Design Considerations for a New Terminal Area Arrival Scheduler

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Design of a terminal area arrival scheduler depends on the interrelationship between throughput, delay and controller intervention. The main contribution of this paper is an analysis of the above interdependence for several stochastic behaviors of expected system performance distributions in the aircraft's time of arrival at the meter fix and runway. Results of this analysis serve to guide the scheduler design choices for key control variables. Two types of variables are analyzed, separation buffers and terminal delay margins. The choice for these decision variables was tested using sensitivity analysis. Analysis suggests that it is best to set the separation buffer at the meter fix to its minimum and adjust the runway buffer to attain the desired system performance. Delay margin was found to have the least effect. These results help characterize the variables most influential in the scheduling operations of terminal area arrivals.

I. Introduction

An advanced scheduling capability focusing on precision scheduling in the terminal area is currently under development at NASA Ames Research Center. Two of the central goals for this development to increase efficiency in the terminal airspace are the determination of efficient aircraft trajectories in the presence of uncertainty and creating a balance among the frequently conflicting objectives. These objectives include increasing throughput, predictability, robustness, and accessibility, while reducing delay, fuel burn, and emissions. The terminal area and airport surface represent the geographical boundaries where flights are subject to the most extensive set of constraints. Therefore, it is expected that managing operations more efficiently in these areas will be critical in accommodating the expected increase in air traffic demand.[1]

Changing from current operational practices to 4-D trajectory-based arrival management is crucial for precision scheduling in the terminal area. Studies have quantified the benefits[2,3] of more precise arrival management by making reasonable assumptions of the precision level afforded by these proposed technologies and simulating a simplified terminal area scheduler with a sensible set of control variables. These studies, however, generally do not determine ranges for the precision needed to realize the same level of benefits, focusing rather on demonstrating the benefit of the concept of operations employing a specific set of technologies. Other studies have established rules-of-thumb to balance system uncertainty and the amount of delay margin needed in the terminal area.[4,5,6] Vandevenne[4] found that the delay margin available in the terminal area should be twice the standard deviation of the arrival time error to the meter fix in order to maintain throughput and keep controller intervention rate below 10%. As a comparison, Erzberger[5] suggests setting the delay margin to be 2/3 of the standard deviation to minimize delay. In field trials with the Traffic Management Advisor (TMA), it was found that to achieve operational effectiveness, the delay distribution to the terminal area was considerably higher than what either Vandevenne and Erzberger established through analytical studies.[6] These studies, however, also do not explore how separation buffers affect system performance.

The purpose of this paper is to provide an analysis of the trade-off among *throughput, delay* and *controller intervention*, with a view toward designing a terminal area arrival scheduler. In addition to delay margin, this paper aims to explore how additional separation buffers between aircraft affect system performance. This work also investigates how to adjust the scheduler to accommodate varying levels of precision and understand the sensitivity of these benefits to changes in the decision variables. Results from this analysis will suggest a set of rules-of-thumb for the operation of a scheduler in order to achieve a desired level of system performance. The results of these analyses help recognize and characterize the factors most influential in the operations of terminal area arrivals.

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The rest of this paper is organized as follows. The terminology used in this paper is first introduced in section II. An overview of the scheduling simulation tool along with a description of the input parameters are provided in section III, while section IV describes the experimental setup. The experimental results using data from Dallas-Fort Worth airspace is presented in section V.

II. Background

Throughout this paper, the term *(arrival) scheduler* refers to a software program that, given a number of aircraft due to arrive at the terminal, produces for each aircraft a scheduled arrival time (STA) at the meter fix and runway threshold the aircraft intends to cross. The analysis is carried out with a stochastically behaved uncertainty in the actual time of arrival (ATA) of the aircraft at the meter fix, and runway threshold, i.e. in the general probabilistic setting used in Ref. 7. In more detail, if STA is the scheduled time of arrival for an aircraft to a given waypoint (e.g., meter fix or runway), then the aircraft's actual arrival time, ATA at the waypoint is $STA+E$, where E is a random variable, henceforth called *arrival time error*. It captures the uncertainty in the aircraft's time of arrival. The presence of this error hinders the compilation of a precise arrival schedule. For instance, suppose two aircraft are scheduled to arrive consecutively at a waypoint with the respective STA_1, STA_2 ($STA_1 < STA_2$), and with the respective errors E_1, E_2. The difference between the actual arrival times, $X = \mathrm{ATA}_2 - \mathrm{ATA}_1$, is called *the separation* between the two aircraft. The specific values of the errors may be such that the separation is below the required minimum, denoted by r, resulting in a *loss of separation*. To mitigate this risk, the choice of values for the STAs in the scheduler proposed here relies on *(separation) buffers* and terminal *delay margins*. Namely, a buffer b for the given waypoint is a time duration such that the STA_1, STA_2 of two consecutive arrivals are chosen by the scheduler to be apart by $(r+b)$, rather than simply r.

III. Methodology

This research aims to suggest general guidelines on how to set control variables typically available in the terminal scheduling domain in the presence of arrival time error to the meter fix and runway. These control variables include:

- a separation *buffer* for the meter fix and runway, i.e. scheduling separations that are slightly larger than required by the FAA and
- a *delay margin* between the arrival meter fix and runway threshold, i.e. the maximum amount of delay that can be absorbed in the terminal area.

The tradeoff between throughput, delay and controller intervention over a range of values for the random and control variables were explored. It is desired to have maximal throughput and minimal delay and controller intervention, subject to meeting the separation requirement. The Stochastic Terminal Area Simulation Software (STASS)[7] was used to conduct the analysis and a brief description of its algorithm and simulation parameters is provided in the next sections.

A. Simulation Software

STASS[7] was used in this study to simulate aircraft sequencing and scheduling in both the Air Route Traffic Control Center (Center) and Terminal Radar Approach Control (TRACON) airspace. Figure 1 shows the airspace topology modeled in STASS, which includes two scheduling points in the TRACON, the meter fix and runway. Arrival times to the meter fixes and runways, ATA_{mf} and ATA_{rwy} are generated by the Center Scheduler and the TRACON Scheduler modules in STASS respectively. Any number of meter fixes and runways can be modeled. These basic scheduling locations are typically used in terminal area scheduling capabilities. The number of meter fixes and runways chosen is dependent on the airport. Analysis using STASS is intended to help understand how scheduling metrics change

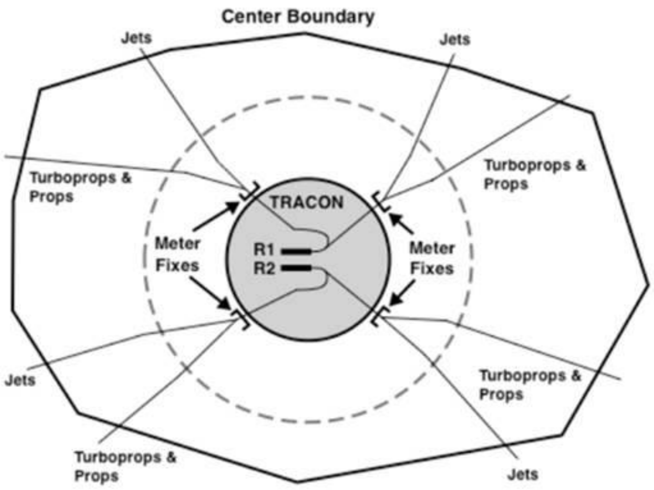


Figure 1. STASS airspace topology.

when varying the control variables. These results then provide a starting point to choose the initial settings for the terminal area scheduler being developed at NASA Ames Research Center. A basic overview of the scheduling process is described next. Detailed description of the algorithm can be found in ref. 8.

