Runway Operational Quality Assurance

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Aviation is one of the most important industries in the United States and around the world, as it is a major driving force in maintaining a good economy. Every year it becomes an increasingly essential mode of transportation for people and various high-value, lightweight goods, and that increase is expected to continue. Runways are the "bottleneck" in the air transportation process and are a major source of flight delays. To meet the demand for more air traffic, especially for major airports, the capacity of runways needs to be increased while maintaining Target Levels of Safety.

The focus of this work is the arrival and landing process of aircrafts onto runways because this is where aircrafts are closest and collision risk is highest. Since this process is inherently stochastic, proposed changes to flight separation standards and runway occupancy times to increase capacity, must be accompanied by a system that monitors the throughput and safety of runways for the approach and landing process. Analysis described in this paper shows that reducing the standard deviation of the runway occupancy time and the air-traffic control buffer both improved safety. These improvements in safety then allowed the reduction in the mean to improve capacity.

I. INTRODUCTION

A. *Background*

Commercial aviation plays a big role in our society and the economy. A well designed air transportation system is one of the major backbones of a strong economy. According to the Federal Aviation Administration (FAA) report the impact of aviation on the economy, civil aviation related goods and services totaled \$1.3 trillion in 2009 and generated 10.2 million jobs with \$394 billion in earnings [2]. Aviation plays a big role in the economy not just by the amount of goods and services transported and provided but by the speed it allows goods and passengers to travel. Currently air travel is the fastest mode of transportation in the US and around the world. Because air transportation is the fastest way to travel the demand for aviation is expected to increase with because of its importance in the economy.

From the years 2011 to 2032, the FAA forecast predicts that the air transportation industry will grow from 731 million passengers to 1.2 billion passengers [1]. The increase in passengers will most likely occur in the top 35 airports which are the airports located in the major cities in the US. These airports represent about three quarters of all yearly passenger enplanements in the US and are expected to have a 75% increase in demand by the year 2025. Since the increase in demand for air transportation occurs in just these airports, there is more of a chance for bottlenecks to occur.

II. CONTEXT

Because of the expected increase in traffic in the busiest airports, the safety of planes landing on the runway is also expected to change relative to the demand. This is due to the fact that planes are closest together, while still moving at high speeds, during the approach and landing process. With the forecast increase in demand for air transportation the safety level of the planes landing on a runway is expected to decrease.

A. *Runway Capacity*

With the expected increase of demand for air transportation concentrated in the top 35 airports, having enough runway capacity in airports to meet the demand is crucial. Based on the FAA's report, *Capacity Needs in the National Airspace System,* many of the top 35 airports and airports around the US are at or nearing their limit on capacity [8]. It was identified that 18 airports around the country would need additional capacity by 2015 and 27 by 2025 if the airport system remains the same as it is today.

The most direct way to increase the capacity of an airport is to build and construct more runways. Unfortunately many of the important urban-area airports where an increase in capacity is necessary are restricted by expensive real-estate or simply do not have the land available to add more runways.

Since increasing the number of runways on a lot of these major airports is limited, increasing airport capacity without adding new runways would entail improving runway throughput, which is defined by how many aircrafts can land on a runway in a certain period of time. There are two rules associated with the capacity of a runway, which are the wake vortex approach separation and simultaneous runway occupancy (SRO) of successive aircrafts that are landing on a runway.

B. *Arrival Event*

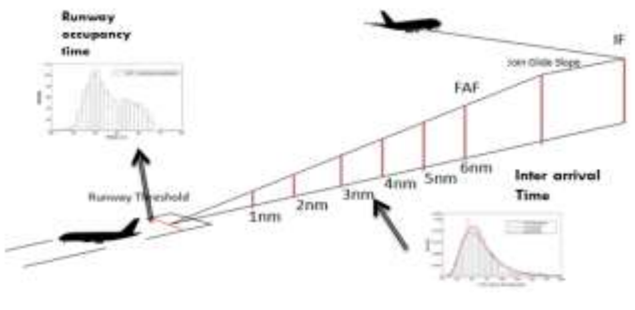

Figure 1Arrival Event with Runway Occupancy Time and Inter-Arrival Time

The arrival event is the main scope of this project. The arrival event is when aircrafts are close to each other and are flying at high speeds. This is when bottlenecks occur with the expected increase in capacity.

