12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM
17 - 19 September 2012, Indianapolis, Indiana

AIAA 2012-5672

Evaluation of an Integrated Arrival Scheduling and Automated Conflict Detection and Resolution System

Arwa S. Aweiss[1] and Todd A. Lauderdale[2]
NASA Ames Research Center, Moffett Field, CA, 94035

Performance of a prototype, ground-based automation system capable of generating fuel-efficient, continuous-descent approach trajectories for all arrival aircraft in a given airspace that are also conflict-free and conform to arrival-time metering constraints is evaluated. The prototype system is evaluated using a combination of runway time-in-trail constraints and calibrated airspeed uncertainty magnitudes. This includes a comparison of analysis of two traffic data and airport configuration scenarios (simple and complex). Three metrics are presented: the first is the percentage of cases that meet the time-in-trail constraint to within a 20-second tolerance. Under both scenarios, the performance of the system is degraded when greater airspeed uncertainty is modeled. Also, the system performs better in the simple traffic scenario indicating that traffic mixes and airport configurations might play a role in system performance. The second metric is used to study system safety by determining the minimum scheduling-time buffer necessary to achieve a 60-second minimum time-in-trail interval at the runway. For the simple traffic scenario, a smaller buffer is sufficient as compared to the complex traffic scenario. Also in both traffic scenarios, the higher the airspeed uncertainty, the larger the spacing buffer required to ensure that the minimum spacing requirement is met. The third metric is scheduling precision, which is used for investigating the need for feedback. Results show that during high traffic periods, tighter coupling of the scheduling and resolution generation system may improve performance, but further work is necessary for a definitive answer.

Nomenclature

AAC	=	Advanced Airspace Concept
ACES	=	Airspace Concept Evaluation System
CAS	=	Calibrated Airspeed
CDF	=	Cumulative Distribution Function
DFW	=	Dallas/Fort Worth Airport
NextGen	=	Next-Generation Air Transportation System
TRACON	=	Terminal Radar Approach Control
TMA	=	Traffic Management Advisor

I. Introduction

A fundamental requirement of safe airspace operation is the ability to keep aircraft safely separated at all times. An aircraft is said to have safe separation if it is separated from all other aircraft vertically by 1000 ft or horizontally by 5 nmi.[1] In addition to safe separation, a second priority is to maintain an efficient flow of traffic through the airspace to meet airport capacities or arrival rates. This is referred to as *arrival traffic management*. Time-based metering is one means of efficiently sequencing and spacing arrival traffic at rates conforming to the maximum arrival rate for a given airport while still satisfying distance-based safety separation standards.[2] A third priority is to improve the efficiency of flight operations so as to reduce aviation's impact on the environment.

Arrival Management is an important aspect of the Next-Generation Air Transportation System (NextGen), and

[1] Aerospace Engineer, Aviation Systems Division, NASA Ames Research Center, Moffett Field, CA 94035 M/S 210-10, Senior AIAA member.
[2] Aerospace Engineer, Aviation Systems Division, NASA Ames Research Center, Moffett Field, CA 94035 M/S 210-10, AIAA member.

one goal of arrival management research is to develop a fully automated system that would maximize airport throughput and maintain distance-based safety separation standards while allowing aircraft to fly continuous descent approaches, which are more fuel efficient than traditional approaches. Most of the previous work on this subject has concentrated on two aspects of the arrival management problem: generating efficient schedules for the arrival fixes and the runway (arrival scheduling)[4, 5] and generating conflict-free trajectories that satisfy time-in-trail constraints at the individual meter (arrival) fixes.[6-8] In arrival scheduling, runway time-in-trail constraints are propagated upstream to fixes along the route. This allows for a balance of aircraft flow among multiple arrival fixes that feed a single runway. Previous automated trajectory generation research has focused on generating safe trajectories that meet time-in-trail constraints at individual arrival fixes.[6-9] In this paper, these two functions (arrival scheduling and conflict-free meet-time trajectory generation) are integrated to enable automated generation of arrival trajectories to multiple arrival fixes that are fuel-efficient and conflict-free and still satisfy runway time-in-trail constraints. This requires the concept of coordinated metering in which metering (arrival time scheduling) at individual fixes is coordinated such that aircraft meet the time-in-trail constraints when landing at the runway. This work is related to the Efficient Descent Advisor (EDA) studies,[10, 11] but two important distinctions are that the resolution system is a fully automated system instead of a controller advisory tool and that it includes non-arrivals in the algorithm when searching for conflict-free trajectories.

For this study, an existing arrival scheduler and a prototype resolution generator are integrated to provide multiple-fix metering. Each of these systems has been evaluated independently in fast-time simulations.[6-8] The goal of this study is to evaluate overall performance of the integrated system and investigate the need for a feedback mechanism between the conflict generator and scheduler. The performance of the integrated system is evaluated in both a perfect prediction environment and in the presence of trajectory prediction errors and the communication process between the resolution generator and scheduler are investigated.

The paper is organized as follows. Section 2 provides background information and descriptions of the scheduling and resolution systems. Section 3 describes the integration concept. The experimental setup and procedures for the evaluation of the integrated system with arrivals into Dallas/Fort Worth airport are discussed in Section 4. An analysis of the performance of the integrated system evaluated in fast-time simulations under two different sets of traffic data and airport configurations using three time-in-trail constraints and under three calibrated airspeed (CAS) uncertainty magnitudes is presented in Section 5. In the last section, a summary highlighting the key findings of this work is presented.