Arrival aircraft originate from the Center boundary heading towards the meter fix. The Center Scheduler determines the flight sequence as dictated by a first-come, first-served heuristic based on their unimpeded estimated time of arrival, ETA_{mf}. The scheduled arrival times, STA_{mf} to the meter fixes are based on ETA_{mf}, delay margin, shortest time-to-fly (TTF) from the meter fix to runway, buffer b and separation requirement r for both the meter fix and runway. The resulting meter fix arrival time STA_{mf} computed by the Center Scheduler are proposed arrival times that indicate when aircraft *should* arrive at the meter fixes. In cases where arrival times may not be met with absolute delivery accuracy, these times are offset by an arrival time error, E. The actual time of arrival to the meter fix is then calculated as $ATA_{mf} = STA_{mf} + E_{mf}$.

The $ATA_{mf} + TTF$ is then used as ETA_{rwy} and as input into the TRACON Scheduler. The TRACON Scheduler calculates STA_{rwy} by choosing the shortest TTF from the meter fix to runway and having $r + b$ separation from the leading aircraft. There may be an arrival time error in meeting the STA_{rwy} and so the $ATA_{rwy} = STA_{mf} + E_{rwy}$.

B. Simulation parameters

STASS includes the capability to model the stochastic behavior of the arrival time errors that occur in the aircraft's STAs to the meter fix and the runway threshold. This behavior can lead to either separation loss or to unnecessary spacing between aircraft. The former effect compromises the safety of the terminal operation, while the latter causes a waste of resources. STASS uses *buffers* and a *delay margin* in the terminal area to reduce the risk of separation loss and waste, respectively. It is also recognized that operationally, controllers will not allow separation to be compromised. Thus, this is an indicator to know when *controller intervention* would be required. To analyze the interaction between the control variables and the stochastic arrival time errors, a range of values was chosen for each variable such that it spanned the most realistic settings. Figure 2 is a stylized illustration of when and where each parameter is used in the simulation.

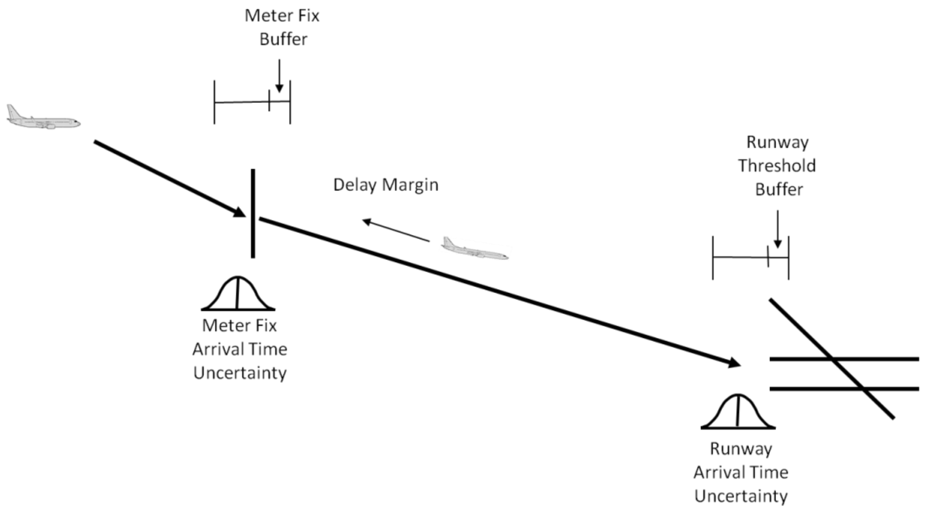


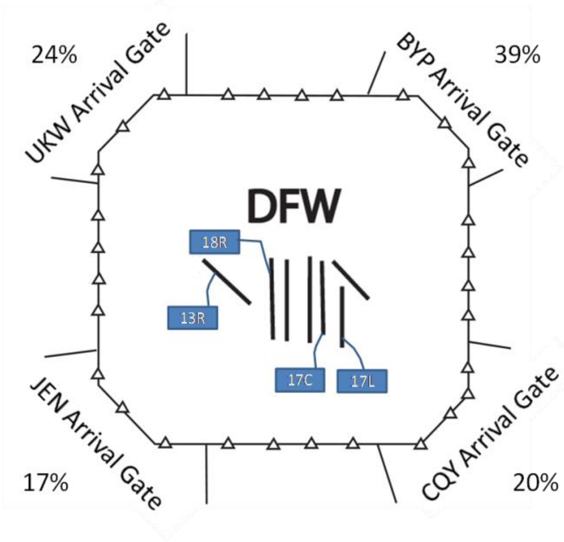
Figure 2. Simulation parameters: 1) meter fix and runway arrival time uncertainty, 2) meter fix and runway buffer and 3) delay margin.

IV. Experiment Setup

A. Dataset

The aircraft dataset was derived from Dallas/Fort Worth (DFW) TRACON traffic. NASA has used DFW as an operational environment to study and test the applicability of its ATM technologies for many years. NASA has gained a significant understanding of DFW operations through its access to vast amount of current air traffic data and analyses.[9,10] Based on this experience base, DFW was chosen for an initial assessment of the system behavior using STASS.

The dataset had a throughput of approximately 168 aircraft per hour, which is considerably higher than today's operations (i.e. 126 aircraft per hour in visual meteorological conditions (VMC)).[11] The number of aircraft in the dataset was increased until the TRACON was fully saturated in STASS so that the analysis could be done on a high demand scenario. DFW operates with two major configurations, North and South flow with aircraft landing and departing to the North and South, respectively. A majority of operations occur in South flow configuration as illustrated in Figure 3. In this configuration, four meter fixes (BYP, CQY, UKW, JEN) feed four arrival runways (18R, 17C, 17L, 13R). Observations from recorded live traffic were used to determine the percentage of traffic going through each fix and as indicated at the respective gates in Figure 3. Figure 4 shows the engine type and weight class distribution.



