Estimating Controller Intervention Probabilities for Optimized Profile Descent Arrivals

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Simulations of arrival traffic at Dallas/Fort-Worth and Denver airports were conducted to evaluate incorporating scheduling and separation constraints into advisories that define continuous descent approaches. The goal was to reduce the number of controller interventions required to ensure flights maintain minimum separation distances of 5 nmi horizontally and 1000 ft vertically. It was shown that simply incorporating arrival meter fix crossing-time constraints into the advisory generation could eliminate over half of the all predicted separation violations and more than 80% of the predicted violations between two arrival flights. Predicted separation violations between arrivals and non-arrivals were 32% of all predicted separation violations at Denver and 41% at Dallas/Fort-Worth. A probabilistic analysis of meter fix crossing-time errors is included which shows that some controller interventions will still be required even when the predicted crossing-times of the advisories are set to add a 1 or 2 nmi buffer above the minimum in-trail separation of 5 nmi. The 2 nmi buffer was shown to increase average flight delays by up to 30 sec when compared to the 1 nmi buffer, but it only resulted in a maximum decrease in average arrival throughput of one flight per hour.

I. Introduction

To reduce fuel consumption, emission and noise during airport arrival operations, a continuous descent at low or idle engine power is desired.[1-11] The Efficient Descent Advisor[6-11] (EDA) is a decision-support tool for air-traffic controllers that can generate trajectory-based clearance advisories that define continuous descent approaches (CDAs). The advisories could also be generated so that they satisfy arrival-scheduling constraints and satisfy minimum separation requirements with respect to the predicted locations of other traffic. These added advisory features could reduce controller workload by reducing the number of times they need to intervene in order to prevent separation violations. However, the addition of these features would

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increase the EDA's complexity, which could make it more difficult and more costly to deploy. It is therefore desirable to understand the benefits having the EDA advisories satisfy these additional constraints.

To estimate benefits of incorporating scheduling and separation constraints into the EDA advisories, simulations of air traffic at two major airports were conducted. Four levels of arrival advisories were evaluated ranging from CDA only advisories, to advisories that, in addition to CDA, met arrival-scheduling constraints and had predicted trajectories that did not violate minimum required separation minimums with any other predicted flights. For each simulation, the number of times that arrival flights violated the minimum separation requirements with all other flights were counted and categorized. In actual operations, when there are predicted separation violations (hereafter referred to as conflicts,) controllers must intervene and issue new advisories to prevent violations from occurring. So the primary benefit of adding additional constraints to EDA advisories is to reduce number of conflicts that occur, thereby reducing the number of controller interventions needed after the EDA advisories were issued.

Previous EDA benefit studies[10,11] assumed that the EDA advisories included scheduling constraints and resolutions to all potential separation violations, whereas the study presented here breaks out the contributions of EDA advisory components. Other research efforts have characterized the frequency and type of separation violations that would occur if corrective actions were not performed.[16-19] However, these studies primarily focused on en-route, not arrival traffic. Several previous studies have focused on how arrival trajectory prediction uncertainties can lead to separation violations.[20-23] These studies modeled the sources of trajectory uncertainties and used Monte-Carlo analysis to determine the separation violation probabilities. Other researchers have used a more analytic approach,[24,25] that does not require the numerous simulation runs needed for Monte-Carlo analysis. In this paper, an analytic estimation of controller intervention rates due to arrival meter fix crossing time uncertainties is included.

The next section of this paper presents the simulation setup, which is followed by presentation of the study results. Then the meter fix crossing time uncertainty analysis and results are presented, followed by some concluding remarks and discussion.

II. Simulation Setup

The simulations modeled en route arrivals, departures and over-flights at two airports, Denver International Airport and Dallas/Fort Worth International Airport, using the Airspace Concept Evaluation System[12] (ACES). The simulation utilized software developed for the Advanced Airspace Concept[13-15] (AAC) to emulate the type of advisories that EDA would need to generate. In addition to providing advisories to resolve conflicts, the AAC software also provided arrival scheduling and sequencing to the airport arrival meter fixes.

A full day of traffic was simulated for both Denver International Airport (DEN) and Dallas/Fort-Worth International Airport (DFW) based on historical demand for May 3, 2007, a high traffic day with minimal weather. ACES simulates all flights in the National Airspace System from gate departure to gate arrival over the entire continental United States. For these simulations, the flight set was filtered down to only flights that arrived, departed or passed through the Air Route Traffic Control Center (center) for the target airport. A summary of the traffic demand is presented in Table 1, which shows the number flights in the center and the number of flights arriving at the target airport. The percentage of jet, turboprop and piston aircraft for the arrival flights are also given.

Table 1. Traffic demand for Denver and Dallas/Fort Worth Airports.

Airport	Center Flights	Arrival Flights	Jet	Turboprop	Piston
Denver	4176	789	90.6%	8.9%	0.5%
Dallas/Fort-Worth	4342	831	96.8%	3.1%	0.1%

A representation of the terminal-area arrival traffic is presented in Fig. 1. The airport, represented here by a couple of runways, resides within a Terminal Radar Approach Control Facility (TRACON) that has arrival meter fixes and departure-fixes (not shown) around its boundary. For these simulations, both arrival meter fixes and departure fixes were located 40 nmi from the airport. Departure fixes were located North, East, South and West of the airport and arrival meter fixes were located Northeast, Southeast, Southwest and Northwest of the airport. It should be noted that this is a simplified representation of the actual arrival route structures that define paired meter fixes at four arrival gates. Arrival flights were routed to arrival meter fixes, where they were organized into vertically separated streams based on their engine types (jet, turboprop and piston). The freeze horizon, represented by the dashed circle, is the point at which the scheduled time of arrival at the meter fix would be frozen. For the purpose of this analysis, the EDA advisories were issued at the freeze horizon. Although the freeze horizon is depicted geometrically, it was defined in terms of the time for a flight to reach the meter fix, which for this study was set to 20 minutes.

Conflicts were defined as two flights having a predicted separation of less than 5 nmi horizontally and 1000 ft vertically. Since the simulation did not model trajectory prediction uncertainty, all predicted conflicts would become minimum separation violations unless an advisory was issued. Also, no unpredicted violations would occur due to trajectory-prediction errors, they would only occur in this study if one or more trajectories were not known at the time an advisory was issued. Since trajectory-prediction uncertainties were not modeled, the effects of missed and false conflict alerts in the EDA benefit mechanisms[26] are not accounted for. These are believed to be second order effects; however there are plans to model these effects in future studies.