II. Background

Arrivals to a single runway at an airport can originate from many different parts of the country. These arrivals are routed through specific spatial locations known as arrival fixes that serve as entry points to the Terminal Radar Approach Control (TRACON). To ensure efficient runway operations, it is important to condition the flow of aircraft before they arrive at the arrival fixes. For this study, a model of the Traffic Management Advisor (TMA) is used to create an efficient arrival sequence and schedule for the runway. TMA is the FAA's current operational system for time-based metering. TMA is a first-come first-served scheduling system that coordinates the traffic flow across multiple arrival fixes by propagating the runway time-in-trail constraints upstream from the runway threshold to the arrival fixes. This system uses estimates of runway arrival times for all arrival flights to construct a sequence for aircraft into that runway. The required delay for each aircraft is then calculated in order to ensure an efficient sequencing scheme for aircraft landing at the runway. Using this required delay and the estimated unimpeded arrival time at the fix, a scheduled time of arrival (STA) at the fix can be calculated for each aircraft. As aircraft approach the airport this scheduled arrival time is updated to account for trajectory prediction uncertainty until the aircraft reaches a specified distance from the arrival fix, known as the "Freeze Horizon". After the freeze horizon, the STA remains constant so that controllers can have a stable target toward which to guide each aircraft. Note that TMA was developed to create schedules based on predicted times of arrival[4-5] and was not intended to generate a conflict-free trajectory nor a fuel-efficient trajectory.

The Advanced Airspace Concept (AAC) was conceived as an automated solution for ensuring safe and efficient enroute aircraft operations.[12] One component of AAC is the Autoresolver algorithm, which maintains aircraft separation from other aircraft, from hazardous weather and from restricted airspace. It provides trajectories to meet time-in-trail constraints. Since these functions all occur at around the same look-ahead time (approximately 20 minutes) the Autoresolver performs these tasks in an integrated fashion where time-based solutions and weather avoidance maneuvers are guaranteed to be conflict free.[13-15] Previous studies of the capabilities of the Autoresolver that provide conflict-free trajectories to meet scheduled times of arrival have focused on uncoordinated flows across arrival fixes where each fix is treated independently.[6-9] For these studies, the Autoresolver relied upon an internal scheduler to create arrival-fix STAs. One feature of this internal scheduler is that there is immediate feedback. If the system is unable to generate a conflict-free trajectory that meets the scheduled time, the Autoresolver will use a later arrival time, and all subsequent STAs will depend on this new information. In the current work, the internal scheduler has been replaced with an off-board system where there is no explicit feedback between the Autoresolver and TMA. In this study, feedback is defined as a mechanism between the TMA scheduler and Autoresolver such that Autoresolver would update TMA of any changes it had to make to the TMA schedule; TMA could then use that information to revise the rest of its schedule. An objective of this study is to determine whether the combined system can function stably given this lack of feedback, or if a feedback mechanism must be added.

III. Integrated Scheduling and Conflict-Free Trajectory Generation

For this study, the experiment test bed needed to support time-based scheduling of arrivals between multiple arrival fixes serving a single runway. To accomplish this, the AAC Autoresolver was interfaced with a model of the TMA scheduler. To merge the two systems, scheduled times of arrival were generated by TMA. These scheduled times were then provided to the Autoresolver. The Autoresolver continually ensures that the aircraft maintain horizontal and vertical separation, and when it receives an STA from TMA, it attempts to create a conflict-free, continuous-descent trajectory that satisfies this STA to within 5 seconds. If the Autoresolver is not capable of hitting this arrival time because of other aircraft in the vicinity, it will develop a conflict-free, continuous-descent trajectory that arrives after the STA but minimizes the deviation from this time. In this system, as shown in Fig. 1 the actual time of arrival that the Autoresolver predicts is not fed back to TMA, so the STAs for subsequent flights are based on the TMA's original computed arrival time. One important feature of this system is that conflicts between arrival aircraft and non-arrivals can be resolved by the non-arriving flight.

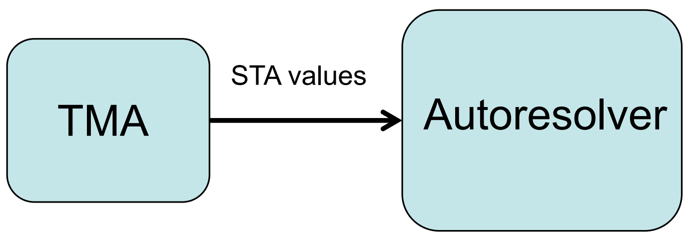


Figure 1. TMA and Autoresolver Interaction

IV. Experimental Procedure

To demonstrate and evaluate the proposed system, an experiment is designed using two different traffic mixes and airport configurations. The first case consists of an artificially generated traffic demand set composed of two continuous streams consisting of 1,000 arrival aircraft originating from each of two airports. Each of these streams is headed to one of two arrival fixes (BYP or WILBR) at Fort Worth Air Route Traffic Control Center ("Fort Worth Center"), and they both land at runway 17C at Dallas/Fort Worth (DFW) airport as shown in Fig. 2. The BYP stream is comprised entirely of Boeing 737-300 aircraft, and the WILBR stream is comprised of entirely E-145 aircraft. The traffic is scripted such that the aircraft will reach their respective arrival fixes to meet the runway time-in-trail constraint on average by alternating across fixes. A Gaussian (0, 2) minute distribution is added to the time-in-trail spacing in the demand set so as to trigger the need for TMA and Autoresolver interaction. This way some flights have less separation between each other when arriving at the fix, but still maintain the runway time-in-trail constraint, on average. This was intended to be a simple scenario to test if the system was functioning properly. For the second, a more realistic traffic scenario was developed that included departures, overflights and arrivals scripted from actual flight plans of the full variety of aircraft types flown in the National Airspace System. Also, an airport configuration consisting of four arrival runways (13R, 17C, 17L, and 18R) and eight DFW arrival fixes is used. The traffic includes a total of 649 flights of which 196 are arrivals (Fig. 3 and Fig. 4).

