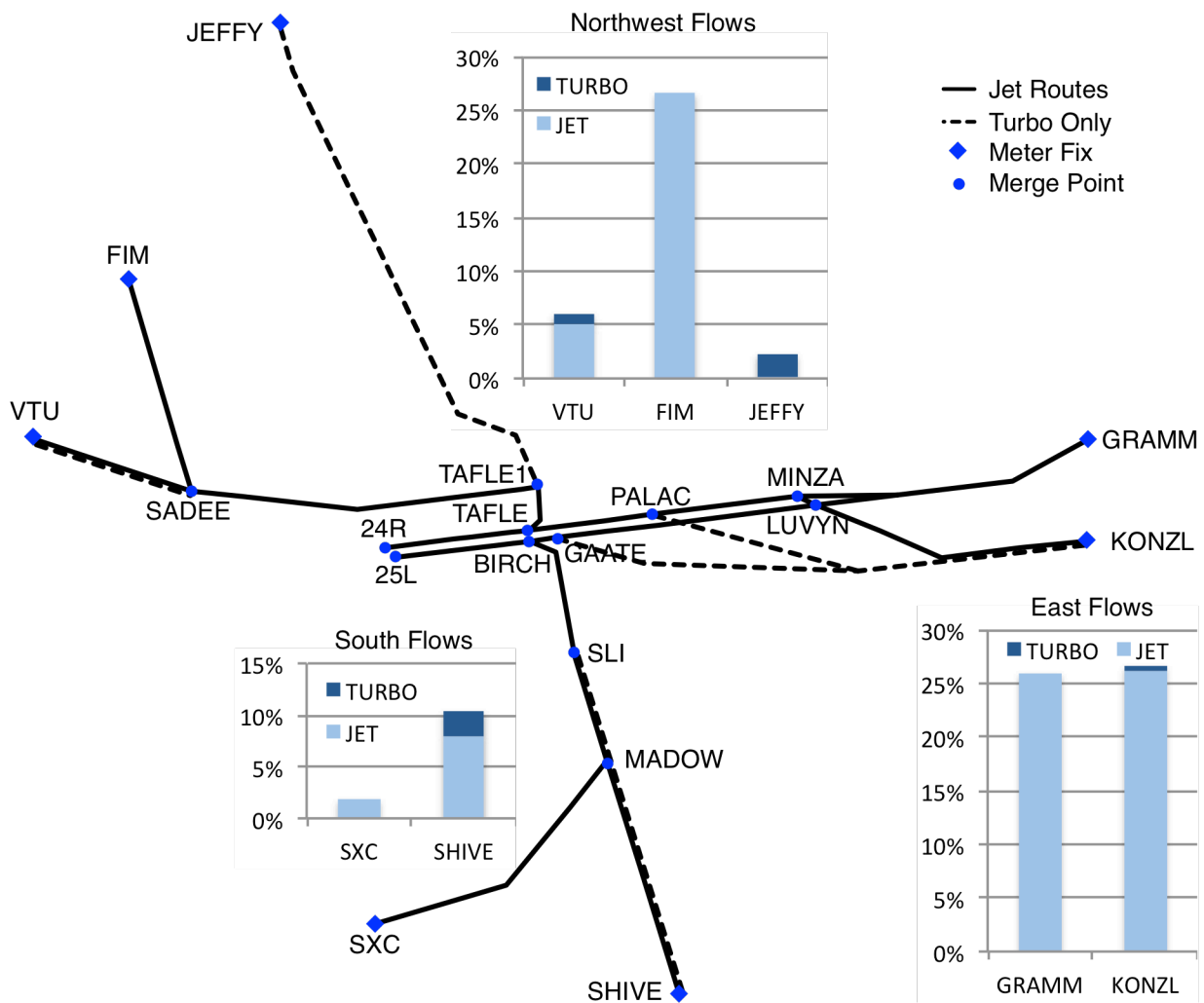


Figure 1. Distribution of observed JET and TURBO traffic across standard arrival routes adapted to LAX.

¹ Estimated 84th percentile (nominal distribution σ) schedule conformance at terminal schedule points.

FIM and only turboprops used JEFFY, whereas VTU was shared between jets and turboprops. Of the two South meter fixes, only a small percentage of jets used SXC, whereas SHIVE was shared between jets and turboprops. Of the two East meter fixes, only jets used GRAMM, whereas KONZL was shared between jets and turboprops. Dashed lines in Fig. 1 depict segregated routes used by turboprops only until they merge with jets downstream. Although turboprops share the VTU, SHIVE, and KONZL meter fixes with jets, the routes are altitude separated until they reach merge points SADEE, SLI, and PALAC or GAATE respectively. Jet weight classes were comprised of 1% super, 15% heavy, 9% B757, 74% large, and 1% small. Turboprop weight classes were comprised of 13% large and 87% small.

The above distributions were used to randomly generate 1000 2-hour traffic scenarios for an 18 aircraft per quarter hour arrival rate. Previous HITL studies of mixed equipage precision scheduling at LAX observed an average throughput of 71 aircraft per hour with standard deviation less than 3 [17]. This equates to 18 aircraft per quarter hour for the purposes of generating traffic scenarios in 15-minute increments as

described above. Each of the 1000 2-hour traffic scenarios included 8 quarter hours of 18 aircraft each totaling to 144 aircraft per scenario.

