A DEPARTURE REGULATOR FOR CLOSELY SPACED PARALLEL RUNWAYS

A Thesis
Presented to
The Academic Faculty

by

Isaac J. Robeson

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Aerospace Engineering in the
School of Aerospace Engineering

Georgia Institute of Technology
December 2011

A DEPARTURE REGULATOR FOR CLOSELY SPACED PARALLEL RUNWAYS

Approved by:

Dr. John-Paul Clarke, Committee Chair
School of Aerospace Engineering
Georgia Institute of Technology

Dr. John-Paul Clarke, Advisor
School of Aerospace Engineering/School of
Industrial and Systems Engineering
Georgia Institute of Technology

Dr. Amy Pritchett
School of Aerospace Engineering/School of
Industrial and Systems Engineering
Georgia Institute of Technology

James Brooks
School of Aerospace Engineering
Georgia Institute of Technology

Date Approved: 26 August 2010

To my parents, for their years of love and support.

ACKNOWLEDGEMENTS

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SUMMARY

Increased efficiency at airports is necessary to reduce delays and fuel consumption. Many of the busiest airports in the nation have at least one pair of closely spaced parallel runways (CSPRs), defined by a separation of less than 2500 ft, with one runway dedicated to arrivals and the other to departures. CSPRs experience a large decrease in capacity under instrument conditions because they can no longer operate independently. In order to mitigate this decrease in capacity and to increase efficiency, proposed herein is a departure regulator for runways so configured, along with a plan of study to investigate the effects of this regulator.

The proposed departure regulator makes use of data from precision tracking systems such as ADS-B to issue automated or semi-automated departure clearances. Assuming sequential departure separations are sufficient for clearance, the regulator will automatically issue, or advise the controller to issue, the departure clearance as soon as the arrival on the adjacent runway has descended below its decision height. By issuing the departure clearance earlier, the departure regulator reduces the gap between a pair of arrivals that is required to clear a departure. By decreasing the gap, the regulator increases the number of opportunities where a departure clearance can be issued, given a particular arrival stream.

A simulation models the effects of the regulator and quantifies the resulting increases in capacity. The simulation results indicate that all forms of the regulator would provide significant gains of between 14% and 23% in capacity over the current operating paradigm. The results also indicate that the capacity gains are greatest at high arrival rates. Therefore, implementation of the departure regulator could significantly decrease the congestion at many major airports during inclement weather.

CHAPTER I

INTRODUCTION

As the demand for air travel increases, so does the need for increased capacity in the National Airspace System (NAS). Airports are often the bottleneck of the NAS. Among other things, this bottleneck is a result of a fixed number of runways to handle the increases in demand, yet increasing the number of runways is often not a viable option at many airports due to cost, zoning restrictions, development close to the airport, and noise regulations. Thus, airports must develop innovative methods for handling the increase in demand with fixed resources.

One of the most common runway configurations is a pair of closely spaced parallel runways (CSPRs). A pair of closely spaced parallel runways has two runways aligned parallel to each other with less than 2500 ft separation between the runway center lines. Of the thirty-five busiest airports in the nation, known as the Operational Evolution Partnership (OEP) airports, nineteen have at least one set of CSPRs. In total, there are twenty-six CSPRs at the thirty-five OEP airports. Thus, increasing the capacity of CSPRs would have a positive effect throughout the NAS.

With the problem of increased demand in mind, proposed herein is a departure regulator, i.e., a tactical air traffic management tool, designed to increase the capacity of CSPRs, especially in instrument meteorological conditions (IMC). The regulator is designed for CSPRs with one runway dedicated to arrivals and the other to departures. With such a configuration, coupling exists between arrivals and departures in IMC, as current procedures do not allow a departure to begin its takeoff roll as long as an arrival is within 2 miles of the runway. The regulator works by utilizing data from precision tracking systems, such as the Automatic Dependent Surveillance Broadcast

(ADS-B) system, to issue automated departure clearances as soon as possible after the arrival on final approach to the parallel runway descends below its decision height (DH).

This thesis begins by looking at the history of CSPRs, examining the current operation of CSPRs, and providing motivation for the regulator. The thesis then lays out the concept of operations for the proposed departure regulator. Three implementations of the departure regulator are proposed, including two automated implementations, where clearances are automatically issued, and one semi-automated implementation, where the controller issues clearances. Safety implications arising from the regulators implementation are considered. These implications include missed approaches and runway incursions. Next, this thesis describes a simulation framework, which was developed to calculate the capacity of runway configurations. This simulation framework is then used to estimate capacity gains with the regulator. Finally, areas for future work are proposed.