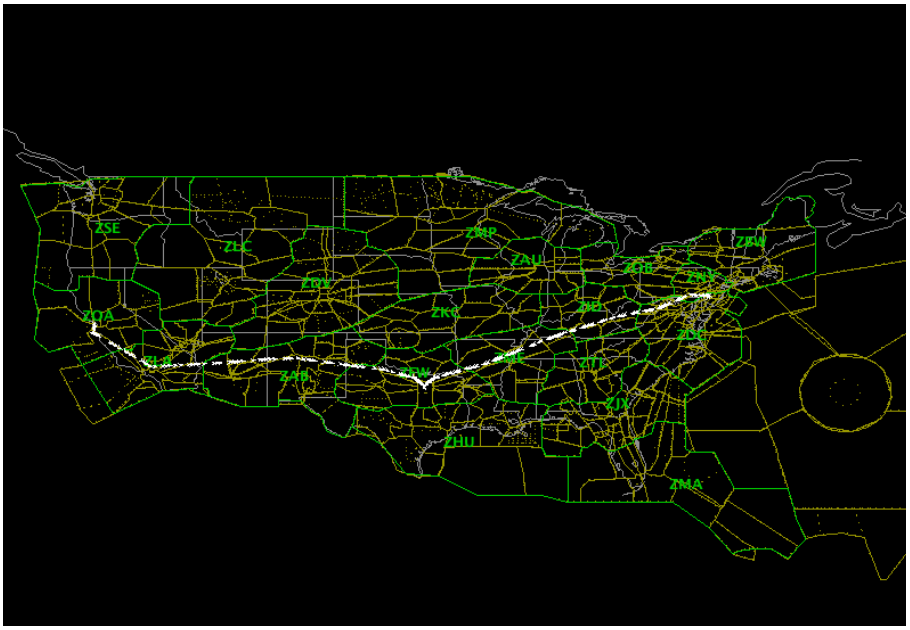


Figure 2. Simple traffic scenario

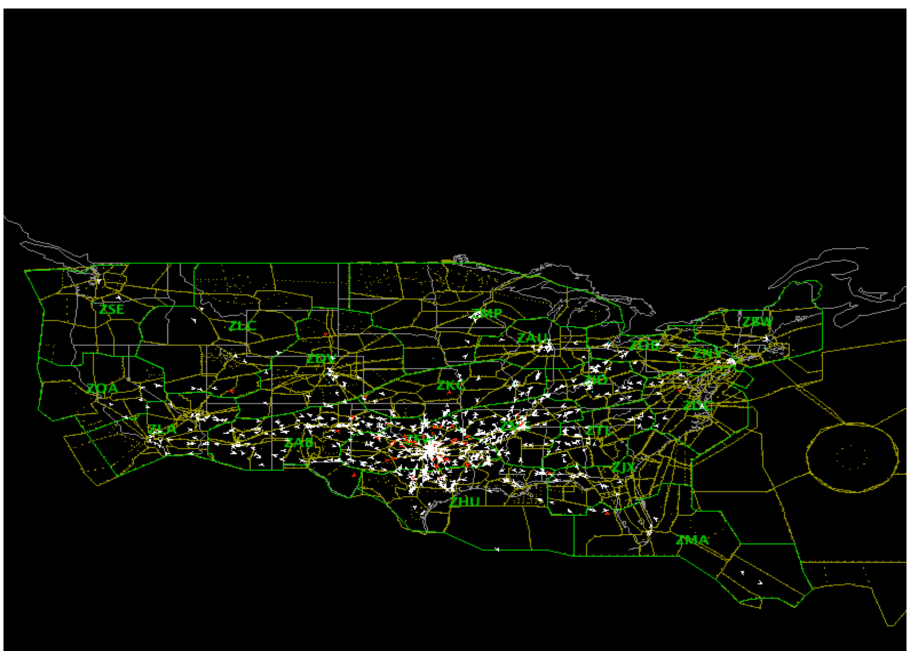


Figure 3. Complex traffic scenario

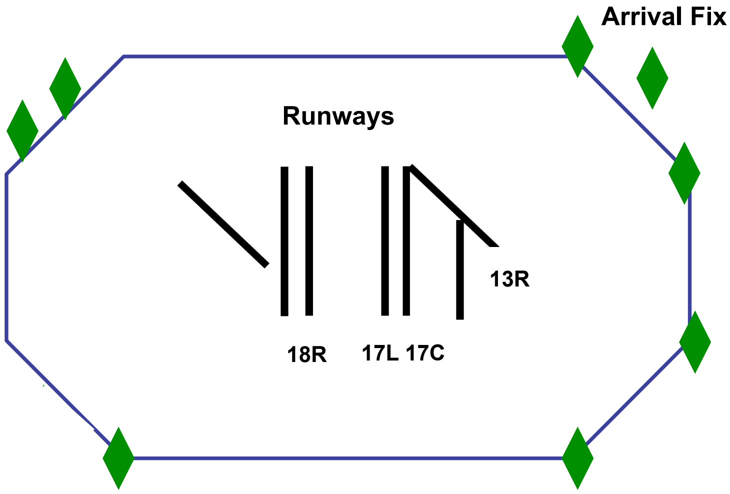


Figure 4. Fort Worth Center and DFW Airport Configuration

The scenarios were simulated using the Airspace Concept Evaluation System (ACES), a multi-fidelity fast-time modeling and simulation system[13] with the AAC Autoresolver and the TMA model both enabled. A total of 18 simulation test cases were executed. Nine runs were a combination of TMA time-in-trail (runway landing) constraints of 72, 87, 101 seconds under 0%, 5%, and 10% CAS uncertainty using the simple arrival-traffic-only scenario. The uncertainty magnitudes are consistent with those used by Lauderdale et al. [13] The other nine test cases used the same time-in-trail constraints and CAS uncertainties, but used the complex traffic scenario. Note that wake vortex separation criteria were not used, and the time-in-trail spacing requirement at the runway was constant for the duration of each test case.