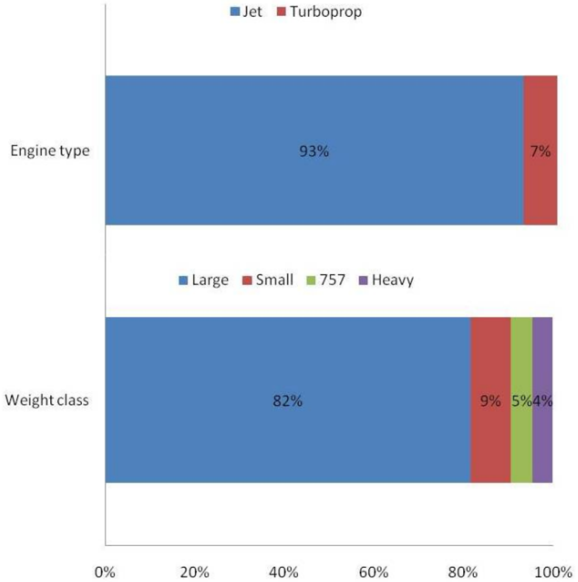


Figure 3. DFW meter fixes and runways used in South flow configuration.

Figure 4. Engine type and weight class distribution.

Tables 1 and 2 show the separation minima used at the meter fixes and runway threshold respectively. The separation requirements at the meter fixes and threshold were based upon the FAA regulations.[12] The minimum in-trail separation of 5 nm was used at the meter fix and those used at the threshold are listed in Table 2. The distance separation requirements were converted to time separation for use by STASS. For the meter fix, an estimated ground speed of the trailing aircraft was used for the conversion. At the threshold, the conversion was achieved by modeling the airspeed profile of each type of aircraft and the wind speed on final approach and then integrating the equations of motion along the final approach path. The result of this process is the time separation matrix given in Table 2 for the case of zero wind.[5] Table 3 lists the TRACON transit times for the South flow configuration given engine type, meter fix and runway. These values were derived by simulating a few representative turboprops and jets using TMA and recording their TTF from each meter fix to each runway. Note that not all runways are available for all meter fixes, based on operational procedures, and so such transit times are missing from the table.

Table 1. Meter fix separation minima in seconds.

Follower	
Jet	58
Turboprop	84

Table 2. Runway threshold separation minima, time (sec) and distance (nm) based.

	sec				*nm*			
Leader\Follower	Small	Large	757	Heavy	Small	Large	757	Heavy
Small	58	54	54	50	2.5	2.5	2.5	2.5
Large	84	54	54	50	4.0	2.5	2.5	2.5
757	84	54	54	50	5.0	4.0	4.0	4.0
Heavy	140	108	108	72	6.0	5.0	5.0	4.0

Table 3. TRACON transit times in seconds for South flow configuration.

Jet

Runway\Meter Fix	BYP	CQY	UKW	JEN
18R	694	851	647	845
17C	676	802	664	860
17L	674	782	---	912
13R	---	---	596	---

Turboprop

Runway\Meter Fix	BYP	CQY	UKW	JEN
18R	792	---	689	945
17C	772	---	707	964
17L	769	905	---	---
13R	---	---	631	854

B. Stochastic variables

An aircraft's actual time of arrival at the meter fix and runway threshold was computed by adding a stochastic arrival time error *E* to its *STA*. The underlying probability distribution for this random error was chosen by truncating the zero-mean Gaussian with the given standard deviation σ to the interval centered at the mean (zero) and having a length of six times its standard deviation. The integral of the resulting function is less than one, hence it does not, strictly speaking, constitute a probability density function. However, the error is negligible, and therefore we could treat it as a probability density function. The standard deviation σ was varied for a relevant range of values for both the meter fix and the runway threshold.

In this study, σ_{mf} ranged from 0 to 30 seconds. When controllers metered DFW arrivals using TMA[6,13], the arrival time error was found to be 100 seconds. In future operations with increasing use of tighter navigation performance requirements, continuous descent approaches (CDAs) and/or optimal profile descent (OPD) procedures, meter fix arrival time errors are anticipated to be reduced to less than 50 seconds. Recent simulations of CDAs have shown meter fix arrival time errors at 30 seconds.[14,15]

In contrast, the delivery accuracy to the runway is more precise than to the meter fix. For this study, σ_{rwy} was also varied from 0 to 30 seconds. Statistical analysis of DFW inter-arrival spacing error during peak traffic [16] show that when given a 2.5 nm or 3 nm minimum separation requirement, controllers manually spaced aircraft with an error of about 19 seconds independent of weight class. For larger separation constraints and during instrument meteorological conditions (IMC), spacing precision decreases approximately 5 seconds. Other studies using fast-time simulation and Human-In-The-Loop experiments have shown inter-arrival errors around 15-25 seconds.[13,17,18] As advanced air traffic management techniques become prevalent, the inter-arrival spacing error is expected to decrease to less than 7.5 seconds.[14,15,18] Assuming arrival time errors are independent, the corresponding runway arrival time error is computed by the root sum square of two successive arrival time errors equals the inter-arrival spacing time error.

C. Control variables

Several control variables available in the terminal domain were identified to account for the effects of the random errors in the arrival times. These were the amount of delay margin in the terminal area and spacing buffers beyond minimum separation at both the meter fix and runway. Increasing the buffer at the meter fix and the runway threshold reduced the frequency of separation loss. A greater delay margin lessened unused spacing that may occur in the schedule, by giving aircraft the flexibility to arrive at the meter fix earlier and absorb more of its delay in the terminal area.

The separation buffer at the meter fix ranged from 0 to 60 seconds. To determine the bounds for the buffer range, it was noted from field trials that TMA was sometimes set an additional 2 nm over the 5 nm minimum separation constraint at the meter fix. To be conservative with the maximal bound, 4 nm was used as the buffer and the temporal conversion was computed assuming meter fix crossing speeds of approximately 250 knots.

The runway separation buffer was varied between 0 to 30 seconds. This range was based on analyses by Ballin and Erzberger[16] that compared actual controller time separations with what was required at the threshold. The difference between these two values was used as the runway buffer and varied between 5 to 30 seconds between different weight class pairs, separation requirements and meteorological conditions.

The delay margin ranged from 5% to 25% of an aircraft's TTF from the meter fix to the runway. As RNAV approaches and CDAs are encouraged in future operating concepts, the controllability within the terminal area will be restricted in order to maintain an efficient schedule and maximize the benefits of such procedures. A prior study estimated that an aircraft can absorb delay of about 10% its TTF by using only speed control.[14]

Table 4. Summary of stochastic and control variables and range of values studied.