C. Route Scenarios

Shortcut path options were designed for jet-dominated routes where the geometry allowed. The shortcut path options are shown in orange in Fig. 2 along with the percent reduction in path distance each shortcut provides in the upper right corner. The orange diamonds mark the decision waypoints, before which the decision to use the associated shortcut must be made. The orange dots are new merge points introduced by shortcuts. Red dots are merge points from the nominal route structure that are bypassed when a shortcut is used. These merge points may be scheduled with reduced buffers due to tactical shortcut availability when nominal routing is assigned by the scheduler.

Of the six shortcuts shown in Fig. 2, two are final sector shortcuts (JAVSI to SAPPI2 and SLI to HUNDA), and the rest are feeder sector shortcuts. In this study, all of the shortcuts could be used tactically, but only the final shortcuts were

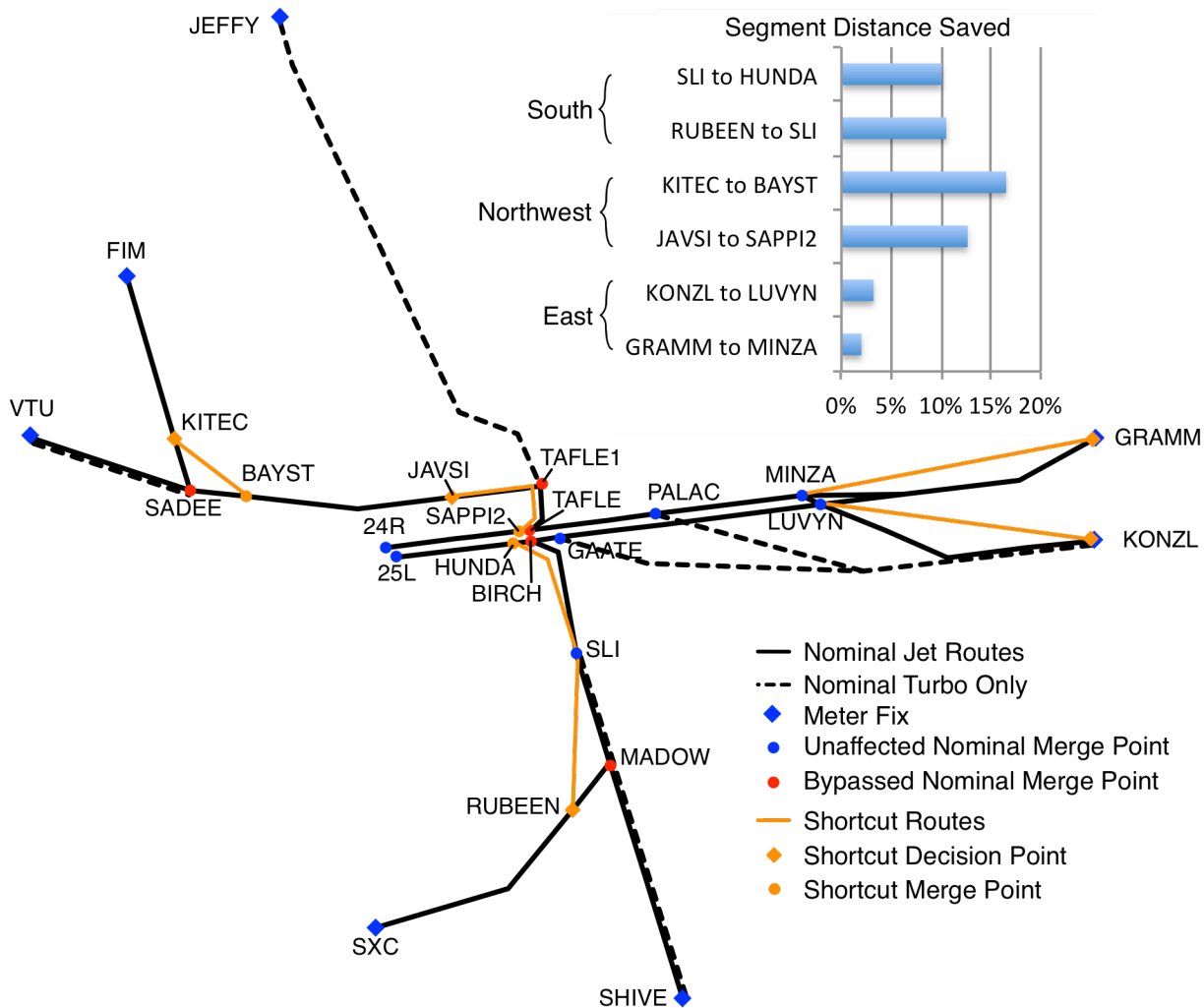


Figure 2. Shortcut routing and segment distance saved relative to standard arrival routes.

allowed to be used strategically by the scheduler. The existence of downstream merge points from the feeder shortcuts would inhibit their ability to offer earlier runway STAs by reducing buffers upstream. Therefore, it would seem advantageous to always schedule to the feeder shortcut routes, as they would provide the same or earlier STAs as the nominal routes. However, given the relatively large error at which flights were delivered to meter fixes, it was expected that the benefit of reserving these feeder shortcuts to tactically aid schedule conformance would be greater. This is why in this study feeder shortcuts were not allowed to be used strategically by the scheduler, only used tactically in simulation.

Simulation results will be compared between the baseline routing shown in Fig. 1 and the shortcut routing shown in Fig 2.