The system was initialized with several parameters. A horizontal conflict detection criterion of 5 nmi and resolution criterion of 7 nmi was enforced. The detection criterion is used for detection of a violation of the 5-nmi horizontal separation requirement. The resolution criterion is the minimum distance between aircraft that Autoresolver has to ensure when searching for a conflict-free resolution. The extra two miles were added to the resolution as a buffer to accommodate for trajectory prediction uncertainty. The vertical conflict detection criterion was 1,000 feet. Autoresolver and TMA are used to maintain time-in-trail constraints at the arrival fixes and runway, respectively. As defined in this simulation, the TMA freeze horizon specifies the time horizon, as measured from the runway, upon which arrival aircraft are assigned an STA by TMA. The Autoresolver freeze horizon, which is measured from the arrival fix, is the point where Autoresolver starts generating conflict-free trajectories to meet the STAs. The Autoresolver freeze horizon was set to 20 minutes so that inbound arrival aircraft would still be in their cruise phase of flight; this is consistent with the freeze horizon used in prior Autoresolver studies.[6-9, 16, 17] The TMA freeze horizon was set to a larger value of 60 minutes to ensure that TMA generates a scheduled time of arrival before the aircraft crosses the Autoresolver freeze horizon. Six of the simulations were run with zero uncertainty, meaning that the planned trajectories are expected to be flown perfectly. The remaining twelve simulations incorporated 5% or 10% CAS uncertainty. Also, the simulation is designed so there will not be any TRACON delay, meaning that each trajectory between the arrival fix and runway would be flown in exact conformance with the trajectory generated by Autoresolver. This implies that the crossing-time accuracy at the arrival fixes were equal to that at the runway. With zero TRACON delay, the magnitude of each flight's meter-fix crossing-time conformance error, of which CAS uncertainty is but one of many sources, represents the residual error for which the TRACON would need to correct in order to meet the runway time-in-trail constraint.

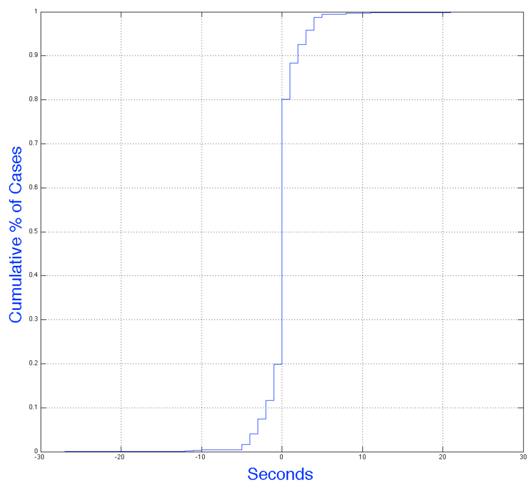
V. Results

The results are presented in three parts. The results presented first characterize the accuracy of the Autoresolver/TMA system in meeting the runway time-in-trail constraints. The results presented second characterize system safety vis- a -vis the relationship between the scheduling time buffer and the 60-second minimum time-in-trail constraint. The results presented third focus on the feedback question through an investigation of scheduling precision.

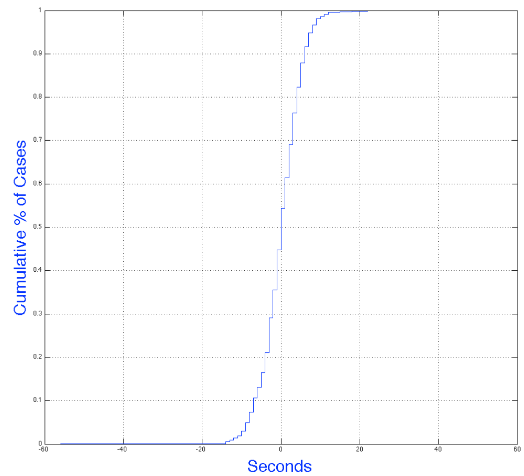
A. System Performance (Accuracy)

To study the success of the integrated system as a whole, the first step is to look at how closely aircraft conform to their runway time-in-trail constraints, which is a measure of accuracy. This can be accomplished by looking at the actual time between consecutive landings at the runway. The accuracy values are calculated for each of the runs, as well as the percentage of cases that fall within a specified range. The percentages are an indication of the relative success of the integrated system in meeting the corresponding time-in-trail constraints. The results are based on a +/- 20-second range around the three time-in-trail constraints. When any uncertainty (in this case CAS) is added in the system, accuracy values indicate the errors for which human approach controllers or an automated landing system in the TRACON would need to correct.