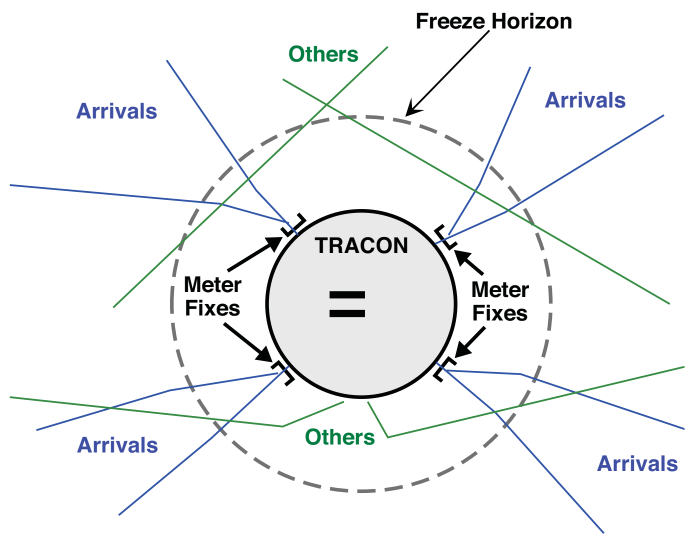

Figure 1. Diagram of the terminal-area arrival traffic model.

Arrival conflicts within the freeze horizon were classified as one of four categories: Meter-Fix, Arrival-Arrival, Arrival-Other and Pop Ups. When two sequential arrivals in the same stream are in conflict and the leading flight is at the meter fix, the conflict is classified as a Meter-Fix conflict. All other conflicts between two arrivals are classified as Arrival-Arrival. When an arrival is in conflict with an over-flight or a departure whose trajectory is known at the time the EDA advisory issued then it is classified as an Arrival-Other conflict. If a conflict only becomes known after the arrival has been issued an advisory, it is classified as a Pop Up conflict.

The AAC software is normally configured to detect and resolve all conflicts, but for this study it was limited to only provide the resolutions required for each of the four different levels of EDA advisory capabilities simulated. These levels are summarized in Table 2. The Level-1 advisory was a CDA only advisory. This provides a trajectory that, while best for each individual flight, does not include any scheduling constraints or avoid any potential separation violations. All of the previously mentioned conflict categories would occur for this type of advisory. The Level-2 advisory included crossing-time separation constraints between sequential flights at the meter fix. The crossing-time separations were set to approximate in-trail separation distances of 6 or 7 nmi, which would give a buffer of 1 or 2 nmi over the 5 nmi minimum separation constraint. The nominal separation times for 5, 6 and 7 nmi were based on the average ground speed for the three aircraft stream types as shown in Table 3. Including crossing-time separation constraints should eliminate all Meter-Fix conflicts.

Table 2. Definition of advisory levels.

Level	Advisory Contents	Conflict Types Eliminated
1	CDA only (with no consideration of arrival scheduling or separation violations)	None
2	CDA plus scheduling of in-trail, meter fix crossing times to achieve 6 or 7 nmi separation	Meter-Fix
3	Level-2 constraints plus resolution of conflicts between arrival flights from the freeze horizon to meter fix	Meter-Fix and Arrival-Arrival
4	Level-3 constraints plus resolution of conflicts between arrival flights and all other known flights from the freeze horizon to meter fix	Meter-Fix, Arrival-Arrival and Arrival-Other

The Level-3 advisory adds the constraint that each arrival's predicted trajectory does not come in conflict with another arrival's predicted trajectory over the arrival's entire path from freeze-horizon to arrival meter fix. Thus, Level-3 advisories should eliminate all Arrival-Arrival conflicts. The Level-4 advisory adds the constraint that each arrival's predicted trajectory is also conflict free from all other known trajectories over an arrival's entire path from freeze-horizon to arrival meter fix. In the simulation, whenever AAC needed to resolve a conflict between an arrival and a non-arrival, the resolution advisory was always issued to the non-arrival. This gives priority to arrivals, which is what would be expected operationally. However, having EDA generate advisories for non-arrival flights would significantly increase the complexity of deploying EDA. The benefit of incorporating such advisories is that all Arrival-Other conflicts should be eliminated.

Pop Up conflicts can occur for all levels of advisories, as they cannot be eliminated by an advisory issued at the freeze horizon, since the trajectories of the Pop Up flights are unknown at that time. Normally, AAC would resolve Pop Up conflicts as they occurred, but this behavior was suppressed for this study.

Table 3. Separation times used to represent separation distances.

Aircraft Type	Average Ground Speed (knots)	Separation Time (sec) For Three Separation Distances		
		5 nmi	6 nmi	7 nmi
Jet	286	63	76	88
Turboprop	223	81	97	113
Piston	159	113	136	158

III. Simulation Results

The frequency and distribution of the four conflict types over the entire day are presented in Fig. 2 for Level-1 and Level-2 advisories at both Denver and Dallas/Fort-Worth. It should be noted that the Meter-Fix conflicts were completely eliminated when Level-2 advisories were issued. Furthermore, although the data is not presented here, Level-3 advisories completely eliminated Arrival-Arrival conflicts and Level-4 advisories completely eliminated Arrival-Other conflicts, leaving only pop-up conflicts. For these last two advisory levels, the frequency values of conflict types that were not eliminated were very nearly the same as they were for Level-2 advisories.