D. Simulation

Traffic scenarios characterized flights with unique meter fix ETA, meter fix, engine type, weight class, and equipment. If a flight had multiple procedure options available (due to final shortcut and runway options), the preferred procedure was assumed to be the one that resulted in the earliest runway ETA. Flights were ordered by this earliest runway ETA for first-come-first-served scheduling. Each flight was scheduled by trial scheduling each of its procedure options using the buffers in Table 1 according to equipment and shortcut availability, and the procedure producing the earliest runway STA was assigned to the flight and its schedule was frozen.

After all flights were scheduled in this way, the simulation processed actual times of arrival (ATAs) at all coordination points in order of the STAs. Flights were not allowed to change sequence. A Gaussian error was added to the closest reachable time to the STA to get a preliminary ATA. For merge points and runways, the Gaussian error was based on the same arrival precision assumed by the scheduler, $\sigma_{CMS}=4.5$ sec for equipped and $\sigma_{RTA}=9$ sec for unequipped aircraft. Delivery precision to the meter fix was assumed to follow a Gaussian error of $\sigma_{MF}=60$ sec without the benefit of precision scheduling and spacing tools in Center airspace. All Gaussian errors were clipped to $\pm 3\sigma$ to avoid extreme outliers.

The reachable time assumes speed control authority can only modify the scheduled time-to-fly (TTF) within a certain range. The control authority assumed in the controller speed advisory tool research was $\pm 15\%$ [18]. However results from a recent HITL experiment suggests that the purely speed-based control authority is less than half this [17]. For this work speed control authority may increase scheduled TTF by 10% (by flying slower earlier) or decrease scheduled TTF by 5% (by flying faster longer). Note that this model is not centered at zero like the speed advisory tool, but gives more flexibility to increase TTF (slow down) than to decrease TTF (speed up) to be more realistic. These limits on TTF range make it possible for errors to cascade to the adjacent coordination point. If the error at a coordination point is late enough such that decreasing the flight TTF by 5% is unable to catch up to the original STA at the next point, the upstream ATA + (TTF-5%)

serves as the closest reachable time to which the next Gaussian error is added.

Each sequential point had an independent error applied to it. To ensure reasonable errors were applied, error was clipped to be within the range of a 10 kn head or tail wind error between sequential points. For example, consider the 2-mi segment between LUVYN and MINZA. Assume the final adjusted scheduled TTF for a flight between these points is 30 sec, making the average speed 240 kn. Assuming at most a 10 kn wind error, the 230 kn to 250 kn average speed translates to a 28.8 sec to 31.3 sec range of reasonable actual TTF. Assume the random sampled Gaussian error is 5 sec suggesting that the actual TTF for this segment be 35 sec. This is outside the reasonable error range for such a short distance, so the actual TTF is clipped to 31.3 sec to calculate the preliminary ATA at MINZA. For this segment distance, equipment is unlikely to make much of a difference in precision. However, it would make a difference in the next segment from MINZA to PALAC where the 13.6 mi segment distance at the same average 240 kn speed results in a reasonable actual TTF range of 195.4 sec to 212.4 sec and an error range of -8.8 sec to 8.1 sec.

The preliminary ATA was then compared to the preceding ATA at the coordination point. If the time spacing is less than the required separation, the preliminary ATA was adjusted back to meet the required separation. Spacing related adjustments that make the actual TTF greater than the scheduled TTF + 10% are assumed to require vectoring.

For shortcut options simulations, schedules must be created for the additional merge points (orange dots) and decision points (orange diamonds) seen in Fig. 2. The decision points that are also meter fixes or merge points use ATA-STA error at the decision point to determine shortcut use. The remaining decision points are scheduled without buffers purely to estimate errors (ETA-STA) at the downstream merge point that the shortcut bypasses. The ATA-STA error at a decision point was assumed to be the same as the ETA-STA at its downstream merge point. All flights that were late (ATA>STA) at the decision point used the shortcut. Shortcut use shortened the scheduled TTF of a route segment by the percentages shown in Fig. 2. The adjusted scheduled TTF was then used to calculate the next downstream ATA as described above.

Simulations were repeated 100 times for each traffic scenario with unique random errors applied in each simulation.

IV. METRICS

The following metrics were computed for comparative analysis between mixed aircraft performance ratios (ranging from 0 to 1 in 0.1 increments) and routing models (baseline vs. shortcut).

A. Throughput

Demand throughput, scheduled throughput, and actual throughput were hourly rates of ETA, STA, and ATA, respectively. Hourly throughputs were calculated as the numbers of ETAs, STAs, and ATAs at either runway between

60 and 120 minutes into each simulation. This time range represents the most consistent runway loading of each 2-hour traffic scenario. The demand and scheduled throughputs were averaged across the 1000 traffic scenarios generated. Actual throughputs were averaged across 100 simulations for each traffic scenario before averaging again across the 1000 traffic scenarios.

B. Scheduled Delay

Scheduled delays were segregated between delay absorbed in the TRACON and delay passed back to the Center. TRACON delays were further segregated between delay absorbed by path and by speed. Center delay is the difference between meter fix STA and ETA. TRACON path delay is the difference between the scheduled route runway ETA and the preferred route runway ETA. TRACON speed delay is the difference between runway STA and scheduled route ETA minus Center delay. Total delay is the sum of Center, TRACON path, and TRACON speed delay, which is also the difference between runway STA and preferred runway ETA. Delays were first averaged across all 144 flights in a single scenario and averaged again across the 1000 traffic scenarios.