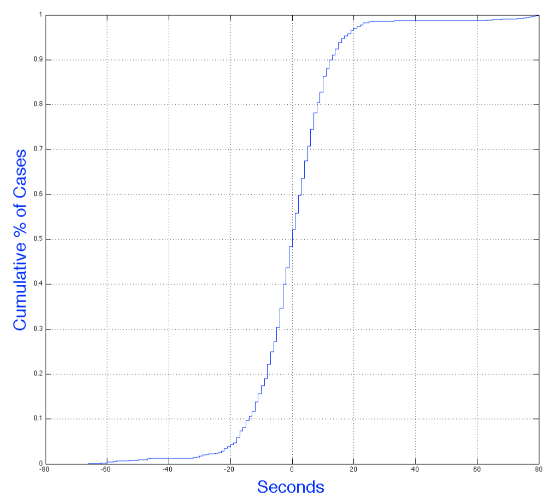
A cumulative distribution function of the consecutive actual landing times for each of the simulation cases is generated for the individual runways and for the combination of all the runways. As an example, Figure 5 illustrates (for the simple traffic scenario) the deviation of consecutive landing times from the desired 72-second time-in-trail constraint for Runway 17C under 0%, 5%, and 10% CAS uncertainty. Looking at the CDF gives an idea of how the percentages of the cases that are within the acceptable range are determined. In a perfect system, 100% of the cases would be at the required landing spacing constraint. For a system with no trajectory prediction uncertainty (as in the 0% uncertainty case), it is assumed that the executed trajectories would be flown perfectly, meaning that any cases, such as those in Fig.5a, that do not meet the time-in-trail constraints are considered an artifact of the design of the system. This has to do with the convergence of the AAC trajectory-generating algorithm, which is currently set to five seconds. This means that if a conflict-free trajectory that meets the STA within 5 seconds is found, it is considered an acceptable trajectory. The algorithm could be improved such that all cases would more closely meet the constraint. However when uncertainty is added, flights can no longer be controlled to arrive perfectly because the errors would come from the execution and not generation of the trajectories. Figure 6 shows a comparison of the results, again for the simple traffic scenario, among the three time-in-trail constraints under three different uncertainty magnitudes. One would expect that that higher uncertainty would decrease accuracy. As shown, the percentages of cases that fall within the range are the lowest for the 10% uncertainty case. Interestingly though, there is less than a 0.5% change between the 0% and 5% case, most likely an artifact of the data sample size. The percentages across the time-in-trail constraints vary little. Except for under 10% uncertainty, the system meets the constraints with a high success rate (> 99%).



(a)



(b)



(c)

Figure 5. Cumulative Distribution of the time between consecutive landings at Runway 17C for the 72-second time-in-trail constraint (simple traffic scenario). (a) 0% CAS uncertainty (b) 5% CAS uncertainty (c) 10% CAS uncertainty

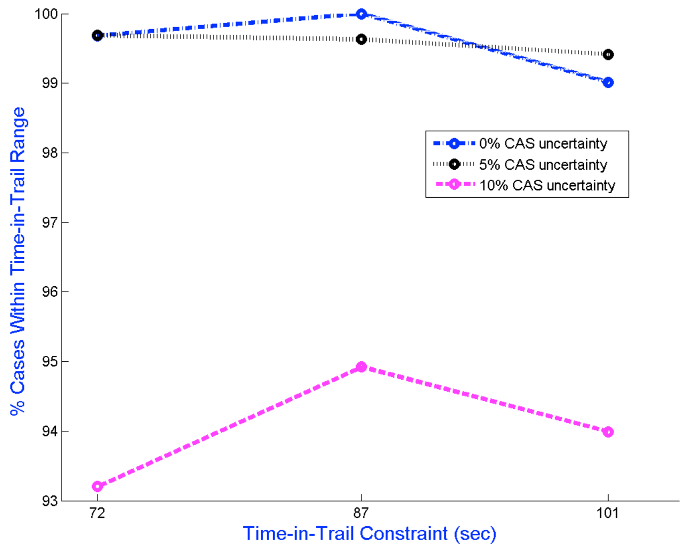


Figure 6. Runway 17C- Percentage of flights within 20 seconds of time-in-trail constraint (simple traffic scenario).

Table 3 shows the results for individual runways for the complex traffic scenario. The percentages differ among the individual runways. In many cases the percentages drop (decreased system accuracy) with increased uncertainty, however there are cases when they remain constant or even increase. This could be due to several reasons, including the runway configuration (number of fixes feeding that runway) and the aircraft sample size differences among the runways. The effects of the runway configuration and sample size will need further investigation to determine the extent to which they explain the differences.

Figure 7 depicts the results for the combined runways, which represents the average performance of the runways. On average, the accuracy of the system decreases when more uncertainty is added, as is evident from the decrease in the percentage of cases that fall within the acceptable error range when CAS uncertainty is increased from 0% to 5% and to 10%. The range for the combined runways is 75% to 94% as compared to 93% to 100% for the simple traffic scenario. This indicates that the system is not fully capable of meeting the time-in-trail constraints within the desired range with a high success rate when the more complex traffic scenario is used. This degradation in system performance could be one indication for the need for a feedback mechanism between the TMA scheduler and Autoresolver. Interestingly, in the complex traffic scenario, while the accuracies for the 72- and 101-second constraints do not differ much, those for the 87-second constraint decrease. Further investigation is needed to ascertain the reason behind this result.

Table 3. Percentage of cases within 20 seconds of time-in-trail constraint

Runway	Time-in-trail (seconds)	0% Uncertainty (Sample size)	5% Uncertainty (Sample size)	10% Uncertainty (Sample size)
13R	72	100.0 (5)	100.0 (5)	80.0 (5)
	87	100.0 (5)	100.0 (5)	100.0 (5)
	101	100.0 (5)	80.0 (5)	80.0 (5)
17C	72	94.4 (36)	86.1 (36)	86.1 (36)
	87	90.0 (30)	76.7 (30)	57.7 (26)
	101	92.6 (27)	88.9 (27)	85.2 (27)
17L	72	83.3 (18)	88.9 (18)	88.9 (18)
	87	83.3 (24)	75.0 (24)	75.0 (24)
	101	93.3 (30)	93.3 (30)	83.3 (30)
18R	72	91.7 (12)	75.0 (12)	75.0 (12)
	87	81.3 (16)	81.3 (16)	68.8 (16)
	101	87.5 (16)	87.5 (16)	81.3 (16)