Stochastic variables	Min	Max
σ_{mf}	0s	30s
σ_{rwy}	0s	30s

Control variables	Min	Max
Meter fix buffer	0s	60s
Runway buffer	0s	30s
Delay margin	5%TTF	25%TTF

V. Results

A series of simulations were conducted to study how airport throughput, delay and the number of controller interventions were affected by the range of control and random variables typically present in the terminal area domain. The tradeoffs between throughput, delay, and controller intervention were then examined to gain insight on how to best set the control variables available in a terminal area scheduler. These variables include 1) the buffer at the arrival metering fix, 2) the buffer at the runway threshold and 3) the delay margin between the arrival metering fix and runway threshold. Given a set of values for each stochastic and control variable, 500 Monte Carlo simulations were run. For each Monte Carlo simulation, each aircraft was given a stochastic arrival time at both the meter fix and runway based on arrival time error term E chosen from the truncated Gaussian distribution with mean at zero and the chosen σ value. The metrics shown in the results section are an average over all 500 runs. Definitions for the metrics used to study the tradeoffs are given below.

Airport throughput is used as an indicator on how well the scheduler performs. With the anticipated increase in air traffic demand, methods to increase or at least maintain throughput are of particular interest for the future air traffic management system. There are several ways to measure throughput. In this study throughput is defined as follows:

Delay an aircraft consumes in order to meet its scheduled time of arrival is calculated as the difference between its estimated time of arrival and actual time of arrival. This quantity is defined for both the runway and meter fix, denoted by the subscript rwy and mf respectively:

Controller intervention during air traffic management may be exercised for a number of reasons which include keeping traffic safely separated, meeting a scheduled time of arrival at a point, heeding traffic flow management restrictions or responding to a pilot's request. For this study, the number of aircraft that stochastically incur a loss of separation due to arrival time error is counted as necessitated intervention by a controller. Controller intervention is the probability of a loss of separation, i.e. of the event $X<r$.

A. Stochastic variables

The general effect of how uncertainty in arrival times affects simulation results is detailed in this section. For these simulation runs, an offset value was added to the scheduled time of arrival of each aircraft (which is its ATA) to simulate the imperfect delivery accuracy when meeting a given arrival time at both the runway and meter fix. The offset value was chosen from a truncated nearly Gaussian distribution centered at zero seconds and having a maximum/minimum spread of ±3σ.

1. Throughput

Figure 5 shows the relationship between the average runway throughput and arrival time error for both the meter fix and runway when the delay margin is set to 10% of an aircraft's time-to-fly (TTF) and the meter fix and runway buffers are set to 0. There is a minimal decline in throughput as σ_{mf} increases from 0 to 30 seconds and virtually no change when increasing σ_{rwy} in the same range. For other scenarios with non zero runway and/or meter fix buffer values, delay margin changes, the change in average runway throughput when varying the uncertainty, are still minimal (i.e. less than one aircraft per hour).

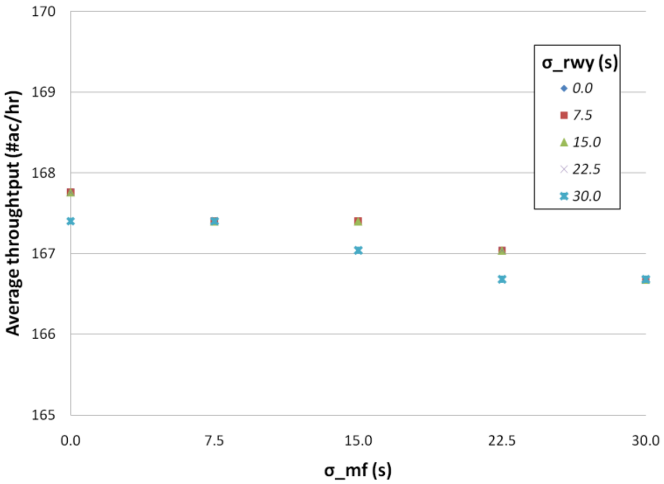


Figure 5. Average runway throughput when varying meter fix (mf) and runway (rwy) arrival time error.

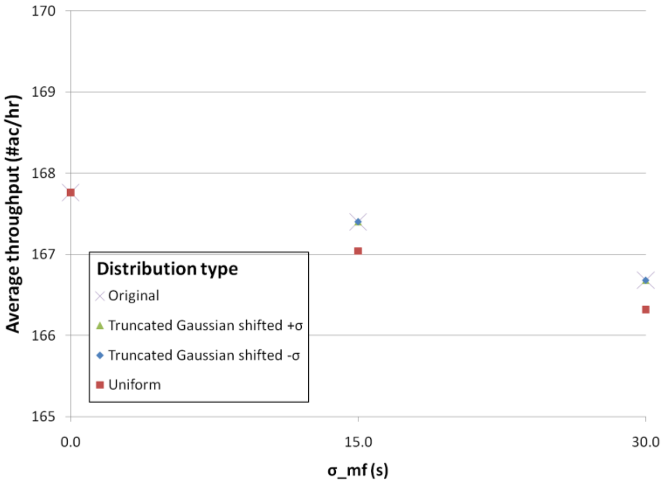


Figure 6. Average runway throughput when varying meter fix (mf) arrival time error using different distribution types.

To test the sensitivity of the distribution used, three other distributions for adding uncertainty to the arrival times were tested. These distributions used were: 1) the truncated Gaussian distribution was shifted by +σ (mf and rwy) 2) the truncated Gaussian distribution was shifted by -σ, and 3) a uniform distribution with maximum and minimum value at ±3σ. Figure 6 shows the average throughput versus σ_{mf} for each of these distributions with the meter fix and runway buffers set to 0 seconds. Comparing the average throughput with the original distribution, there is minimal change when using different distributions. Likewise, for non zero buffer values, changes in throughput with various sigma values were also insignificant. For all these cases, average throughput remained the same despite increasing uncertainty and holding all other variables constant. This is due to the way throughput is calculated and averaged over a large number of runs. Essentially, the first and last aircraft arrival times shifted in the same direction by approximately the mean value of the distribution.

2. Delay

A look at the average delay per aircraft, however, shows that there is an increase in delay as the uncertainty in arrival times increase. Figure 7 illustrates how much delay increases as σ_{rwy} and σ_{mf} increases for each of the tested distributions. In the scenario where the Gaussian distribution centered at zero seconds was used, an increase of up to 30 seconds in σ_{rwy} and σ_{mf} resulted in a change in delay by about 20 and 60 seconds respectively. The uncertainty in arrival times at the meter fix resulted in a larger effect than that at the runway since the scheduled spacing between aircraft pairs is larger at the meter fix. When the truncated Gaussian distribution is shifted by +σ and –σ, the change in average delay increases and decreases by +σ and –σ respectively. Using the uniform distribution centered at zero, the difference in average delay is larger than when using the truncated Gaussian distribution centered at zero. It is interesting to note that the change in delay for each distribution remains the same regardless of changes in the σ values. For example, Figure 7 (left) shows the change in average delay when varying the σ_{rwy} values and holding σ_{mf} fixed at zero. For non-zero values of σ_{mf}, generating a plot similar to Figure 7 would be identical.