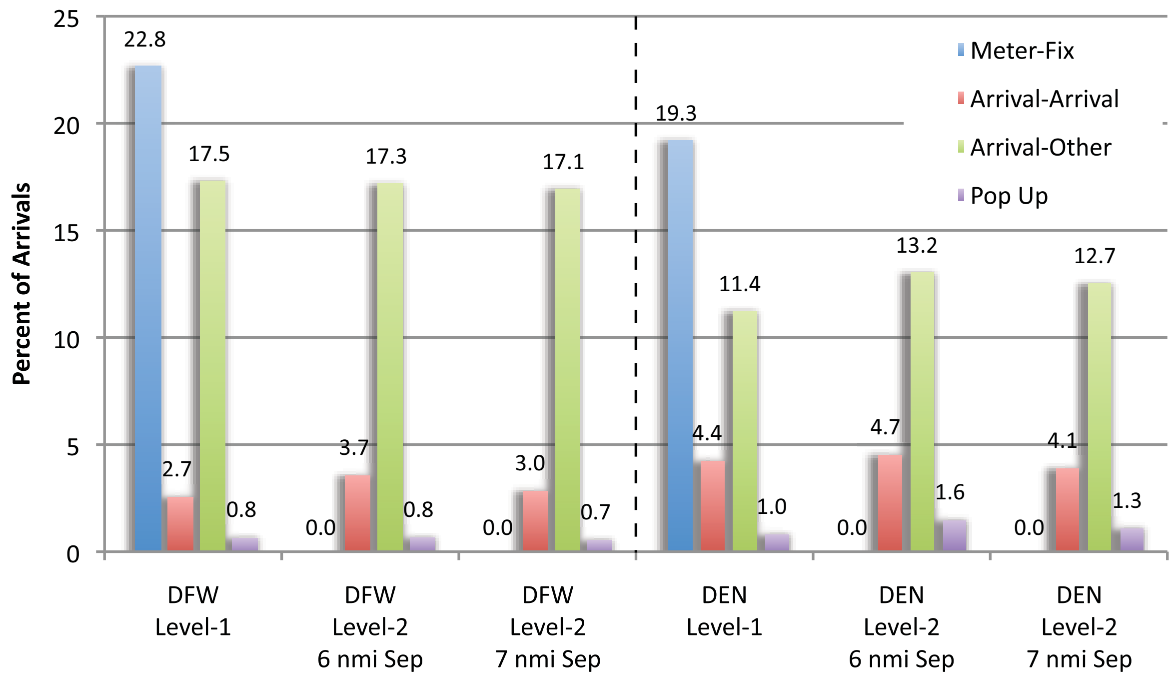

Figure 2. Frequency and type of conflicts for arrival traffic at Dallas/Fort-Worth (DFW) and Denver (DEN) airports for a full day of traffic for Level-1 and Level-2 advisories.

Figure 2 shows that, for Level-1, Meter-Fix conflicts make up the majority of the conflicts at both airports, accounting for 22.8% of all arrival conflicts at Dallas/Fort-Worth and 19.3% at Denver that would occur if each arrival were given its optimum descent trajectory with consideration of minimum separation constraints. The next most frequent category was Arrival-Other conflicts at both airports. Both airports had slight increases in Arrival-Arrival conflicts, compared to the Level-1 values, when 6 nmi meter fix spacing was included in the advisories. These values were slightly reduced going from 6 nmi to 7 nmi separations.

The percentage of arrivals with Meter-Fix and Arrival-Other conflicts was higher at Dallas/Fort-Worth, which was probably due to that airport having higher sustained levels of demand at its northern meter fixes than occurs for any of Denver's arrival meter fixes. Denver, however, has a higher rate of Arrival-Arrival conflicts. This is most likely due to Denver having more turboprop and piston traffic, resulting in more conflicts between arrivals in different arrival streams. For both airports, the percentage of Pop Up conflicts was very low. It was slightly higher for Denver, which may also have been due to its greater percentage of non-jet traffic.

A time history of the arrival demand and conflict rates at each arrival meter fix for Dallas/Fort-Worth is presented in Fig. 3 for Level-1 advisories. The Northwest and Northeast meter fixes see the highest arrival demand and consequently, the highest conflict rates. Both of these fixes have Meter-Fix conflict rate peaks exceeding 10 per hour, while only the Northeast meter fix has few Arrival-Other conflict rate peaks of 10 or 11 per hour. For all fixes the Arrival-Arrival conflict rate never exceeds 3 per hour and the Pop Up conflict rates never exceed 1 per hour.