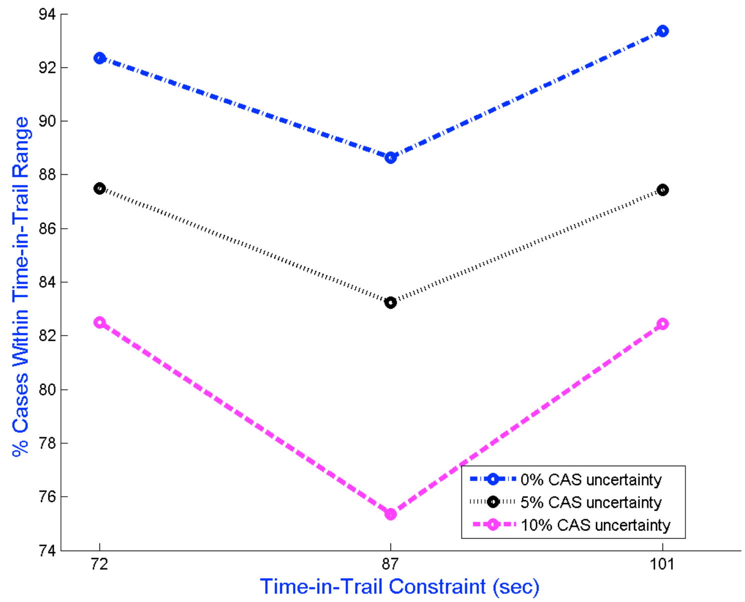


Figure 7. Combined Runways- Percentage of flights within 20 seconds of time-in-trail constraint (complex traffic scenario).

B. Scheduling Time Safety Buffer

The second metric is used to study one aspect of system safety by determining what scheduling time buffer needs to be applied to achieve a specific minimum time-in-trail constraint. This buffer can be added to account for trajectory uncertainty to ensure that the target time-in-trail requirement is safely met. For this measure, the percentage of cases where consecutive aircraft land less than 60 seconds apart at the runway is determined for each of the three time-in-trail constraints. For this study, the 60-second constraint was defined as the minimum safe spacing between consecutive landings at a runway. Figure 8 shows a comparison of those percentages under the varying constraints and uncertainties for the simple traffic scenario. For both the 0% and 5% uncertainty case, scheduling for consecutive landings of 87 seconds at Runway 17C (i.e. a 27-second buffer) is needed to fully meet the safety requirement (i.e. 0% of cases fall below 60 seconds). However, scheduling for 101 seconds is necessary for the scenarios with 10% uncertainty modeled. Figure 9 shows a comparison of the percentage of cases, for the combined runways, with less than 60 seconds of inter-arrival spacing under the varying constraints and uncertainties for the complex traffic scenario. On average under all three uncertainty magnitudes, not even a 41-second buffer is enough. If, for example, two percent of arrival pairs are allowed to violate the 60-second spacing requirement, then a 27-second buffer would be sufficient under 0% and 5% uncertainty and 41 seconds under 10% uncertainty. This indicates that in this system for these scenarios, when trying to schedule for a specific time-in-trail spacing at the runway, scheduling on the conservative side by adding a buffer is necessary. More detailed results for the individual runways are shown in Table 4.

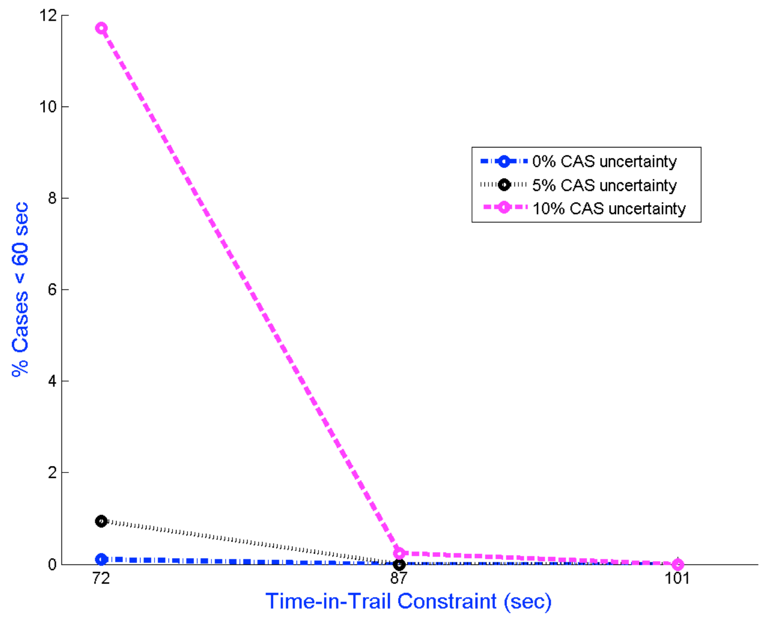


Figure 8. Runway 17C- Comparison of percentage of arrival pairs with < 60 seconds inter-arrival spacing for each time-in-trail constraint and each uncertainty level (simple traffic scenario).