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The main points to focus on are the runway occupancy time (ROT) and the inter-arrival time into the final approach fix (IAT) to increase capacity. ROT is dependent on the fleet mix of arriving aircrafts and the time it takes each different aircraft to exit the runway after it crosses the threshold. IAT depends on the fleet mix, the minimum wake vortex separation distance and an added ATC buffer which is usually ten seconds with varying standard deviation.

Capacity of a single runway is determined by the throughput in a given amount of time. It defines the average movements(arrivals) that can be performed in an hour time. Capacity can be determined by the IAT and the ROT.

- ☐ The capacity of the runway to meet **SRO** (Simultaneous Runway Occupancy) runway determined ROT (runway occupancy time)

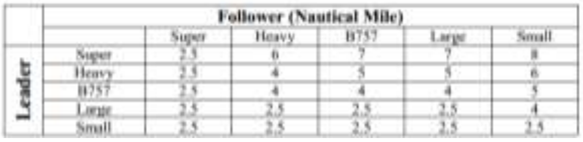
$$\text{Capacity}(1\text{ hr}) = 3600\text{sec}/\sum \text{ROT}_i$$

- ☐ The Runway throughput for a runway with homogeneous fleet mix to account for the **ATC Separation Buffer** for maintaining **Wake Vortex Separation Distance** requirements is determined by the separation distance plus the **buffer distance**.

$$\text{Capacity}(1\text{ hr}) = 3600/(\sum t_{ij} + b)$$

C. *Safety*

Over half, 51%, of fatal aviation accidents occur during approach and landing phases of flight because this is when aircrafts are brought closer together and are still moving at high speeds [3]. Reducing wake vortex separation would increase the risk of collision and reduce safety of landing aircrafts. Aircraft should be separated not only to avoid collision, but also to avoid wake turbulence encounters. Wake turbulence is a disturbance caused in the air from a passing aircraft. About 70% of wake turbulence caused accidents occur during the approach phase of flight for the same reason accidents occur [9]. The severity of wake turbulence depends on the speed and size of an aircraft. Since the effects of wake turbulence increase when the size of aircrafts increases, to make sure aircrafts are separated appropriately to avoid wake turbulence encounters, the FAA has set separation standards for arriving aircrafts at the runway threshold [6].



		Follower (Nautical Mile)				
		Super	Heavy	B757	Large	Small
Leader	Super	2.5	6	7	7	8
	Heavy	2.5	4	5	5	6
	B757	2.5	4	4	4	5
	Large	2.5	2.5	2.5	2.5	4
	Small	2.5	2.5	2.5	2.5	2.5

Table 1Wake Vortex Separation Minima

Table 1 illustrates the minimum distance aircrafts should be separated based on the leading and following aircrafts. To avoid wake turbulence encounters, air traffic controllers usually have a buffer added to the separation of each aircraft.

One other safety risk during the landing process is simultaneous runway occupancy (SRO). Simultaneous runway occupancy is the occurrence when two landing planes occupy the same runway. Currently it is not allowed and is considered a major safety violation. One of the main focuses on runway safety is to avoid simultaneous runway occupancy. Having two aircraft on a runway while landing greatly increases the chances of a collision happening. The likelihood of simultaneous runway occupancy occurring increases with the increase of arrival rate since the leading aircraft brakes to exit the runway while the following aircraft maintains approach speed.

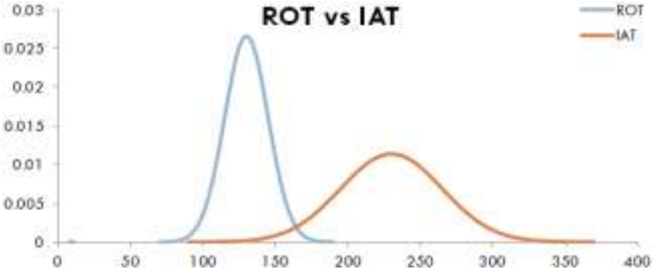


Fig. 2Union set between ROT and IAT into runway threshold – Overlap represents P(SRO)

Figure 2 shows distributions for the runway occupancy time (red) and the inter-arrival time (blue) between aircraft landing at Detroit Airport. IAT is the interval between each successive aircraft at the runway threshold. ROT is the amount of time a landing aircrafts stays on the runway.