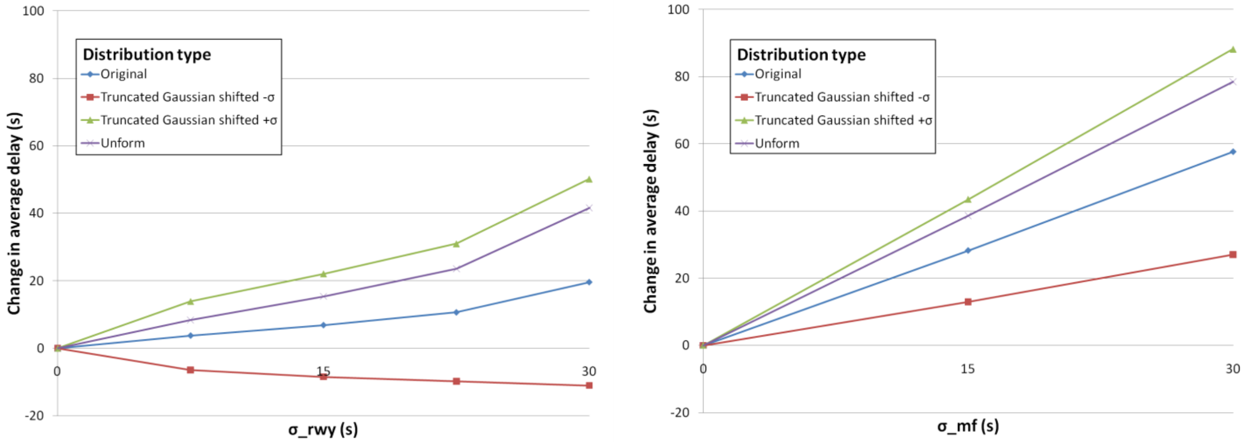


Figure 7. Change in average delay when varying runway (rwy) and meter fix (mf) arrival time error using different distribution types.

These results suggest that average delay is sensitive to changes in the mean of the distribution used. Average delay is also sensitive to changes in the distribution shape and can cause changes in delay that are near equivalent to mean changes. Furthermore, given an arrival time error at a point, the rate in which the average delays changes remains constant regardless of increases in arrival time error elsewhere in the system.

3. Controller intervention

Figure 8 shows the amount of controller intervention needed to keep aircraft minimally separated when varying σ_{rwy} and σ_{mf}, expressed as a percentage of total aircraft. While varying one buffer, the other buffer was set to 0s and delay margin was set to 10%TTF. As expected there is a much higher percentage of aircraft with separation loss at the meter fixes since these fixes are fully saturated. Also, because the traffic is fully saturated at the fixes, the loss of separation rate remains the same regardless of the meter fix delivery accuracy. At the runways, fewer aircraft experience a loss of separation since the meter fix serves the terminal at a rate that is less than the airport capacity. The average aircraft spacing at the meter fix is larger than required at the runways, thus there is some extra room for meeting scheduled arrival times exactly at the runway. As the runway delivery accuracy decreases, however, the loss of separation rate does increase.

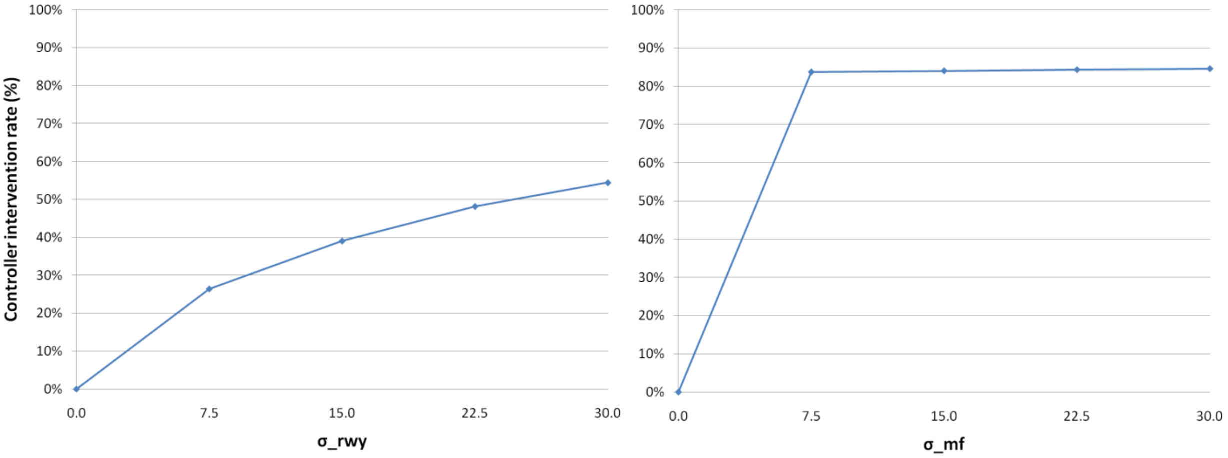


Figure 8. Percentage of controller intervention as a function of runway and meter fix arrival time error.

B. Control variables

The effects on throughput, delay and controller intervention setting various control variables are described next. These control variables include the amount of delay that can be absorbed in the terminal area (referred to as the delay margin) and additional buffer spacing scheduled between aircraft at both the meter fix and runway.

1. Throughput

The FAA has developed guidelines specifying minimum separation requirements for all combinations of leading and following aircraft type as specified in Tables 1 and 2. Exact spacing between aircraft cannot always be achieved. Setting the spacing beyond the minimum spacing requirements provides a buffer for the controllers to handle uncertainties in the system. During busy traffic periods, however, this added separation between aircraft results in a reduction in throughput.

Figure 9 show the percentage decrease in average throughput as the runway and meter fix buffer increases. Increasing the meter fix buffer has more of an effect in decreasing the average throughput than increasing the runway buffer. The runway buffer has no effect on throughput after setting the meter fix buffer past 20 seconds. There is less than a 10% change in average throughput when increasing the buffer at the runway up to 30 seconds versus a 30% change using the same value for the meter fix buffer. The largest drop in average throughput occurs when the runway buffer is at 30 seconds as expected, but when there is no meter fix buffer. This is because the terminal area is more saturated when the meter fix buffer decreases and so changes in the runway buffer would have more of an impact on throughput.