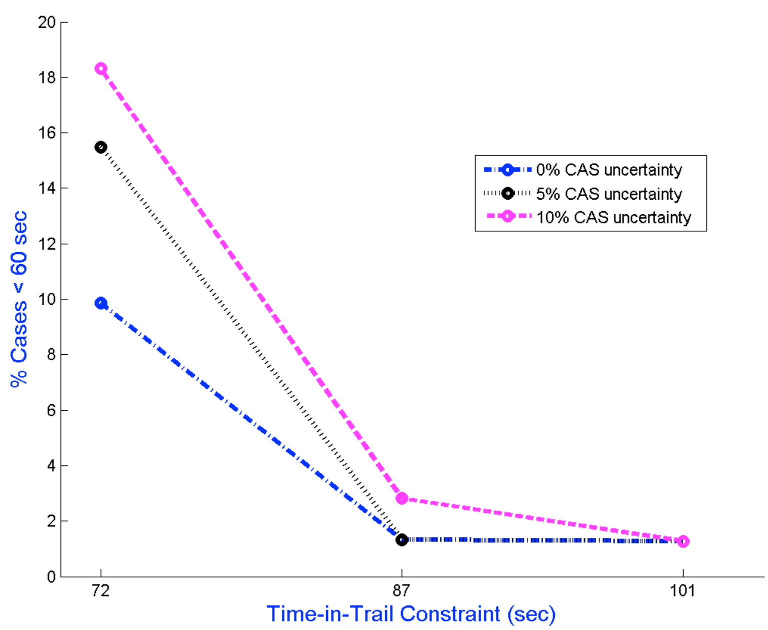


Figure 9. Combined runways- Comparison of percentage of arrival pairs with < 60 seconds inter-arrival spacing for each time-in-trail constraint and each uncertainty level (complex traffic scenario).

Table 4. Percentage of cases < 60 seconds

Runway	Time-in-trail (seconds)	0% Uncertainty (Sample size)	5% Uncertainty (Sample size)	10% Uncertainty (Sample size)
13R	72	0.0 (5)	0.0 (5)	20.0 (5)
	87	0.0 (5)	0.0 (5)	0.0 (5)
	101	0.0 (5)	0.0 (5)	0.0 (5)
17C	72	11.1 (36)	19.4 (36)	19.4 (36)
	87	0.0 (30)	0.0 (30)	0.0 (26)
	101	0.0 (27)	0.0 (27)	0.0 (27)
17L	72	11.1 (18)	16.7 (18)	22.2 (18)
	87	0.0 (24)	0.0 (24)	4.2 (24)
	101	0.0 (30)	0.0 (30)	0.0 (30)
18R	72	8.3 (12)	8.3 (12)	8.3 (12)
	87	6.3 (16)	6.3 (16)	6.3 (16)
	101	6.3 (16)	6.3 (16)	6.3 (16)
Combined Runways	72	10.0 (71)	15.5 (71)	18.3 (71)
	87	1.3 (75)	1.3 (75)	2.8 (71)
	101	1.3 (78)	1.3 (78)	1.3 (78)

C. Scheduling Precision

To investigate whether feedback between Autoresolver and TMA would help improve system performance, the scheduling precision was plotted as a function of actual landing time. Recall that if Autoresolver is unable to generate a conflict-free trajectory that meets the TMA scheduled time, it will use a later arrival time, and all subsequent STAs will depend on this new information. The difference between this Autoresolver STA and the TMA STA is what is referred to as scheduling precision. This is used to check for the possibility that if Autoresolver keeps revising the STA and TMA is unaware, then the shift between the TMA scheduled values and the revised Autoresolver values would propagate backwards rendering the future TMA STA values obsolete. For example, Fig. 10 shows a plot of scheduling precision versus actual landing time for the 72-second time-in-trail under 0% CAS uncertainty case for Runway 17C of the complex scenario. As shown, most of the bad precision cases mostly occur during high traffic periods. For this scenario, the system performance was relatively stable in the no feedback mode, but scheduling performance seemed to degrade somewhat during high traffic periods. Feedback might have been useful in those situations; however further work is required to investigate whether the addition of feedback will yield significant improvements in other situations.

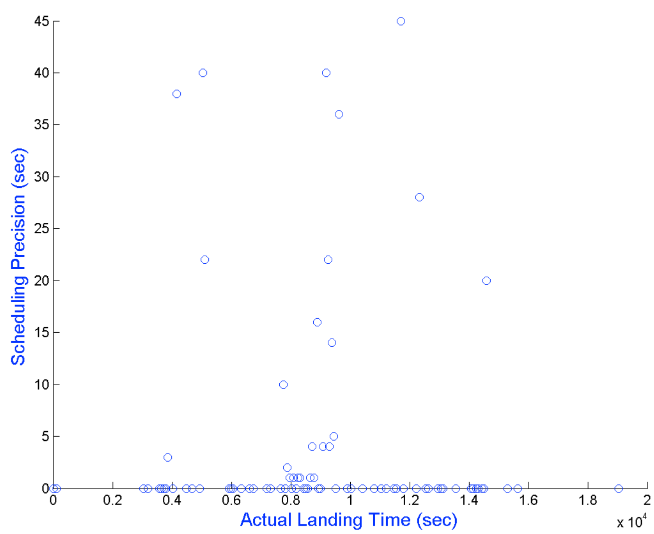


Figure 10. Runway 17C- Time series of scheduling precision vs. actual landing time for the 72-second time-in-trail constraint under 0% CAS uncertainty (complex traffic scenario).

VI. Summary

In this paper two separate systems, the Traffic Manager Advisor (TMA) and the Advanced Airspace Concept (AAC) Autoresolver, were combined to provide integrated arrival management. The goal was to evaluate overall system performance and to investigate the need for a feedback mechanism between TMA and Autoresolver. As part of the study, the degree to which the automated resolution generator could conform to the schedules generated by the arrival scheduler and a time scheduling safety buffer needed to meet a 60-second minimum-time-in-trail requirement were determined. The performance of the integrated system under 0%, 5% and 10% CAS uncertainty using 72, 87, and 101-second time-in-trail constraints for both a simple traffic scenario and a complex traffic scenario was tested.

Three metrics were presented in this paper. The first metric is the percentage of cases that satisfied the runway time-in-trail constraint within a specified range. This would be indicative of the performance of the system in terms of accuracy. In this study, the results were presented based on +/- 20-second tolerance around the desired inter-arrival spacing interval. For the simple traffic scenario under both 0% and 5% uncertainty, it was found that the system is capable of meeting, with a high success rate (> 99%), the time-in-trail constraints within the desired range. Under 10% uncertainty, the success rate was lower (93% to 95%). In the complex traffic scenario, on average the accuracy of the system decreased when more uncertainty was modeled. The range for the combined runways was 75% to 94% as compared to 93% to 100% for the simple traffic scenario. This indicates that in the complex traffic scenario, the system was not fully capable of meeting the time-in-trail constraints within the desired range with a high success rate.