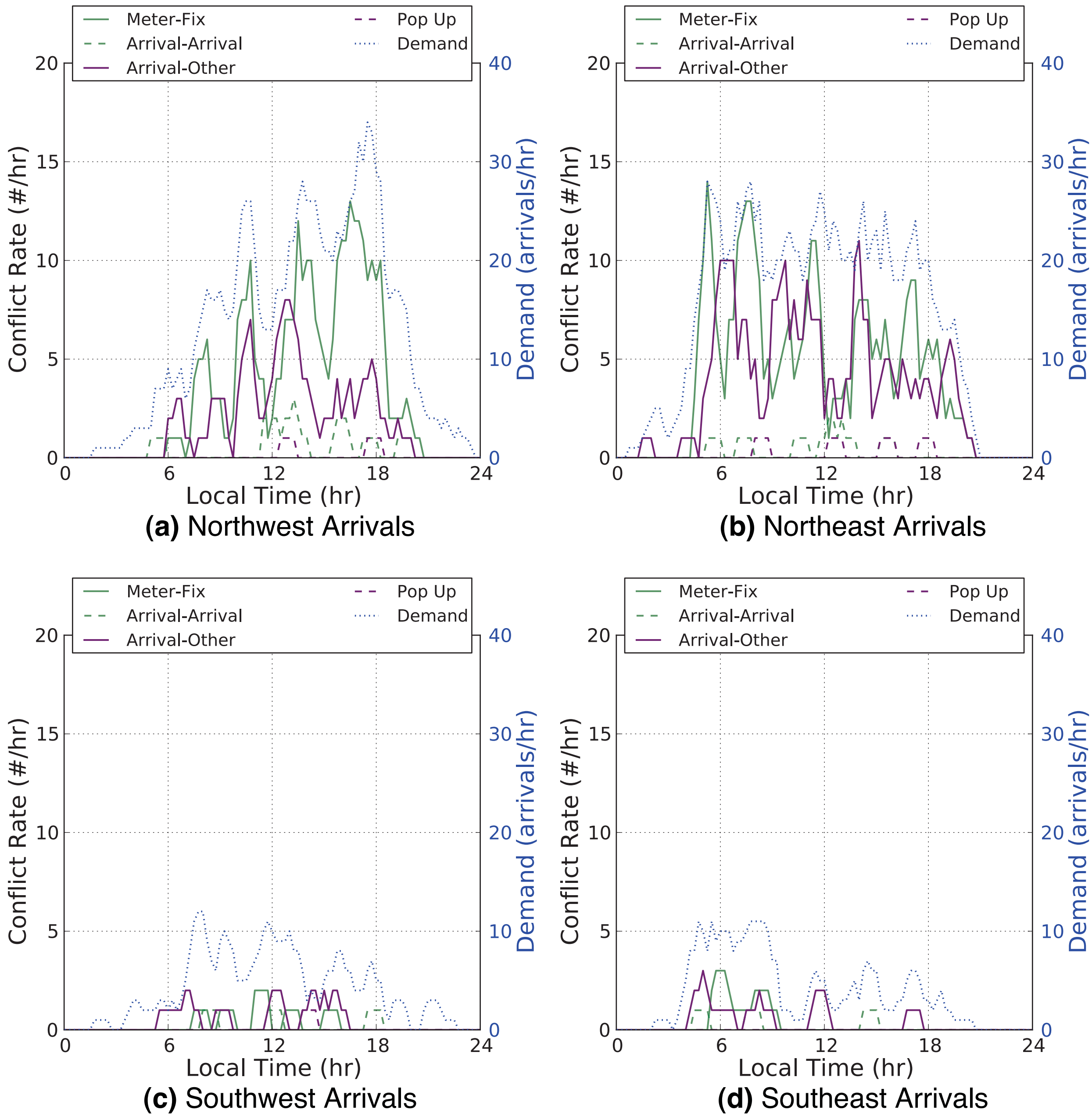

Figure 3. Arrival demand and conflict rates for Dallas/Forth-Worth International Airport at each meter-fix as a function of time for Level-1 advisories. *Based on one-hour moving averages.*

A similar time history of the arrival demand and conflict rates at each arrival meter fix for Denver is presented in Fig. 4 for Level-1 advisories. Each meter fix has periods of high demand throughout the day. The Southwest meter fix has a notable Meter-Fix conflict rate peak of 16 per hour in the late afternoon and the Southeast meter fix has a similar peak of 15 per hour at 6 AM. The Arrival-Other conflict rate stays at 3 per hour or less for the northern fixes, but goes up to 5 per hour for the Southwest meter fix and 7 per hour for the Southeast. The largest rate for

Arrival-Arrival conflicts is a peak of 6 per hour at the Southwest meter fix. Pop Up conflicts are rare, with a small peak of 2 per hour showing up for the Northeast meter fix.

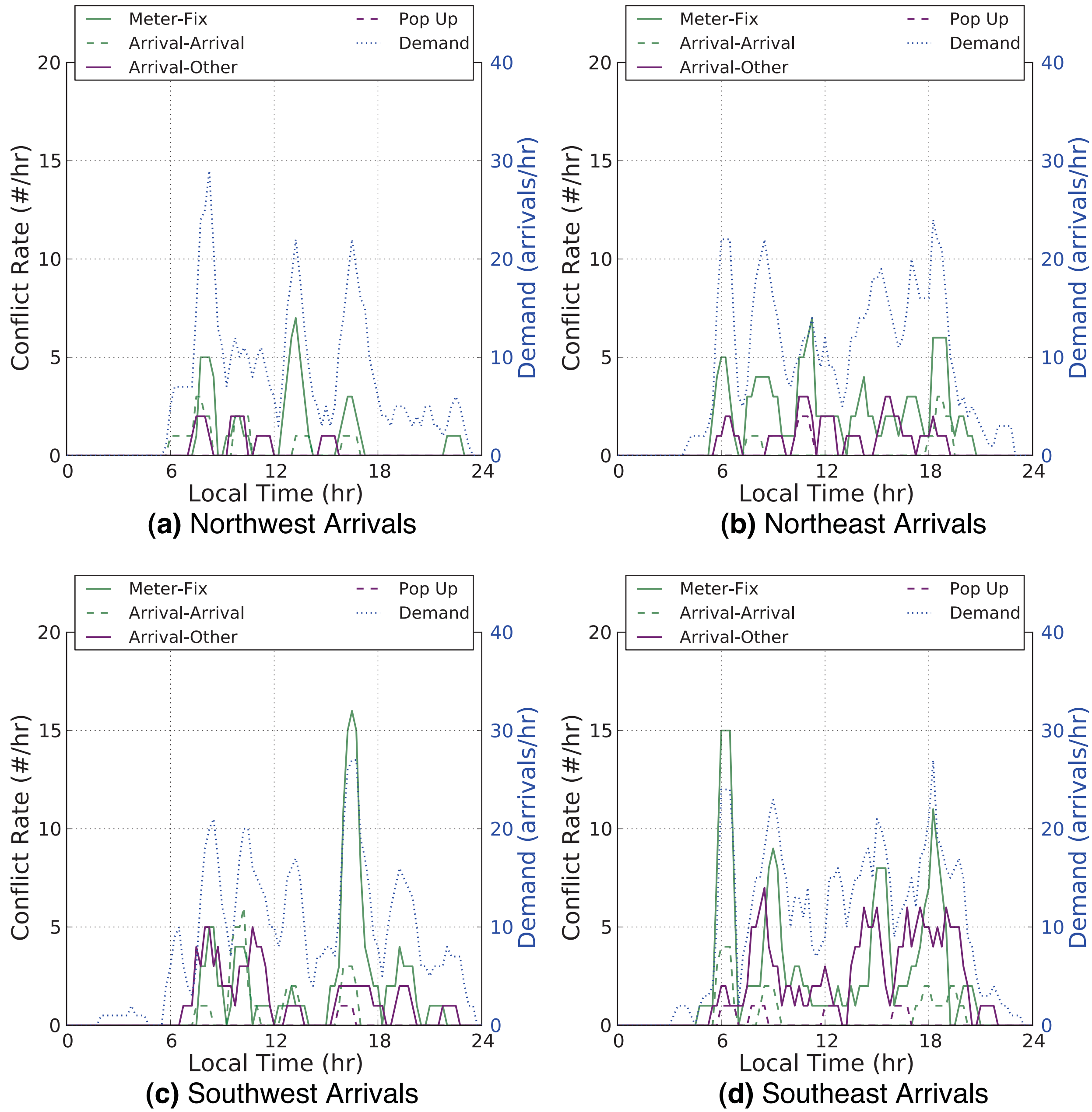

Figure 4. Arrival demand and conflict rates for Denver International Airport at each meter-fix as a function of time for Level-1 advisories. *Based on one-hour moving averages.*

The arrival trajectories for a 24 hour period from the freeze horizon to meter fix are shown in Fig. 5 for Dallas/Fort-Worth and Denver Airports for Level-2 advisories having meter fix separations of 6 and 7 nmi. Trajectories that include delays or maneuvers to meet crossing time constraints are shown in blue, unaltered trajectories are shown in green. As the scheduled meter fix separation increases, more flights need to be maneuvered or slowed down to meet the constraint. For Dallas/Fort-Worth, 30% of the flights were maneuvered for 6 nmi separations, see Fig. 5(a), and 35% were maneuvered for 7 nmi separations; see Fig. 5(b). For Denver, 26% of the flights were maneuvered for 6 nmi separations, see Fig. 5(c), and 30% were maneuvered for 7 nmi separations; see Fig. 5(d).