The overlap between these two distributions represents the probability of simultaneous runway occupancy. Based on current standards the probability of the occurrence of SRO should be 0 or (P(SRO)=0). That is clearly not the case as there is always a probability of this happening due to the stochastic nature of ROT and IAT. Currently the occurrence of SRO is not measured as a probability. Measuring this occurrence as a probability like shown in the figure above provides a better reflection of runway performance in terms of monitoring SRO.

1) *Throughput vs. Safety*

Wake turbulence encounter and SRO are the two main events to avoid when dealing with the safety of incoming aircrafts. Unfortunately reducing these risks (separating aircraft more) comes at the price of reducing runway throughput.

Fig. 3 Arrivals vs. Safety – Runway safety decreases as throughput increases *[12]*

The relationship between average throughput and runway related safety is shown in Figure 3. Safety is defined by 1 minus the probability of SRO or 1-P(LTI<ROT). Throughput is shown as arrivals per quarter hour. Safety is sacrificed as average throughput increases.

Essentially the problem comes down to having to increase runway throughput and making sure that runway safety is properly maintained. This is problematic because the safety and runway throughput have shown to have an inverse relationship.

D. *Next Generation Air Transportation System*

To address the capacity shortfall, the FAA has planned to implement a new National Airspace System called the Next Generation Air Transportation System or NextGen. NextGen will be implemented in stages between 2012 and 2025. The system proposes to convert the aging ground based airport system to a satellite-based system using more GPS technology. Several new technologies part of the new system could improve runway capacity.

1) *Automatic dependent surveillance-broadcast (ADS-B)*

ADS-B is a surveillance technology part of NextGen which will allow for more precise positioning of aircrafts monitored by GPS. Pilots will be provided a display which will show all the aircrafts in the vicinity and show their altitude, speed and direction of flight. Ground and ATC will also be given this information and will be able to project the position of each aircraft as time progresses [10]. The ability for air-traffic controllers and pilots to pinpoint an aircraft's location more precisely can make it possible to reduce in-trail separation.

This new technology proposes to reduce the variances of ROT and IAT (by reducing the ATC buffer standard deviation). Once the variance is reduced the means can be shifted resulting in increased capacity.

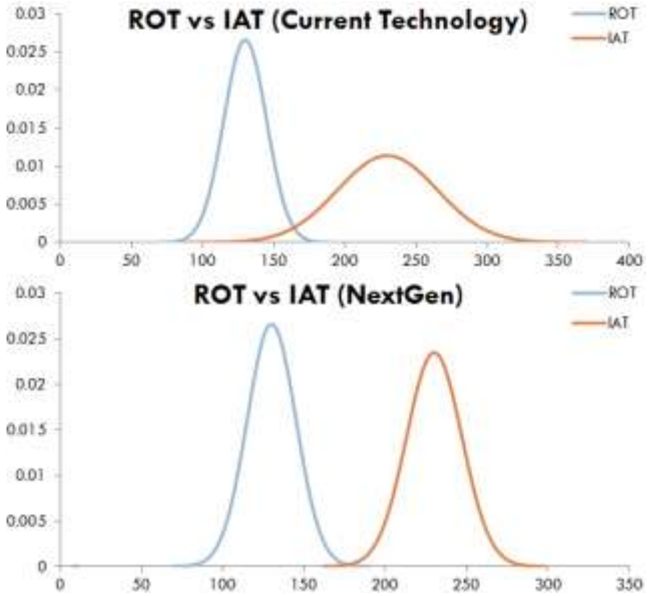


Fig. 4 Comparison between ROT vs. IAT for current technology and NextGen technology

Figure 4 is a conceptual look at how NextGen technology can be used to improve throughput and maintain safety. The figure portrays the union set between ROT and IAT and shows the difference between the union set for current standards and conceptual with NextGen technology implemented. ADS-B proposes to reduce the IAT variance. The bottom figure shows a decreased overlap between the distributions than the top figure which shows current technology. The expected decrease in variance from the IAT distribution is expected to also reduce the probability of simultaneous runway occupancy or P(SRO). In theory the improvements of NextGen could lead to reduced variance of these distributions, but its effects on throughput and safety are not known.