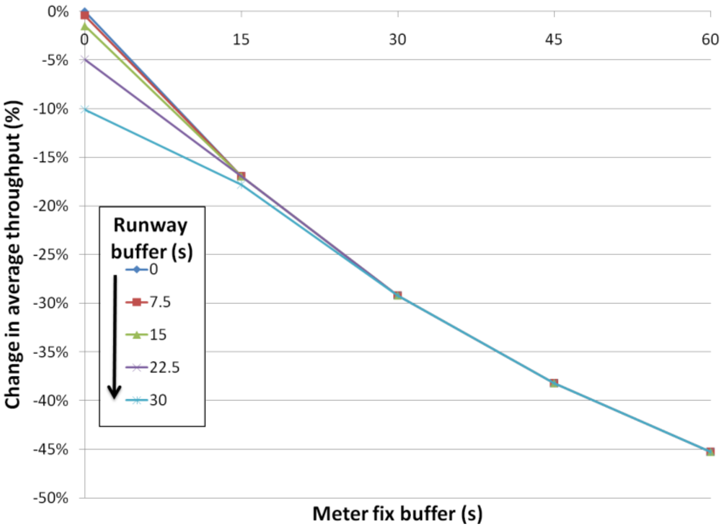


Figure 9. Percentage decrease in throughput when varying runway and meter fix buffer.

To ensure a saturated traffic flow in the terminal area, aircraft are sometimes scheduled to arrive earlier at the TRACON boundary. In this case, aircraft delay is allocated to the terminal area (referred to as the delay margin) so that controllers have some leeway in maneuvering the aircraft as needed to tighten the sequence as much as possible. Figure 10 shows the tradeoff between throughput, delay margin and additional buffer used at the runway and meter fix. Throughput is less sensitive to changes in the delay margin than buffer sizes. Varying the delay margin has no effect on the throughput for any given level of buffer used at the meter fix, since high level of demand at the fixes exceed any amount of delay that would be absorbed in the terminal area instead.

After the aircraft passes through the meter fix, however, using less delay margin does have a slightly adverse effect on throughput. For small runway buffers less than 15 seconds, changes in the delay margin has almost no effect on the throughput since there is a sufficient amount of pressure in the terminal area to keep throughput constant. As the runway buffers increase, aircraft are arriving later since there is more spacing between the aircraft. In this case, increasing the delay margin helps maintain throughput by offsetting the later arrival time with an earlier one. Figure 10 shows that a gain in throughput is achieved as a result of increasing the delay margin based on the time that it takes for an aircraft to fly from the meter fix to the runway. The throughput increase is small, about 5% when increasing the delay margin is increased from 5% to 10% and even less with higher margins. For this dataset, a 10% delay margin amounts to approximately 70 to 90 seconds of delay absorbed in the terminal area, which can be mostly achieved using only speed changes. Increasing the delay margin beyond 10% of an aircraft's time-to-fly, however, means that both path and speed control are used which may increase controller intervention. Moreover, it is less efficient for an aircraft to absorb delay during descent than in cruise.[19]

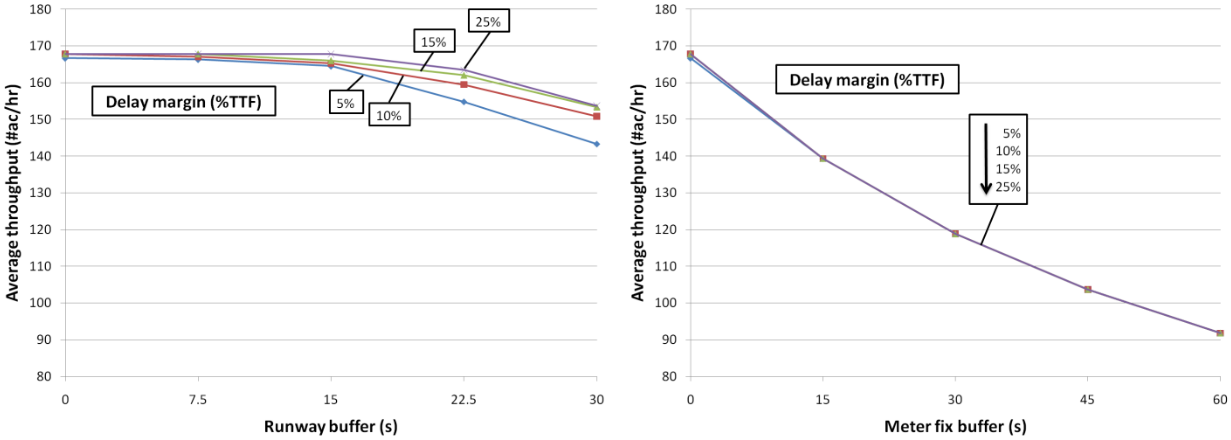


Figure 10. Average runway throughput when varying scheduling buffers and delay margin.

2. *Delay*

Figure 11 shows the percentage change in average delay incurred when using non-zero buffer values. Increasing the meter fix buffer has a larger effect on delays than increasing the runway buffer, 260% versus 90% respectively. The largest change in average delay resulting from increasing the runway buffer occurs when the meter fix buffer is zero. When the meter fix buffer is zero, the change of delay is only affected by the increase in runway buffer. When meter fix buffer increases, however, there is such a large amount of induced delay that increasing the runway buffer has less of an effect.

Percentage change in the average delay resulting from varying the delay margin while increasing runway and meter fix buffers (holding the other fixed at 0) are illustrated in Figure 12. These scenarios had no stochastic variables. Increasing the delay margin reduces the average delay, with larger sensitivity to the runway buffer choice up to 16% in the range examined. The delay increases are too large when increasing the buffers at the meter fix for the delay margin to make much of a difference. The delay margin has more of an effect on reducing average delay when runway buffers are larger since the delay margin helps offset some of the larger spacing between aircraft.

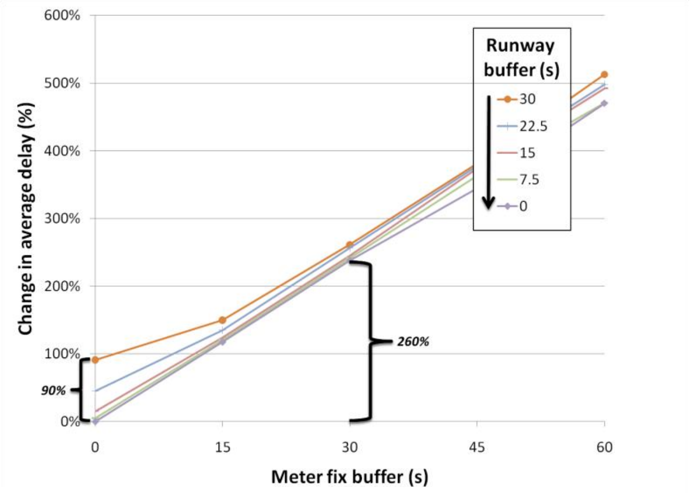


Figure 11. Change in average delay when varying runway and meter fix buffer.