C. Workload

The highest priority controller task is maintaining separation. The percentage of instances when the preliminary ATA must be modified was used to represent speed control workload. Similarly, vectoring workload was measured separately as the percentage of instances a flight's actual TTF on any route segment is greater than the speed control authority range of scheduled TTF +10%. This may happen when an ATA is pushed back significantly.

D. Shortcut Usage

Shortcut usage was evaluated for the shortcut routing case only as the baseline routing case did not have any shortcuts. Both scheduled and tactical shortcut usage was measured. For all flights with the option of scheduling to a particular shortcut, scheduled shortcut usage is the percentage of flights assigned to the shortcut route by the scheduler. These percentages were calculated across all 1000 traffic scenarios. Only the final shortcuts (JAVSI to SAPPI2 and SLI to HUNDA) were available as schedulable shortcut route options. VTU and FIM flights were used to evaluate JAVSI to SAPPI2 scheduled shortcut usage. SXC and SHIVE flights were used to evaluate SLI to HUNDA scheduled shortcut usage.

Tactical shortcut usage was evaluated for all shortcuts (two final and four feeder). For all flights scheduled to the nominal path and able to use a particular shortcut tactically, tactical shortcut usage is the percent of flights that used the shortcut in simulation. These percentages were calculated across all 100 simulations per scenario across all 1000 traffic scenarios.

E. Schedule Conformance

Schedule conformance is the difference between ATA and STA at each coordination point. Standard error (standard deviation from zero) and mean error were calculated at each

coordination point across all 100 simulations per scenario across all 1000 traffic scenarios. Standard deviation from the mean was originally considered as a schedule conformance metric. However, the typical shape of the error histograms was asymmetric with peaking close to zero, short tails on the left (early) and long tails on the right (late). Therefore, standard error was chosen rather than standard deviation to represent the error spread.

V. RESULTS

This section presents the comparative analysis of the metrics between baseline and shortcut routing and between CMS and RTA equipage.

A. Throughput

Shortcut routing achieved higher scheduled and actual throughput at lower equipage ratios, but this benefit decreased as the RTA ratio increased.

Figure 3 shows average demand, scheduled, and actual throughput for baseline and shortcut routing cases as the ratio of RTA equipped aircraft increases from 0 to 1.

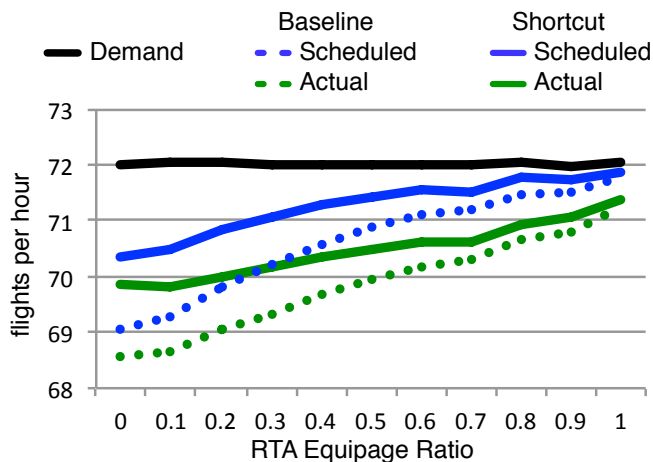


Figure 3. Demand, scheduled, and actual throughput

The black demand throughput line is consistently ~72 aircraft per hour. This shows how the traffic scenarios of 18 aircraft per quarter hour at the meter fixes projected the same demand rate to the runways. The dashed and solid colored lines represent baseline and shortcut routing cases respectively. The blue and green lines represent scheduled and actual throughput respectively. Scheduled and actual throughput for both routing cases increases as the ratio of equipped aircraft increases. The actual throughput is consistently ~1 aircraft per hour lower than the scheduled throughput for both routing cases. Both schedule and actual throughput for shortcut routing are ~1.5 flight per hour greater than baseline routing at low RTA ratios. However, this benefit diminished as the RTA ratio increases until no shortcut routing benefit is seen at when all aircraft are RTA equipped. This is because as the average required slot size of aircraft decreases, there are more natural gaps in the schedule and shortcuts make less of an impact.

B. Scheduled Delay

A much larger difference in delay was seen between baseline and shortcut routing than between RTA and CMS aircraft. Most of the additional scheduled delay for baseline routing was applied to the Center.

Figure 4 shows the average total delay segregated by CMS and RTA equipage for each case and equipage ratio. The dashed and solid colored lines represent baseline and shortcut routing cases respectively. The blue and green lines represent CMS and RTA average total delay respectively. The inverse effect to throughput is seen as delay decreases with increased RTA equipage. Although RTA delay is usually less than CMS delay, the difference is minimal. A much larger difference in delay is seen between baseline and shortcut routing. The shortcut routing delay reduction over the baseline ranges from over 1 minute at low equipage ratios to ~20 sec at high equipage ratios.