E. *Stakeholder Analysis*

1) *Federal Aviation Administration (FAA)*

Since the FAA's main focus in dealing with runway operations is safety, they are the primary stakeholder to the system. Safety of incoming aircraft through the runway is their main concern as there is an expected increase in demand. The FAA set rules and regulations to ensure the runways are safe and have planned to employ NextGen technology in the upcoming years to improve the overall airspace system.

2) *Air-traffic controller*

Runway air-traffic controllers play an important role in the landing of aircrafts. They control the movements of arriving and departing aircrafts through a runway. They focus on maintaining safety of the runway by keeping aircrafts properly separated based on the FAA's regulation. Keeping aircraft coming through runways efficiently is also a concern along with safety.

3) *Airlines*

The airlines are the primary user of the runway by providing the air transportation service. The goal of the airlines is to maintain safety as well as accommodate for the increase in demand by increasing runway capacity. Increasing a runway's capacity or throughput would benefit the airlines by allowing more aircraft through runways and avoiding delays. Increasing capacity while maintaining safety would help the airlines maximize profit.

4) *Pilots*

Airline pilots are one of the key players in the landing process of an aircraft. Their actions during landing and approach are based on the pilot's coordination with the air-traffic controllers. The pilots concern during the landing process is the safety of their aircraft as it lands.

5) *Airports*

Airports provide a regional mode of transportation. Their revenue comes from aeronautical and non-aeronautical activities. Revenue increases with more people coming through the airports.

6) *Stakeholder Tensions*

One of the main tensions comes from FAA and the Airlines. Although both are concerned with the safety on the runway, the airline's concern for increasing capacity conflicts with the FAA's goal of keeping airport runways as safe as possible. There needs to be a balance between both safety and capacity in order to satisfy both stakeholders.

There is also tension between the goals of the airlines and the pilots. The pilots are just concerned with the safety of their aircraft, but airlines are concerned with safety as well as making sure aircrafts are flowing through runways as efficiently as possible.

F. *Problem Statement*

The future utilization of runways to meet the growing demand for air transportation has a risk which is a probability of loss of safety. Technological improvements such as ADS-B are expected to improve capacity while maintaining safety by changing the variance of ROT and IAT (standard deviation of ATC buffer). Current measures of safety being used right now do not adequately reflect the performance and safety of a runway in terms of probability of violations. Monitoring separation of aircraft landing on a runway will be better served to be treated and measured as a stochastic process rather than discrete events.

1) *Need Statement*

There is a need for a system to monitor how changes to IAT mean and the variances of IAT and ROT affect throughput and safety. Current measures of safety being used right now do not adequately reflect the safety of a runway. A system is needed to monitor the change of throughput and safety while changing variance of these distributions.

III. DESIGN ALTERNATIVES

The two factors that were found to affect safety and capacity are runway occupancy time (ROT) and the spacing of each aircraft. The design alternatives will be chosen based on changing these two main parameters.

First, **changing the ROT distribution** by reducing its standard deviation, second **changing the IAT distribution**, would be achieved by changing the ATC buffer standard deviation, the third **changing the ATC Buffer mean**.

IV. RUNWAY OPERATIONAL QUALITY ASSURANCE (ROQA) SYSTEM

A. *System Design*

The ROQA system is a stochastic data collection and analysis system which could be used by the FAA and air traffic control. The main focus of the system is to maintain and monitor safety as well as allow for an increase in throughput through an airport runway.

The system will be composed of a data collection process where data such as the different distributions will be collected and used in the ROQA system. The output of the system will provide the user of the system with a metric to measure safety, specifically, percentage of separation violations and percentage of simultaneous runway occupancy. The output will be used to evaluate the safety and capacity levels of an airport runway.