The second metric is used to characterize system safety vis-a-vis the relationship between the scheduling time buffer and the 60-second minimum time-in-trail constraint. For the simple traffic scenario, in the 0% and 5% uncertainty cases, a buffer of 27 seconds was needed to fully meet the requirement; a buffer of 41 seconds was sufficient for cases with 10% CAS uncertainty. For the complex traffic scenario, on average under all three uncertainty levels, a buffer of more than 41 seconds was necessary. If, for example, two percent of arrival pairs were allowed to violate the 60-second spacing requirement, then a 27-second buffer would be sufficient under 0% and 5% uncertainty and 41seconds under 10% uncertainty. This indicates that in this system for these scenarios, when trying to schedule for a specific time-in-trail spacing at the runway, scheduling on the conservative side by adding a buffer is necessary.

The third metric, scheduling precision, is used to investigate the need for feedback. The addition of feedback would require a modification such that the AAC Autoresolver would update TMA of any changes it had to make to the TMA schedule; TMA could then use that information to revise the rest of its schedule. The system performance was relatively stable in the no feedback mode, but scheduling performance seemed to degrade somewhat during high traffic periods. Feedback might have been useful in those situations; however the results are not conclusive since they are only based on these specific traffic scenarios and therefore at this time, no claim can be made regarding the potential benefits of feedback. Other simulations are needed to help determine if potential improvements are significant enough to warrant such an addition.

Future Work

Future work includes investigating the reason behind the lower system performance of the 87-second time-in-trail constraint as compared to both the 72 and 101-second constraints. Future work could also include investigating the effects on the performance of the system with increased traffic density, varying airport configurations, and the addition of different types of uncertainties such as wind and weight. Those results will also go towards the goal of determining the potential benefits of adding TMA/Autoresolver feedback.

Acknowledgments

The authors would like to thank Sonali Kochar for her help in integrating Autoresolver with TMA. The authors give special thanks to Jason Otto and Brian Andrade for their help in the data analysis process.

References

[1]Department of Transportation, Federal Aviation Administration, Air Traffic Control, Order JO 7110.65S, 14 February 2008, http://www.faa.gov/air_traffic/publications/

[2] Sokkappa, B.G., "The Impact of Metering Methods on Airport Throughput," MITRE MP-89W000222, 1989.

[3]Department of Transportation, Federal Aviation Administration, NextGen Implementation Plan, 2012, http://www.faa.gov/nextgen/implementation/plan/

[4]Wong, G., "The Dynamic Planner: The Sequencer, Scheduler, and Runway Allocator for Air Traffic Control Automation," NASA/TM-2000-209586, 2000.

[5]Swenson, H. N. et al, "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," *1st USA/Europe Air Traffic Management Research & Development Seminar*, Saclay, France, June 17 - 19, 1997.

[6]Farley, T., Kupfer, M., and Erzberger, H., "Automated Conflict Resolution: A Simulation Evaluation Under High Demand Including Merging Arrivals," *7th AIAA Aviation Technology, Integration and Operations Conference*, Belfast, Northern Ireland, 2007.

[7]Kupfer, M. et al, "Automated Conflict Resolution: A Simulation-Based Sensitivity Study of Airspace and Demand," *26th International Congress for the Aeronautical Sciences*, Anchorage, AK, 2008.

[8]Farley, T. Erzberger, H., "Fast-Time Simulation Evaluation of A Conflict Resolution Algorithm Under High Air Traffic Demand," *7th USA/Europe ATM R&D Seminar*, Barcelona, Spain, 2007.

[9]Aweiss, A. S., Farrahi, A. H., Lauderdale, et al, "Analysis of a Real-Time Separation Assurance System with Integrated Time-in-Trail Spacing," *10th AIAA Aviation Technology, Integration, and Operations Conference*, Fort Worth, TX, 2010.

[10]Coppenbarger, R., Mead, R., and Sweet, D., "Field Evaluation of the Tailored Arrivals Concept for Datalink-Enabled Continuous Descent Approach," Journal of Aircraft, Vol. 46, No. 4, 2009, pp. 1200-1209.

[11]Coppenbarger, R. et al, "Development and Testing of Automation for Efficient Arrivals in Constrained Airspace," *27th International Congress of the Aeronautical Sciences,* Nice, France, 2010.

[12]Erzberger, H., "Transforming the NAS: The Next Generation Air Traffic Control System," NASA/TP-2004-212828, October 2004.

[13]National Aeronautics and Space Administration, http://www.aviationsystemsdivision.arc.nasa.gov/research/modeling/aces.shtml

[14]Lauderdale, T.A., Cone, A.C., and Bowe, A.R., "Relative Significance of Trajectory Prediction Errors on an Automated Separation Assurance Algorithm," 9th *USA/Europe Air Traffic Management research and Development Seminar*, Berlin, Germany, 2011.

[15]Erzrberger, H., "Automated Conflict Resolution for Air Traffic Control," *25th International Congress of the Aeronautical Sciences*, Germany, 2006.

[16]Erzberger, H., "Separation Assurance in the Future Air Traffic System," *ENRI International Workshop on ATM/CNS,* Tokyo, Japan, 2009.

[17]Erzberger, H., Lauderdale, T.A., Chu, Y.C., "Automated Conflict Resolution, Arrival Management and Weather Avoidance for ATM," *27th International Congress of the Aeronautical Sciences (ICAS)*, Nice, France, 2010.