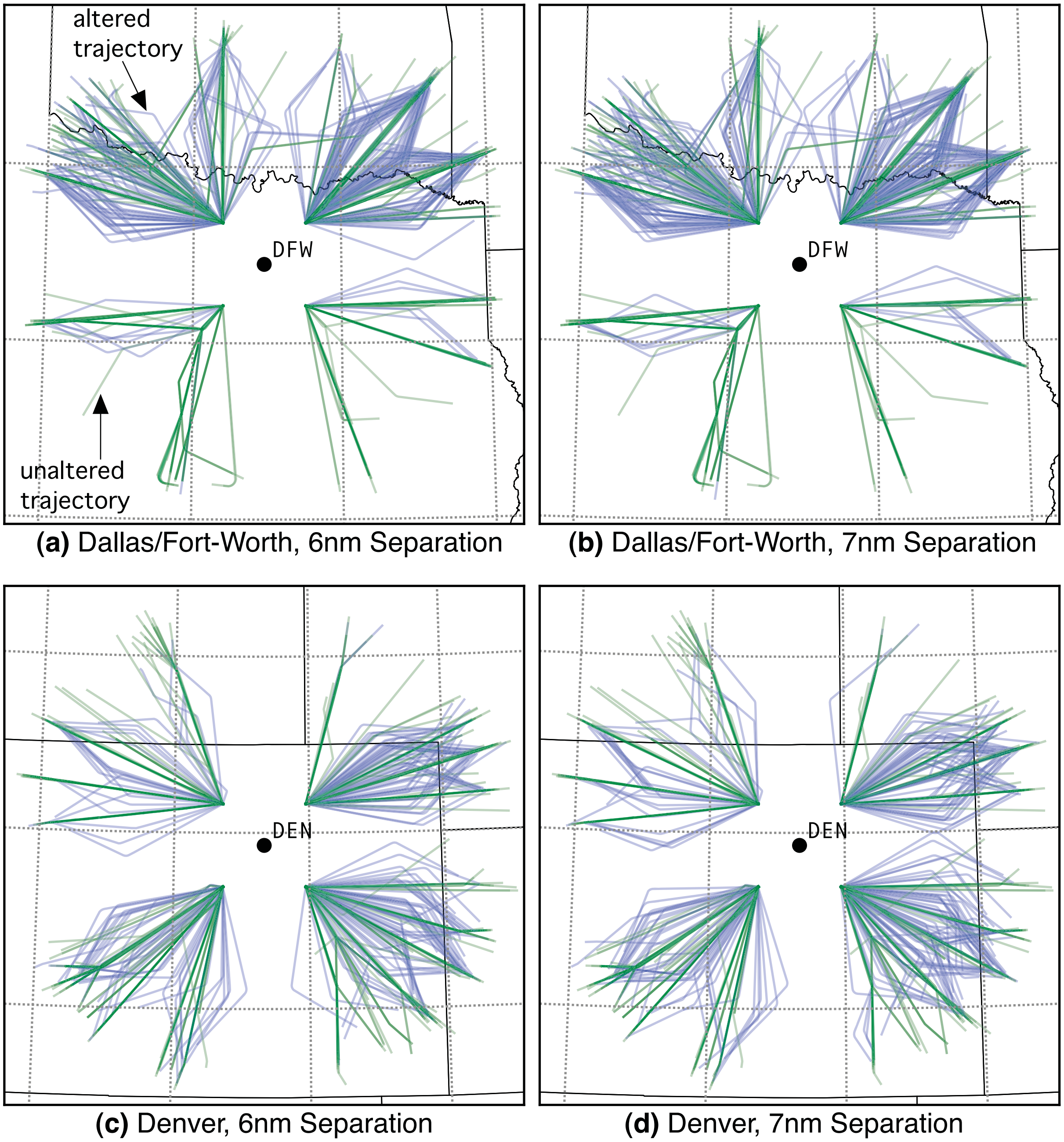

Figure 5. Arrival trajectories for Dallas/Fort-Worth and Denver Airports for Level 2 advisories. *Trajectories that include delays or maneuvers to meet crossing time constraints are shown in blue, unaltered trajectories are shown in green.*

The average delay per flight due to the scheduling of arrival meter fix crossing times is presented in Fig. 6(a) for Dallas/Fort-Worth and Fig. 6(b) for Denver, along with average demand. Dallas/Fort-Worth exhibits two peaks, above 40 sec, in the mean delay value in the early morning when demand is extremely low. This is due to a handful of flights arriving at nearly the same time to the same meter fixes. Delay averages from periods of the day with much higher demand levels should be less susceptible to such statistical anomalies. During the higher periods of the demand, the 6 nmi meter fix separation constraint resulted in average delays that ranged from 10 to 40 sec at Dallas/Fort-Worth. Increasing the separation constraint to 7 nmi, would occasionally increase the average delay by 20 sec, but overall the added delay was much less. The delay averages at Denver were very similar, with the exception of a spike in average delay around 6 A.M. where the mean delay for 6 nmi separations reached 65 sec and the mean delay for 7 nmi separations reached 95 sec. In terms of flight throughput, the effect of increasing meter fix separation constraint 6 to 7 nmi was minimal. The largest decrease in average throughput due increasing the buffer from 1 to 2 nmi was only 1 flight per hour and this only occurred occasionally at either airport. The loss in throughput would likely be more significant at airports where peak demands exceed capacity for longer periods of time.