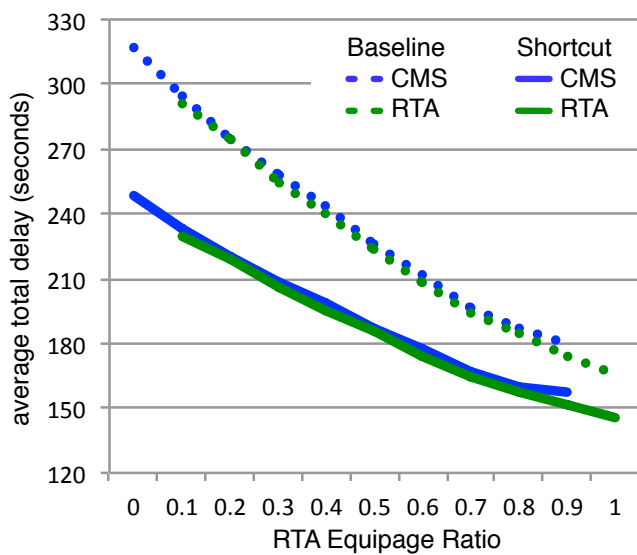


Figure 4. Average total CMS and RTA delay

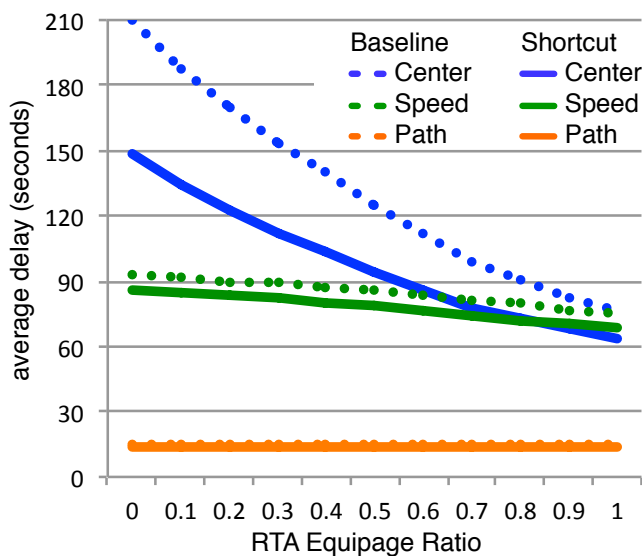


Figure 5. Average Center, TRACON speed, and TRACON path delay.

Figure 5 segregates delay by Center, TRACON speed, and TRACON path delay. Center delay is the most responsive to equipage ratio. This is because, even at high equipage ratios, the demand is so high that the TRACON's ability to absorb delay is saturated, pushing all residual delay to the Center. The baseline case path delay is fixed, as scheduling to shortcuts is not an option. The path delay for the shortcut routing case is almost as high as the baseline case suggesting that very few flights were scheduled to shortcuts.

C. Workload

In general, both routing cases had much higher (~ 3 times) percentages of controller intervention required to prevent loss of separation than the 20% designed for in the isolated merge point case studied from previous research. This was due to large errors introduced at the meter fixes that cascaded to subsequent flights without any relief in demand to recover. Increasing the spacing buffers is one way to add some relief by pushing more schedule delay to the Center. Another approach that should be explored in future work is to use a more realistic wind error model. Whereas it is realistic to expect sequential flights to the same point to have very different errors, it is less realistic to expect the errors of the same flight at adjacent points along a route to have very different errors due to wind.

Figure 6 compares speed control workload between shortcut and baseline routing for varying equipage ratio. The workload percentages reduce very slightly (~1%) as the RTA equipage ratio increases and the average required slot size becomes smaller. The difference between shortcut and baseline routing is far more pronounced. The shortcut routing workload percentages are 8-10% lower than those of the baseline routing.

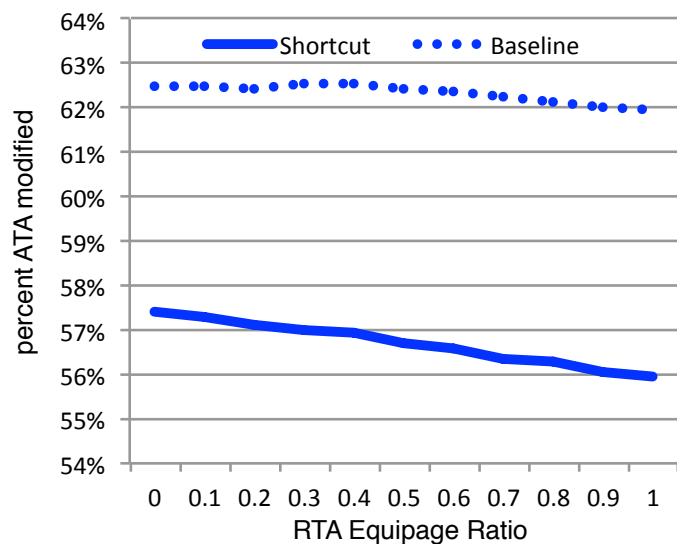


Figure 6. Speed control workload vs. equipage ratio

There were no instances of vectoring for all simulations. This shows that even though the high meter fix arrival

uncertainty causes cascading separation delays, they can be managed within the bounds of speed control modeled.

D. Shortcut Usage

Overall, relatively few flights were scheduled to final shortcuts but more were scheduled to shortcuts as the RTA ratio increased. On the other hand, a large percentage of flights used shortcuts tactically, especially when the flight scenario was dominated by one equipage level. Scheduled shortcut results are shown in Fig. 7, and tactical shortcut usage results are shown in Figs. 8-10.