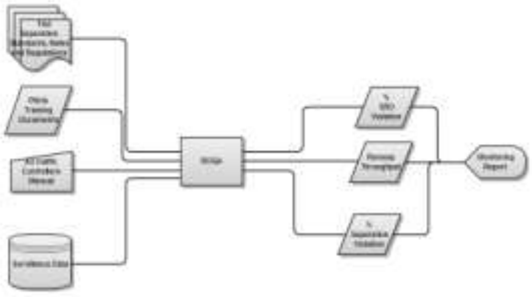


Fig. 5 ROQA Input-Output Diagram

B. *JAVA Simulation*

A prototype ROQA system was developed using a Java simulation of the approach and landing process to a single runway. The simulation is used to show how changing several variables in the approach and landing process affects safety and throughput.

1) *Equations*

a) *Distance to Runway*

Dist(t) = Dist(t-1) – (Ground Speed * Time)

b) *Approach Speed to Ground Speed*

Ground Speed = cos(Glide Angle)x(Approach Speed)

c) *NM/Hr to NM/Sec*

NM/Sec = NM/Hr*.000278

d) *Compression Case*

(3600*(RunwayLen+followSep/followSpeed
RunwayLen/leadSpeed))
(H-HLSM, L-LMS, M-MS, S-S)

e) *Expansion Case*

(3600*(followSep*1)/followSpeed)

f) *Compression Time*

Runway Len*(followspeed-leadspeed)*3600

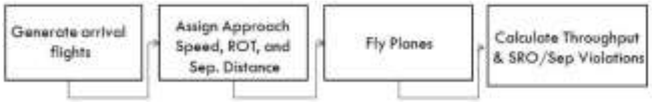


Fig. 6 Flow chart of ROQA Event Simulator – the flow chart represents each process of the simulation

Using a fleet mix representative of DTW airport, where the probability of a small (S), medium (M), large (L), or heavy (H) plane is 13.4%, 6%, 76.6%, and 4% respectively, a random string of *n* nonhomogeneous arrival flights is generated and stored using a linked list data structure. As each aircraft is created, a speed and ROT is also generated and will become associated with that aircraft. Our model assumes that both speed and ROT follow normal distributions and is allowed to do so because the "long tail" scenarios are rare and our model is just concerned with the normal case. Based on whether the plane created is small, medium, large or heavy, a speed is drawn from a normal distribution with mean 90, 110, 130, or 150 with a default standard deviation of 5 and a ROT is drawn from a normal distribution with mean 50, 55, 60, or 70 with a default standard deviation of 5. Our model then assigns a separation distance to each aircraft based on the wake vortex separation distance table. Here the ATC buffer is also accounted for and the model handles the case when the lead plane is faster than the follow, known as the expansion case, and when the lead plane is slower than the follow, known as the compression case. In order to calculate the separation time for the expansion case, the model uses equation (5) in the cases where Lead=H: Follow=H,L,M,S,Lead=L:Follow=L,M,S,Lead=M:Follow=M,S ,Lead=S:Follow=S. To calculate the separation time for the compression case, the model uses equation (4) and covers the other cases not included in the expansion cases. The ATC buffer is drawn from a normal distribution with a mean of 10 and default standard deviation of 5.

After creating all the aircrafts, the next step in the model calls "fly", a method of each aircraft, which uses the parameters associated with each aircraft to generate its trajectory starting when the aircraft enters the final approach fix, 6 nm from the runway and down a 3 degree glide slope, until it lands on the runway, updating every second. These trajectories are then used for lead/follow comparisons in order to determine if a separation violation or SRO violation has occurred. If the distance between where the lead plane and follow plane are on the glide slope becomes less than the wake vortex separation distance associated with the follow plane, then a separation violation has occurred. If after the lead plane lands the follow plane has less time in the glide slope than the ROT associated with the lead plane, an SRO violation has occurred. The output from this simulation is the throughput of the runway, and the number of separation violations and SROs which occurred, as a percentage.

C. *Verification*

The results from the simulation were compared to Figure 3, which showed the relationship between safety and throughput.