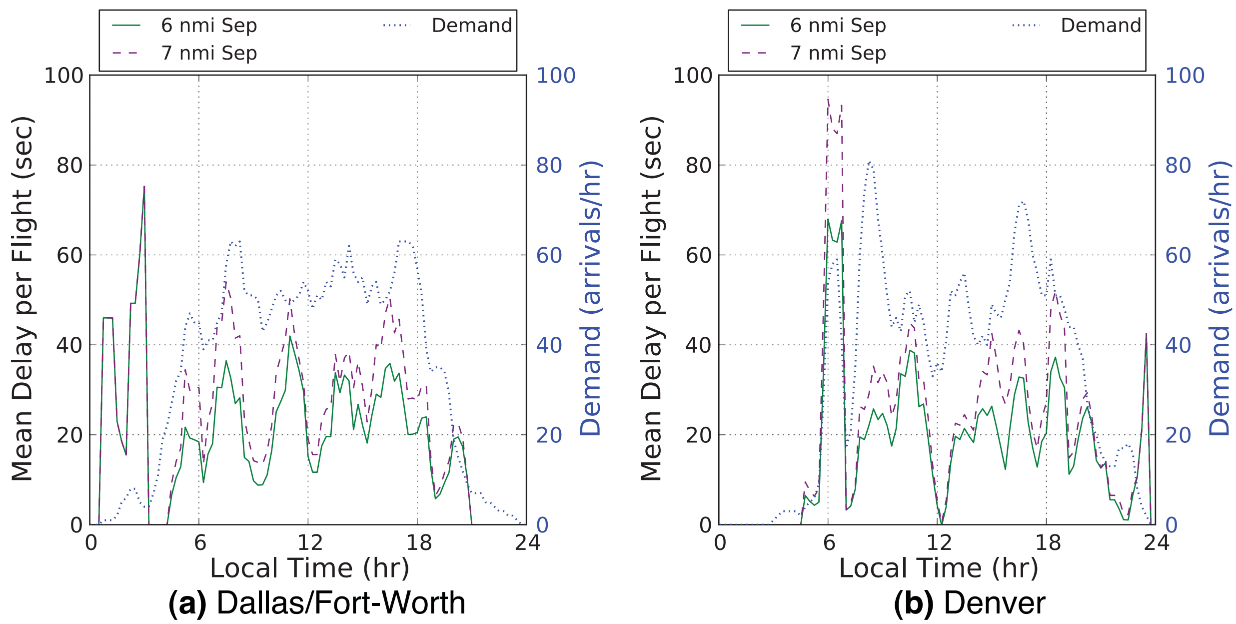

Figure 6. Arrival demand and mean delay per flight for Level-2 advisories at (a) Dallas/Fort-Worth and (b) Denver airports. *Based on one-hour moving averages.*

IV. Meter Fix Conflict Probabilities Due To Scheduling Uncertainty

When meter-fix scheduling constraints are included in EDA advisories, it is expected that sequential arrivals will be scheduled to cross the arrival meter-fix with in-trail spacing greater than the required minimum. However, due to errors in the trajectory predictions used by EDA, some separation violations might still occur unless the controllers intervene to prevent them. There are several potential sources for the uncertainty in trajectory predictions; these include uncertainties in the assumed wind speed and direction, lack of accurate aircraft state information such as weight, speed and performance parameters, or uncertainty in aircraft intent such as where the top-of-descent will occur and what the descent profiles will be.

The analysis presented here estimates the probability of Meter-Fix conflicts due to uncertainties in the meter fix crossing-times of sequential flights within an arrival stream. It is assumed that the uncertainty distributions for flights are independent. However, the analysis does include the effect of controller interventions to maintain safe separations. So if a flight's meter fix arrival is delayed by an intervention, then the flight following it will have a greater chance of conflict. While this has no effect on two isolated flights, the effect can be significant on tightly scheduled arrival streams with several flights.

Fig. 7 depicts the meter fix crossing time probability distribution functions (PDFs) for a leading and following aircraft and how the PDF of the following aircraft is altered by controller interventions. In this figure, a copy of the leader PDF, shifted by the minimum separation time, *s*, is shown by the dashed line. Since it overlaps the unconstrained PDF of the follower, there is a significant probability of conflict. The solid blue line shows the PDF of the follower if it is delayed to achieve minimum separation whenever potential conflicts occur. Compared to the unconstrained arrival time PDF, this PDF has a higher peak, smaller standard deviation and a slightly larger mean value. If the PDFs of the leader and the unconstrained follower are Gaussian, then the constrained follower PDF can be approximated with a Gaussian distribution, as was done by a Nikoleris, et.al.[25] However a general calculation procedure, suitable for any type of leader or follower distribution, was developed instead.

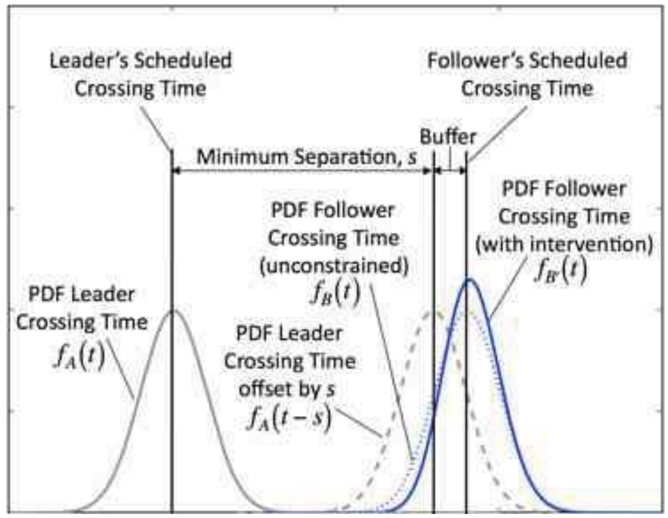

Figure 7. Probability distribution functions for the meter fix crossing times of the leading and the following aircraft in a sequential arrival pair.

For this procedure, the leading flight, A, has a probable crossing time given by the PDF, $f_A(t)$, and the following flight, B, has an unconstrained probable crossing time given by the PDF, $f_B(t)$, where the variable *t* represents time. These PDFs have associated cumulative distribution functions, $F_A(t)$and$F_B(t)$, which are the integrals of $f_A(t)$ and $f_B(t)$ with respect to *t*. If *s* is defined as the minimum time difference between the actual crossing times of the two flights for them to remain safely separated, then, if the difference between the actual crossing time of A and the unconstrained actual crossing time B were less than *s*, flight B would need to be delayed until the actual crossing time difference was equal to *s*.