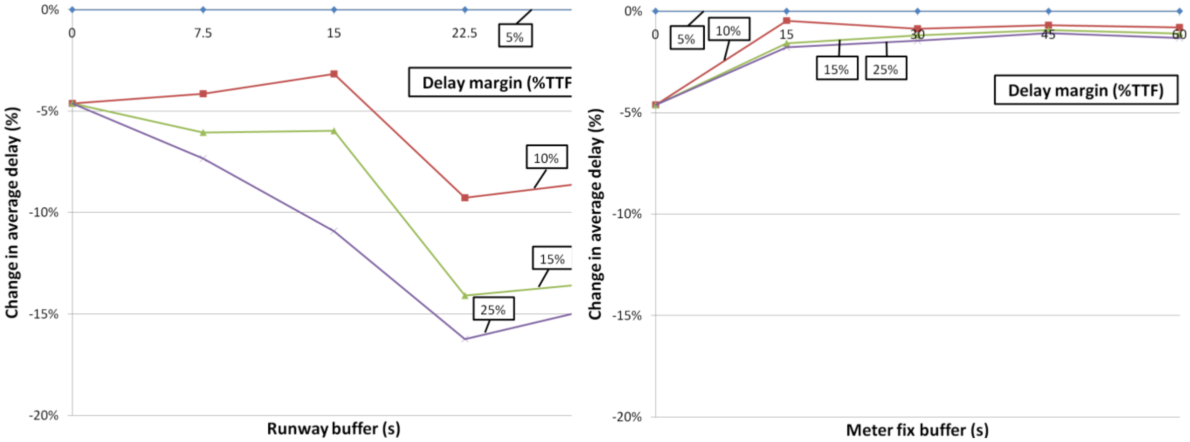


Figure 12. Percentage change in average delay when varying scheduling buffers and delay margin.

3. *Controller intervention*

Figure 13 shows the percentage of aircraft that need controller intervention in order to maintain safe separation at the runway with various arrival time error, meter fix and runway buffer values. The plots depict two general trends. First, increasing the arrival time error to the runway increases the percentage of aircraft with separation loss. Second, an additional spacing buffer between the aircraft helps to reduce the number of aircraft not properly separated due to the arrival time error.

For the highest level of σ_{rwy} used, a meter fix buffer of 15 seconds results in up to a 20% reduction in controller intervention versus the 22.5 seconds of runway buffer needed to achieve the same effect. Increasing the meter fix buffer to 30 seconds, however, reduces the controller intervention slightly less than what the same level of runway buffer can do. Increasing the runway buffers results in a more or less constant rate of controller intervention reduction, about 1% decline per 1 second of additional buffer. In cases where the arrival time error at the runway is greater than 15 seconds, runway buffers larger than 30 seconds or an addition of a meter fix buffer would be needed to reduce the number of controller interventions below 10%.

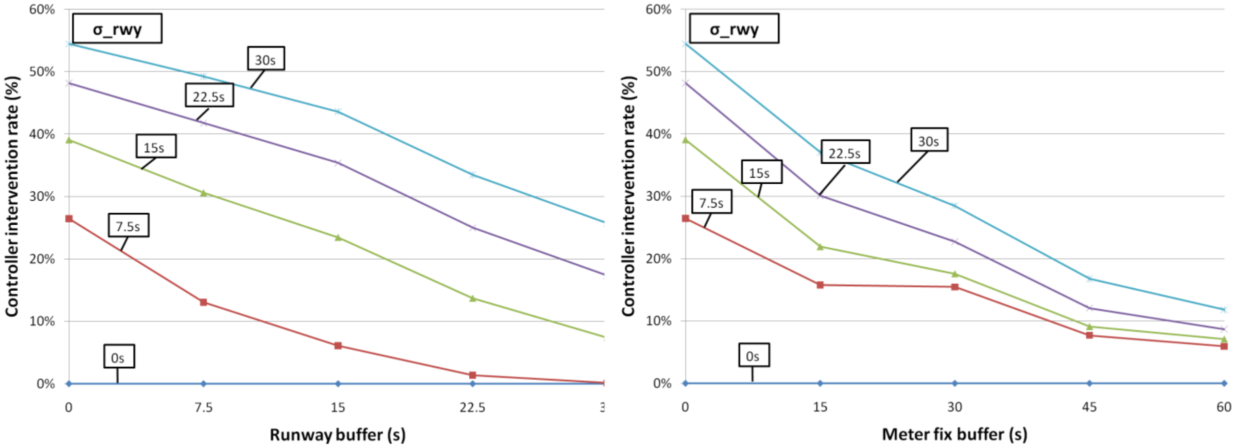


Figure 13. Percentage of controller intervention when varying scheduling buffers and runway arrival time error.

The delay margin was found to have a small influence on the resulting number of controller interventions, regardless of meter fix buffer, runway buffer and system uncertainty combinations. Figure 14 shows how the separation loss at the runway changes with the delay margin while keeping the σ_{rwy} at 15 seconds. Increasing the amount of delay to be absorbed in the terminal area (i.e. the delay margin) resulted in a slight increase in the number of controller interventions up to 5%. These results were seen for all values of σ_{rwy}.

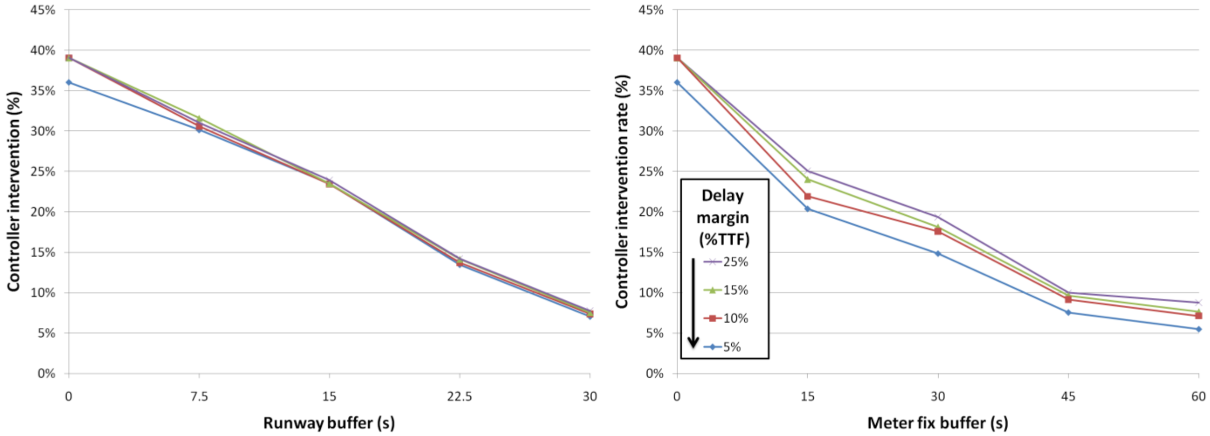


Figure 14. Percentage of controller intervention rate when varying scheduling buffers and delay margin.