Fig. 7 Output from the ROQA simulation has similar results from earlier study showing reduction in safety with increasing throughput

The Figure 3 and Figure 7 show similar results. Both the ROQA simulation and the study above show an inverse relationship of throughput vs. safety. The results differ in the way results were obtained.

D. *Analysis*

The results of the simulation reveal how changes to the parameters IAT (mean and variance) and ROT (variance) affect safety and throughput. Safety will be measured by the percentage of SRO and separation violations. Throughput will be measured by the amount of landings per hour. Since the simulation is not measuring for a fatal accident or collision, the acceptable rate of SROs and separation violations will be two magnitudes below the ICAO accident rate of 10^{-7} to 10^{-9} per aircraft flight, which is around 10^{-4} to 10^{-5} violations per aircraft flight. [11].

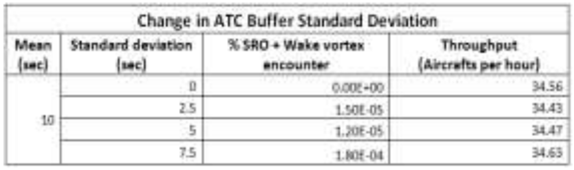
V. RESULTS AND ANALYSIS

For the first phase of the results, changes to the standard deviation of the ATC buffer and the ROT were changed. The purpose of this phase is to figure out which change in parameters affects the percentage of violations and throughput. This phase will also determine which variable (ATC buffer and ROT standard deviation) affects percentage of violations and throughput. The second phase of the results changes the mean of the ATC buffer.

The objective is to find out which parameter maximizes throughput while maintaining proper safety.

A. *Change in Standard Deviation on ATC Buffer and ROT*

For runs changing the standard deviation of the buffer, the values were changed by increments of 2.5 with values of (0, 2.5, 5, 7.5) with 5 being the control. The main reason for changing the ATC buffer standard deviation would be to anticipate how new NextGen technology might affect runway performance in terms of throughput and violation percentage.



Change in ATC Buffer Standard Deviation			
Mean (sec)	Standard deviation (sec)	% SRO + Wake vortex encounter	Throughput (Aircrafts per hour)
10	0	0.00E+00	34.56
	2.5	1.50E-05	34.43
	5	1.20E-05	34.47
	7.5	1.80E-04	34.63

Table 2 Results – change in ATC Buffer Standard Deviation

Table 2 shows the results for the percentage of violation and throughput with changing the standard deviation of the ATC buffer. The throughput did not change throughout the simulation. The throughput values had an average of 34. The values of the % of violations did change with the change of standard deviation. Runway related risk or percentage of SRO or separation violation, increased as the standard deviation increased.

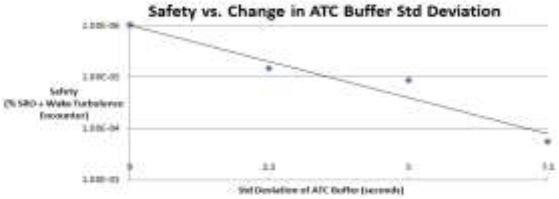
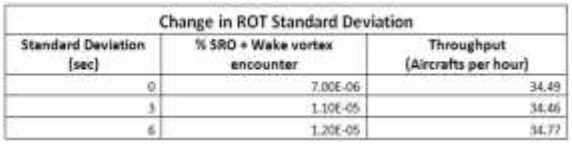


Fig. 8 Plot of change in safety with change in ATC Buffer Std Deviation

The graph from Figure 8 plots the data from the table 2. The x-axis is the standard deviation level and the y-axis is the safety level. From the graph we can see a better visual how the ATC-buffer standard deviation affects the safety. Increasing the standard deviation decreases the safety. At standard deviation of 7.5, the safety level at that point showed to be below the runway risk rate of 10^{-4} to 10^{-5}. The relationship between standard deviation of ATC buffer and safety is shown to have an inverse relationship.

The results for changing the standard deviation of each aircrafts ROT were changed by increments of 3 with values of (0, 3, 6).