Figure 7 shows the percentage of flights that were scheduled to one of the final shortcuts when available. These results are for the shortcut routing case only as the baseline routing had no shortcuts. Relatively few flights (4-16%) were scheduled directly to the shortcuts. The scheduler assigned most flights to nominal routing to take advantage of reduced scheduling buffers and accommodate the high demand. More flights are scheduled to the shortcuts as the equipage ratio increases. This is because the relatively smaller RTA buffers are sufficient enough in more instances to do without further reducing the buffers with tactical shortcut options. Lower demand traffic scenarios with more natural gaps would be expected to have more flights scheduled to shortcuts.

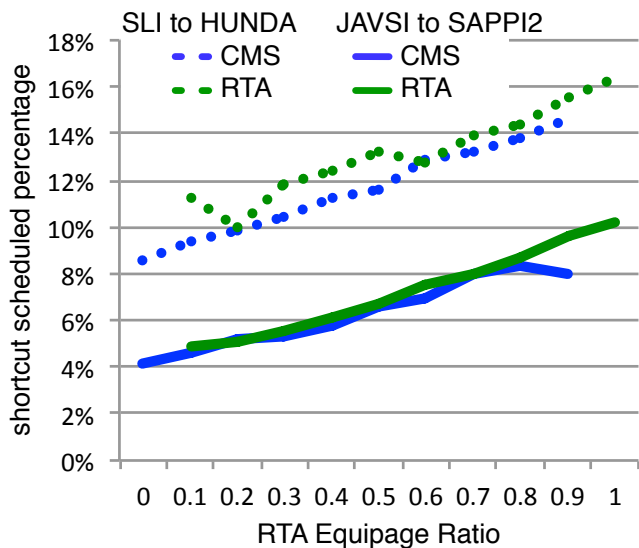


Figure 7. Percent time shortcut is scheduled

In general, the RTA flights are scheduled to shortcuts only slightly more often due to their smaller buffers. This accounts for the only slightly lower total delay for RTA than CMS flights seen in Fig. 4.

Tactical shortcuts are used any time a flight on the nominal route arrives at the tactical shortcut decision point late. In the absence of any systemic factors, the tactical shortcut would be used 50% of the time due to the use of zero mean uncertainty distributions. However, the total percent tactical shortcut usage is consistently high, over 92%. This means that flights arrive at the tactical shortcut decision point late more than 92% of the time. This is due to large meter fix arrival uncertainty and cascading separation delays.

Figure 8 shows the percent of tactical shortcut usage segregated by CMS and RTA equipage for each equipage ratio. Shortcut usage is highest when the scenario is dominated by one equipage level. The minority equipage level uses tactical shortcuts less often.

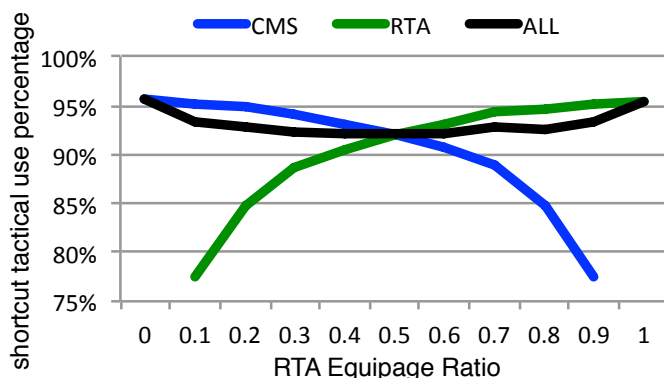


Figure 8. Percent tactical shortcut usage by equipage

Figure 9 shows the percent of tactical shortcut usage segregated by shortcut route. A few of the shortcuts are used less often than others. Figure 10 shows the average number of flights with the option of using each tactical shortcut, which is indicative of the traffic load on the route. Tactical shortcut usage is higher on more heavily loaded routes because there are fewer natural gaps and therefore more cascading separation delays causing flights to be late at the shortcut decision points more often. However, even the very light loading of the route offering the RUBEEN to SLI shortcut has 75% shortcut usage. This is due to the asymmetric speed control authority given to recover from large meter fix arrival uncertainty. Flights early to the meter fix may increase their TTF by 10%, whereas late flights may reduce their TTF by only 5%. This shifts the average reachable target ATA later than the STA at the decision point.

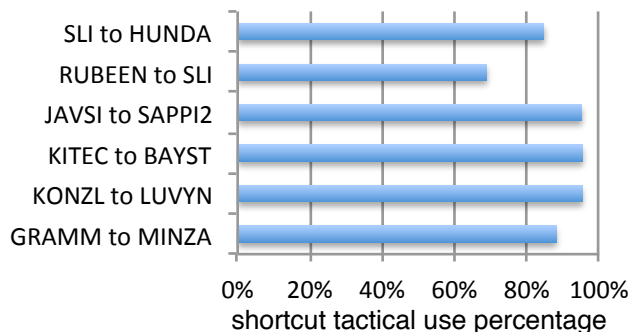


Figure 9. Percent tactical shortcut usage by route

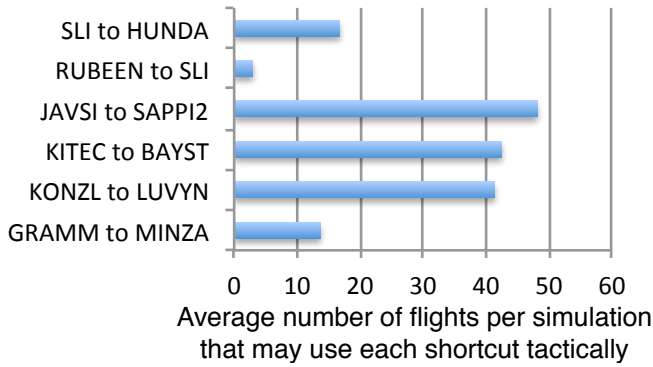


Figure 10. Tactical shortcut availability by route

E. Schedule Conformance

The greatest differences in schedule conformance were seen between shortcut and baseline routing rather than equipage or equipage ratio. Therefore, the results presented in this section are average conformance standard error and mean error values across all equipage ratio scenarios.