To cacluate the PDF for flight B's actual crossing time when interventions are used to maintain separation, Eqn. 1 is used. As shown, the constrained PDF of the follower, $f_{B'}(t)$, is the sum of two probability distributions. The first, represented by the term $f_B(t)F_A(t-s)$, is the PDF representing the case where the unconstrained actual crossing time of B is greater than or equal to the actual crossing time of A plus *s*. The value $F_A(t-s)$ in this term is the probability that the crossing time of A is equal to $t-s$ or less, which is multiplied by the probability that unconstrained crossing time of B is *t*. The second probability distribution, represented by the term $f_A(t-s)F_B(t-\delta t)$, is the PDF representing the case where the unconstrained actual crossing time of B would be less than the actual crossing time of A plus s by a value of δt or more (in continuous calculations δt is vanishingly small, in discrete calculations δt is the minimum time resolution). The value $F_B(t-\delta t)$ in this term is the probability that the crossing time of B is less than $t-\delta t$, which is multiplied by probability that the crossing time of A is $t-s$. The integration of this second term in Eqn. 1, from t equal -∞ to ∞, gives the total probability that a conflict between flights A and B would occur.

$$f_{B'}(t) = f_B(t)F_A(t-s) + f_A(t-s)F_B(t-\delta t) \quad (1)$$

In this study two buffer values were used that represented 1 nmi and 2 nmi of flight time, so that the minimum scheduled spacing between flights at the meter fixes would be 6 nmi and 7 nmi respectively. However, the scheduled spacing between sequential arrivals at a meter fix was often greater than the 6 nmi or 7 nmi minimums because the arriving flights had arrived in the area already separated by greater distances before scheduling occured. In these cases, the probability of violation would be less because they had larger "buffer" values. For this analysis the crossing-time uncertainty distributions were assumed to be Gaussian with standard deviations of 15 s based on values presented in Green, et.al.[27] The calculations in Eqn. 1 were perfomed using discretized probability functions and the meter fix times of arrival from the simulations of Level-2 advisories described earlier.

Fig. 8 shows the mean conflict rates for a 24-hour period for the arrival meter fixes at Dallas/Fort-Worth. As expected, conflict rates are higher for the Northern fixes that have higher demand. For scheduled separations of 6 nmi, the mean conflict rate peaks at around 5 per hour. The peaks drop to a little over 2 per hour for scheduled separations of 7 nmi. The results for Denver are presented in Fig. 9. The peaks of the mean conflict rates for separations of 6 nmi are general below 4 per hour, with the exception of one peak at 6 A.M. for the Southeast meter fix. This peak is due to a group of arrivals that show up within a single 15 min period. At this airport the mean conflict rate peaks drop to a little under 2 per hour for scheduled separations of 7 nmi.

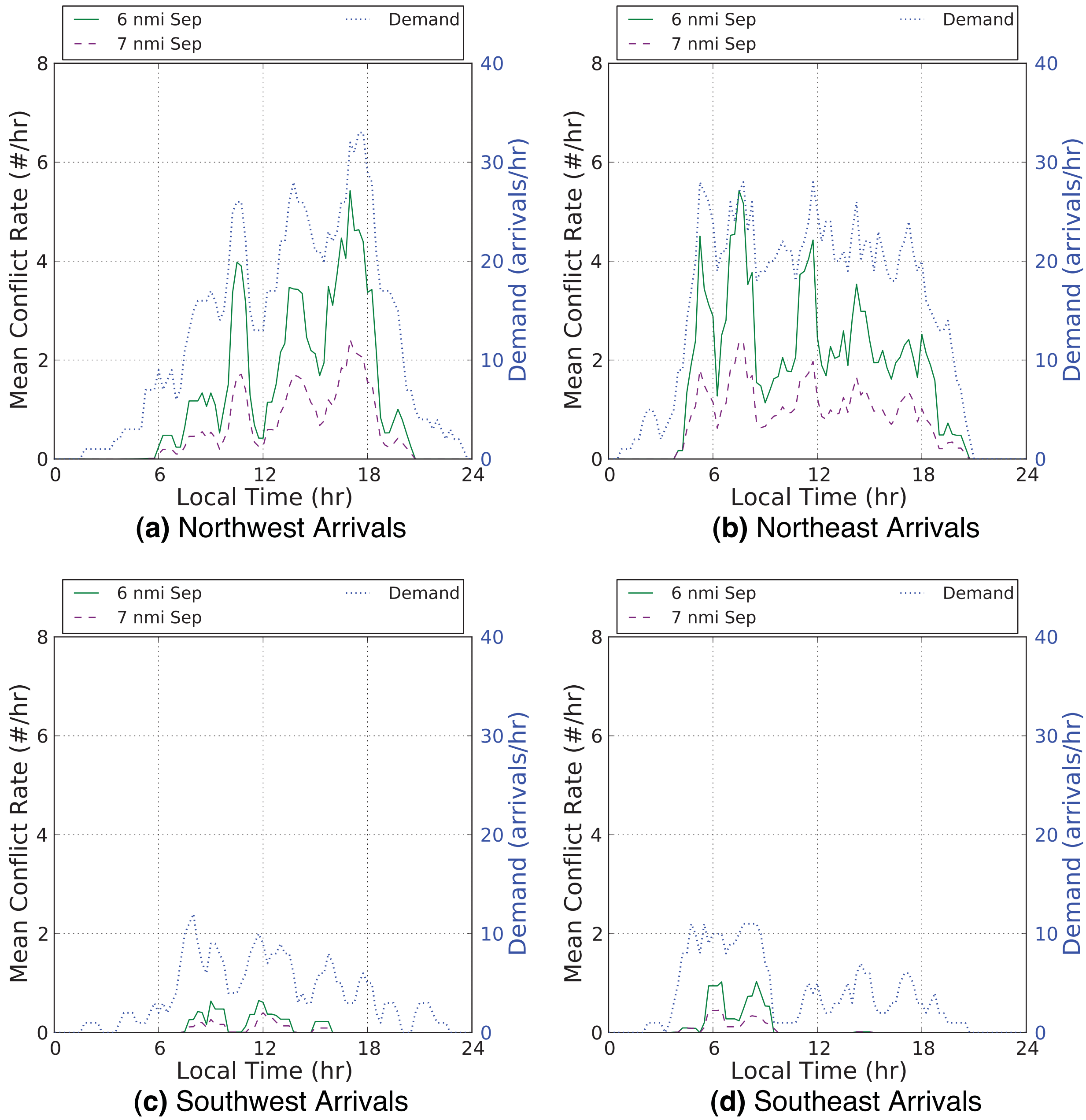

Figure 8. Arrival demand and mean conflict rates for Dallas/Fort-Worth Airport at each meter fix as a function of time for Level 2 advisories. *Based on one-hour moving averages and a Gaussian meter-fix crossing time uncertainty with a 15 second standard deviation.*