Change in ROT Standard Deviation		
Standard Deviation (sec)	% SRO + Wake vortex encounter	Throughput (Aircrafts per hour)
0	7.00E-06	34.49
3	1.10E-05	34.46
6	1.20E-05	34.77

Table 3 Results – change in ROT Standard Deviation

The results from changes to the ROT standard deviation showed similar results to the results when changing the standard deviation of the ATC buffer. The throughput stayed fairly the same throughout each run of the simulation. In terms of safety, decreasing the standard deviation of ROT did affect safety but not as much as changing the standard deviation of the ATC buffer.

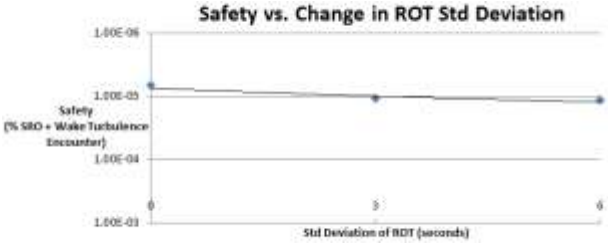


Fig. 9Plot of change in safety with change in ROT Std Deviation

As seen in Figure 9, an increase in ROT standard deviation did decrease the safety level, but not quite as much as changing the standard deviation of the ATC buffer.

The results from changing the standard deviation of the ATC buffer and ROT show that changing the standard deviation of the buffer changes the safety. It is shown that increasing the standard deviation of both ROT and ATC buffer both decrease safety or the percentage of violations which occur. The ATC buffer did show to change the safety the most. Although changing the standard deviation of both ROT and safety changed the percentage of violations which occurred, the throughput stayed fairly the same throughout each simulation run whether or not the standard deviations for ROT and ATC buffer were decreased or not.

B. *Change in mean of ATC buffer*

The second phase of results involves changing the mean of the ATC buffer rather than changing the standard deviation. The decision to change the mean of the ATC buffer was made because it affects the mean of the inter-arrival distribution and could possibly increase throughput. The standard deviations of ROT and the ATC buffer will be held constant at 5. The mean will be tested at its original value at 10 then will be decreased by increments of 2.5

Change in ATC Buffer Mean			
Mean (sec)	Standard Deviation (sec)	% SRO + Wake vortex encounter	Throughput (Aircrafts per hour)
2.5	5	6.70E-02	39.43
5		5.00E-03	38.56
7.5		6.00E-04	37.02
10		1.70E-05	34.43
12.5		1.00E-06	33.29

Table 4 Results – change in ATC Buffer Mean

Table 4 shows the results from the simulations changing the mean. The results show a change in both the percent of violations as well as change in throughput. As the standard deviation decreased, the throughput increased but the percentage of violations increased as well. Changing the mean showed more change in violations and throughput than just changing the standard deviation.

Fig. 10 Plot of safety vs. throughput – reductions in the mean of ATC buffer increase throughput but decreases safety

Figure 10 shows a visual of safety vs. throughput while changing the mean of the ATC buffer. Increasing the mean to 12.5 seconds increased safety but decreased capacity as well. Decreasing the mean to 7.5, 5 and 2.5 showed a big change as the capacity was increased but safety was sacrificed. Decreasing the mean to 2.5 decreased the safety level to well below the acceptable rate of 10^{-4}.

These results show that increasing the throughput can be achieved by decreasing the mean of the ATC buffer. Although throughput is increased the safety is in turn sacrificed. The results show that decreasing the ATC buffer and ROT standard deviations both decrease the percentage of separation violation and simultaneous runway occupancy occurrences.

VI. RECOMMENDATIONS AND FUTURE WORK

Based on the results from the simulation, it is recommended that a reduction to the standard deviation of the ATC buffer is implemented to improve safety. Reducing the standard deviation of the ATC buffer showed to improve safety.

Once the safety is improved the mean of the ATC buffer can be reduced to improve throughput. The only way to increase capacity while maintaining proper safety is to reduce the variance of IAT and ROT first, then reduce the mean of IAT. The technological improvements are expected to reduce the variance of IAT and ROT, but reducing the mean can only be achieved by changing procedure such as ATC buffer and/or separation minima.

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