Figure 11 shows the progression of conformance metrics along the highest demand Northwest path, from FIM at the bottom to 24R at the top. Starting at the FIM meter fix, baseline and shortcut routing metrics are very similar as they both reflect the zero mean 60-second standard deviation arrival uncertainty modeled as flights first enter the simulation. As traffic progresses toward 24R, both baseline and shortcut routing cases reduce the standard error, but the shortcut routing case is more effective. The baseline shows a consistent increase in mean error as traffic progresses through increasingly congested merge points. The shortcut routing case shows more erratic mean error behavior along the same path but ultimately the mean error is only a few seconds greater at the runway than the meter fix.

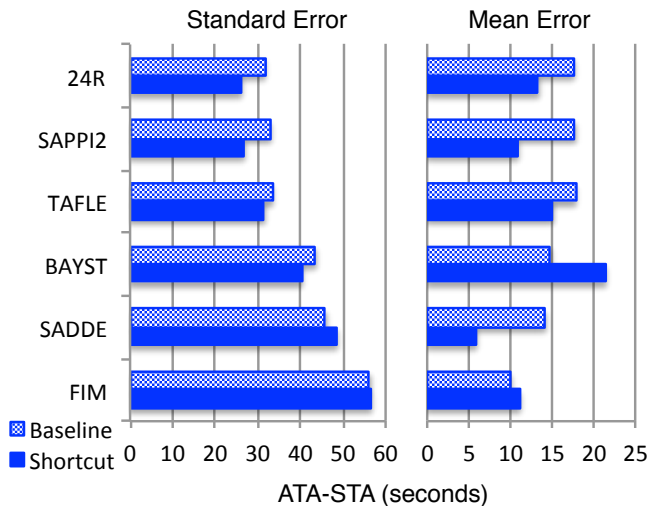


Figure 11. Conformance metrics progression from FIM to 24R

Conformance metrics along other paths from the Northwest and South had similar yet less pronounced patterns due to lower traffic volume. High traffic volume flows from the East resulted in similar standard error to the FIM flow but much higher mean error. This can be seen in Fig. 12 showing the conformance metrics for feeder merge points organized by flow.

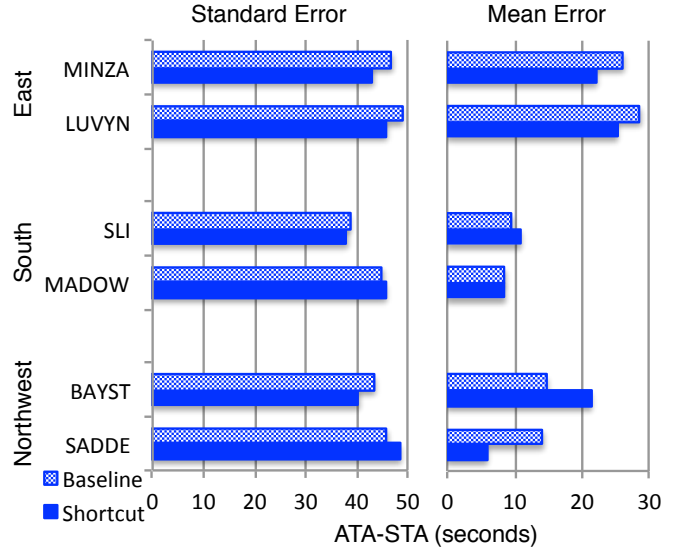


Figure 12. Feeder merge point conformance metrics

Even though the East flows serve over half the traffic demand, they not only have fewer shortcut options than other flows, but they do not bypass any merge points and offer very little additional range for scheduled delay. In future work, it would be interesting to see how routing allowing more symmetric shortcut availability affects the results.

VI. CONCLUSION

This paper presented an evaluation of the tactical shortcuts concept applied to a model of TBFM arrival scheduling at LAX with mixed equipage. The TBFM model reduced the scheduling buffers of flights to merge points with a tactical shortcut due to the increased schedule conformance expected. It also reduced the scheduling buffers of flights equipped to enable higher schedule conformance at any merge point. In the high traffic volume scenarios tested, the increased throughput and reduced scheduled delay benefits seen (for shortcuts vs. baseline routing and as the ratio of equipped flights increased) were directly due to reducing these buffers and scheduling flights into smaller slots. Due to the increased schedule conformance, the benefits were achievable without increasing (in fact reducing) controller workload.