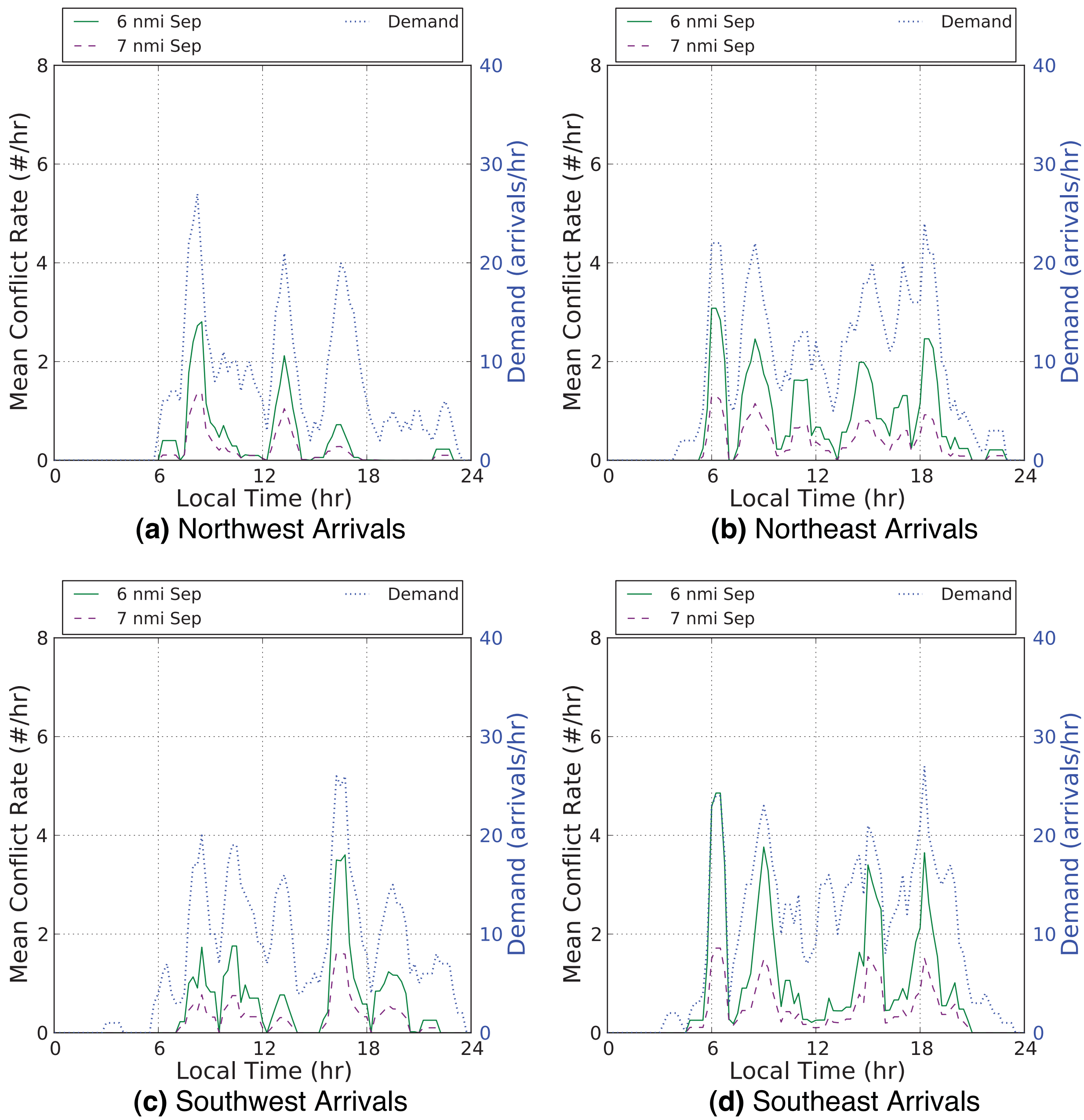

Figure 9. Arrival demand and mean conflict rates for Denver International Airport at each meter fix as a function of time for Level 2 advisories. *Based on one-hour moving averages and a Gaussian meter-fix crossing time uncertainty with a 15 second standard deviation.*

V. Concluding Remarks and Recommendations

Simulations of arrival traffic at Dallas/Fort-Worth and Denver airports were conducted to evaluate incorporating scheduling and separation constraints into EDA advisories in order to reduce the number of controller interventions.

The greatest reduction in the number of controller interventions would be achieved by having EDA advisories include arrival meter fix separations. This eliminated over half of the all predicted separation violations at both airports and more than 80% of the predicted violations between arrival flights. Up to 16 Meter-Fix conflicts per hour are eliminated at some meter fixes. However, a few Meter-Fix conflicts will still encountered due to crossing-time errors; up to 5 per hour for 6 nmi separations and about 2 per hour for 7 nmi separations.

Including Arrival vs. Arrival de-confliction up stream of the meter fixes in the advisories would eliminate 2 to 3 conflicts per hour, with some occasional peaks of 5 to 6 conflicts per hour at high demand meter fixes. This is not a large benefit, only 6% of all conflicts for Dallas and 12% for Denver, but including de-confliction between arrival flights in the advisories can be achieved without greatly increasing the complexity and development cost of EDA and is therefore the recommended option.

Adding de-confliction of arrivals vs. departures and over-flights has the potential to eliminate an additional 32% of the conflicts at Denver and 41% at Dallas/Fort-Worth. There are 10 to 11 Arrival-Other conflicts per hour at very busy meter fix arrival regions, though at most meter fixes in the simulation only about 5 to 6 of these conflicts would occur per hour at peak times. Although this category of conflicts was the second most prevalent in this study, it is the opinion of the authors that adding such de-confliction capability to EDA advisories would be both costly and technically risky in that it would require the development of entirely new functionalities that lie outside the scope of EDA. An alternative strategy is to reduce the rate of these conflicts procedurally and have controllers handle the rest of them as they arise. It should be kept in mind, that, similar to what was shown in meter fix crossing-time uncertainty analysis, trajectory prediction uncertainties would still lead to some arrival vs. non-arrival conflicts occurring even if conflict resolution advisories were issued to non-arrivals concurrently with EDA arrival advisories. Thus, occasional controller intervention for such conflicts can never be completely eliminated in an advisory-based system for EDA.

Extending the meter fix crossing separation constraint from 6 nmi to 7 nmi was shown to increase the average delay per flight by as much as 30 sec, but it only resulted in an occasional maximum decrease in average arrival throughput of one flight per hour. The benefit of increasing the separation constraint from 6 nmi to 7 nmi was that number conflicts due meter fix crossing time uncertainty could be halved.

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