C. Scheduler design considerations

One use of these results is to help understand how scheduler parameters should be set for a desired operational concept. For example, NASA Ames Research Center is testing a mid-term concept for super-dense terminal area operations that investigates the effect of utilizing more precise scheduling. The scheduler used in this concept is based on the TMA,[20] where aircraft are scheduled to both the meter fix and runway adhering to minimum separation requirements and arrival rate constraints. These aircraft are assigned a fixed route approximately 200 nm prior to entering the terminal area boundary. Controllers are then expected to meet meter fix and runway arrival times produced by the scheduler within 30 and 15 seconds respectively, while using speed adjustments as the primary means of control in the terminal area.

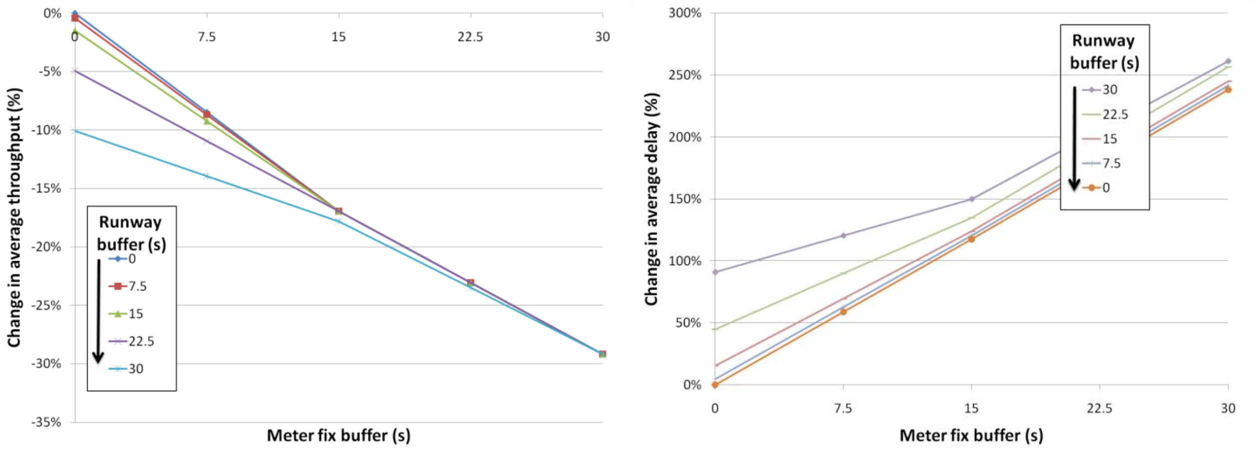


Figure 15. Change in average throughput and delay when varying runway and meter fix buffer.

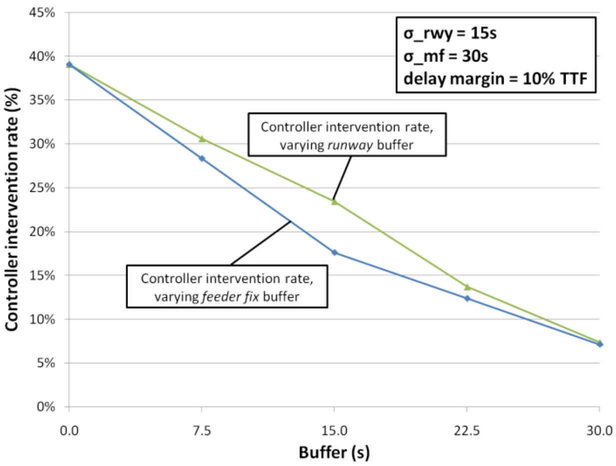


Figure 16. Controller intervention rate when varying runway and meter fix buffer.

To help understand how best to set meter fix and runway buffers, Figures 15 and 16 show the change in average throughput, delay and controller intervention while varying buffer levels. The terminal delay margin was set to 10% of an aircraft's TTF in order to model the amount of control afforded by using only speed adjustments. The controller intervention rate in Figure 15 is plotted for both varying meter fix and runway buffers while the other buffer is set to 0. The plot suggests, first of all, that increasing the meter fix buffer does a slightly better job at reducing controller intervention than increasing the buffer at the runway. Increasing the meter fix buffer, however, is more costly in throughput and delay as seen in Figure 16. For a desired level of controller intervention, a slightly larger amount of runway buffer would have to be used. The resulting impact on throughput and delay, however, is significantly smaller. In this case, to maintain throughput, it is best to set the runway buffer to 15 seconds, resulting in less than a 10% increase in delay and cutting the controller intervention rate in half.

In general, here are some points to consider when evaluating terminal area scheduling operating schemes:

- *Better accuracy in meeting scheduled arrival times does help decrease delay and the percentage of controller interventions.* Delay increases by $2\sigma_{mf}$ and $0.67\sigma_{rwy}$, and the percentage of controller interventions needed to maintain minimum separation at the runway is about $2\sigma_{rwy.}$ It may be difficult, however, to improve delivery accuracy considerably. Alternatively, the same system performance levels resulting from improving meter fix and runway delivery accuracy can be attained by appropriate settings of the scheduler control parameters appropriately.

- *Set meter fix buffer to its minimum.* Throughput and delay are more sensitive to increases in meter fix buffer size. Controller intervention can be reduced purely using runway buffers while keeping the impact on throughput and delay at a fractional level.
- *Adjust runway buffer to attain desired system performance.* Controller intervention rate reduces by about 1% per 1 second of runway buffer used. Runway buffers have less effect on decreasing throughput and increasing delay, up to 10% when the meter fix buffer is set to zero. Thus, when possible, it is best to set the appropriate runway buffer to achieve the desired level of performance.
- *Choose delay margin based on desired concept of operations.* There are only slight improvements to throughput and delay with higher delay margins, balanced against a small increase in controller interventions. Too few aircraft in the terminal area may give controllers less flexibility in changing scheduling sequence. Having too much delay to be absorbed in the terminal area, however, will increase controller workload and disrupt a smooth flow.

VI. Conclusion

A terminal area scheduler was modeled to conduct a trade study of various key parameters relevant to a terminal area scheduler. Experiments were conducted to study the impact of different values for the system uncertainty levels and control variables on throughput, delay and runway separation violations. A set of design considerations for a terminal area scheduler was then generated from these findings.

Results show that, as expected, reducing system uncertainty does improve system performance. In cases where uncertainty cannot be further reduced, the same level of system performance can be achieved by setting the control variables of the scheduler appropriately. To do so, the meter fix buffer should be set as small as possible and only the runway buffer should be altered to achieve the desired level of controller intervention rate without significant impact on throughput. The delay margin should be set to a reasonable amount and was found to induce marginal improvements in system performance. In general, more focus and care should thus be placed on setting the appropriate buffer values than the delay margin. The results of this study were used to help define the initial parameters for a prototype terminal area precision scheduler being evaluated at NASA Ames Research Center in human-in-the-loop (HITL) simulations.

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