Results showed that the throughput and delay benefits of shortcut routing over baseline routing diminished as the equipage ratio increased but the workload benefits increased. Increasing the equipage ratios and average scheduling slot size was essentially equivalent to reducing the traffic demand with the same scheduling slot size. Therefore, we can assume that when traffic demand is lower and additional throughput is not

needed, the workload benefits will still remain. Giving the scheduler the ability to use the shortcuts strategically (as with the final shortcuts in this study) negates this low traffic volume benefit. The tactical shortcuts are no longer being used to reduce buffer and squeeze in extra flights, but to mitigate scheduling disturbances. Reserving tactical shortcut options rather than scheduling to the shortest route makes the schedule more robust. The largest source of scheduling disturbance modeled in this study was large meter fix delivery uncertainty and the purely tactical feeder shortcuts were vital to mitigating meter fix uncertainty disturbances. However, tactical shortcuts could be used to mitigate other types of common disturbances that would cause flights to be late, such as head wind, slowing for turbulence, or deviation around weather. Overall, the tactical shortcuts concept showed potential as a valuable enhancement to TBFM scheduling and spacing.

REFERENCES

- [1] S. Zelinski, "Benefits of precision scheduling and spacing for arrival operations," 31st Digital Avionics Systems Conference, Williamsburg, Virginia, October 14-18, 2012.
- [2] B. Korn, H. Helmke, and A. Kuenz, "4D trajectory management in the extended TMA: coupling AMAN and 4D FMS for optimized approach trajectories," 25th Congress of the International Council of the Aeronautical Sciences (ICAS), Hamburg, Germany, September 3-8, 2006.
- [3] H. Helmke, R. Hann, M. Uebbing-Rumke, D. Muller, and D. Wittkowski, "Time-based arrival management for dual threshold operation and continuous decent approaches," 8th USA/Europe Air Traffic Management R&D Seminar, Napa Valley, California, 2009.
- [4] M. Uebbing-Rumke and M. Temme, "Controller aids for integrating negotiated continuous decent approaches into conventional landing traffic," 9th USA/Europe Air Traffic Management R&D Seminar, Berlin, Germany, 2011.
- [5] H. Swenson, J. Thipphavong, A. Sadovsky, L. Chen, C. Sullivan, and L. Martin, "Design and evaluation of the terminal area precision scheduling and spacing system," 9th USA/Europe Air Traffic Management R&D Seminar, Berlin, Germany, 2011.
- [6] J. Thipphavong, H. Swenson, L. Martin, P. Lin, and J. Nguyen, "Evaluation of the terminal precision scheduling and spacing system for near-term NAS application," Applied Human Factors and Ergonomics, San Francisco, CA, July 21-25, 2012.
- [7] H. Swenson, J. Jung, J. Thipphavong, L. Chen, L. Martin, and J. Nguyen, "Development and evaluation of the terminal precision scheduling and spacing system for off-nominal condition operations," 31st Digital Avionics Systems Conference (DASC), Williamsburg, Virginia, October 14-18, 2012.
- [8] M. Kupfer, T. Callantine, L. Martin, J. Mercer, and E. Palmer, "Controller support tools for schedule-based terminal-area operations," 9th USA/Europe Air Traffic Management R&D Seminar, Berlin, Germany, 2011.
- [9] A. Haraldsdottir, J. Scharl, J. King, and M. E. Berge, "Arrival management architecture and performance analysis with advanced automation and avionics capabilities," AIAA 9th Aviation Technology, Integration and Operations (ATIO) Conference, Hilton Head, South Carolina, September 21-23, 2009.
- [10] Callantine, T. J., C. Cabrall, M. Kupfer, L. Martin, J. Mercer, E. A. Palmer, "Investigating the impact of off-nominal events on high-density 'green' arrivals," 30th Digital Avionics Systems Conference (DASC), Seattle, Washington, October 16-20, 2011.
- [11] S. Zelinski, "Design considerations for shortcut path-based time recovery," 32nd Digital Avionics Systems Conference (DASC), Syracuse, New York, October 6-10, 2013.
- [12] L. Meyn, "A closed-form solution to multi-point scheduling problems," AIAA Modeling and Simulation Technologies (MST) Conference, Toronto, Ontario Canada, 2010.
- [13] S. Zelinski, "Precision arrival scheduling for tactical reconfiguration," AIAA 14th Aviation Technology, Integration and Operations (ATIO) Conference, Atlanta, Georgia, June 6-10, 2014.
- [14] G. Wong, "The dynamic planner: the sequencer, scheduler, and runway allocator for air traffic control automation," NASA TM-2000-209586, April 2000.
- [15] J. Klooster, A. DelAmo, P. Manzi, "Controlled Time of Arrival Flight Trials – Results and Analysis," 8th USA/Europe Air Traffic Management R&D Seminar, Napa, CA, 2009.
- [16] K. Swieringa, M. Underwood, and B. Barmore, "An evaluation of a flight deck interval management algorithm including delayed target trajectories," AIAA 14th Aviation Technology, Integration and Operations (ATIO) Conference, Atlanta, Georgia, June 6-10, 2014.
- [17] J. Thipphavong, J. Jung, H. Swenson, K. Witzberger, M. Lin, J. Nguyen, L. Martin, M. Downs, and T. Smith, "Evaluation of the controller-managed spacing tools, flight-deck interval management and terminal metering capabilities for the ATM technology demonstration #1," 10th USA/Europe Air Traffic Management R&D Seminar, Chicago, IL, 2013.
- [18] T. Prevot, "How to compute a slot marker – calculation of controller-managed spacing tool efficient descents with precision scheduling," 31st Digital Avionics Systems Conference (DASC), Williamsburg, Virginia, October 14-18, 2012.

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