CHAPTER II

LITERATURE REVIEW

2.1 CSPRs Operations

The regulations governing the operation of closely spaced parallel runways are found in Joint Order 7110.65T [9], which was issued by the Federal Aviation Administration. This document "prescribes air traffic control procedures and phraseology for use by personnel providing air traffic control services" [9], and as such it covers all cases concerning the operation of CSPRs. However, the human element of operations at closely spaced parallel runways is less well defined. The communication and response times of controllers and pilots in the en-route environment have been studied in [3]. The communication and response times considered in this paper provide a useful baseline for these times. However, as these times were observed under different circumstances, they cannot be applied directly to departure clearances. Regarding communication and response times specific to departure clearances, MITRE has recorded measurements of the time between the start of the departure clearance to the start of takeoff roll [4].

2.2 Current CSPRs Research

Because of the large impact that CSPRs have on the capacity of airports, especially OEP airports, much has been published concerning methodologies for improving the capacity of CSPRs. However, most of this research is focused on the optimization of arrivals. For example, [12] examines a paired approach procedure to CSPRs using ADS-B to longitudinally space aircraft when there are instrument meteorological conditions at an airport. Reference [17] describes a feasibility study performed to

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consider the possibility of using simultaneous offset instrument approaches at Newark. In [14], the capacity effects of two different proposed simultaneous arrival procedures for CSPRs under IMC are considered.

The goal of the proposed regulator is to increase the departure rate for one parallel runway while at the same time maintaining or increasing the corresponding arrival rate on the other runway. The net result of such an improvement in the departure rate is an increase in the capacity (the sum of the arrival and departure rate) envelope of the given runway configuration and by extension the given airport. This thesis provides the first steps to the development of such a regulator: defining the concept, developing a concept of operations, and determining the capacity increase that would result from the introduction of the regulator.

2.3 Decision Support Tools

The proposed regulator would act as a decision support tool for controllers or pilots. A current example of a decision support tool for center controllers is the Traffic Management Advisor (TMA), which assists controllers in merging and spacing aircraft arriving in a TRACON [18]. For controllers in the tower, Airport Surface Detection System – Model X (ASDE-X) provides increased situational awareness, especially at night or in poor visibility conditions. ASDE-X is a surface surveillance radar that allows controller to observe the location of aircraft and transponder-equipped vehicles on the airport surface.

With regards to decision support tools for pilots on the airport surface, two examples are runway entrance lights (RELs) and takeoff hold lights (THLs) as described in [16] and [7]. These lights are used to provide the pilot with information regarding the status of the runway that the pilot is about to cross or to takeoff from. The RELs indicated when it is unsafe to cross an active runway and the THLs indicate when it is unsafe to begin takeoff roll. However, these systems differ from the proposed

regulator in that the proposed regulator would be issuing clearances, while the RELs and the THLs can only prohibit clearances, not issue them.

2.4   Capacity Calculations

The capacity of an airport can be determined from empirical data of the historical arrival and departure rates. Reference [11] describes this process and methods for optimizing airports using the resulting capacity curves. In [11], the capacity of an airport is defined as the curve describing the tradeoff between the maximum arrival and departure rate. This definition of capacity is used throughout this paper. However, because this research proposes changes to current procedures, no empirical data for operations using this data currently exists. Thus, capacity curves for the departure regulator could not be produced using empirical data. For this reason, a simulation was developed to calculate the capacity.

There are multiple airport simulations that currently exist with varying levels of complexity. One of the earliest capacity models is the Airfield Capacity Model (ACM), which was developed by the FAA and MITRE and was last updated in 1981. This airport model is limited in its capability as it allows only allow the user the choice of 15 predefined runway configurations [15]. Another capacity model is the Airport Runway Capacity Calculator (ARCC), developed at MIT for use with the MIT Extensible Air Network Simulation (MEANS) [2]. ARCC has a similar limitation to ACM in that airport models are hard coded and are not easily adjusted. On the opposite end of the spectrum are complex commercial airport models such as SIMMOD, which offers the user a very high level of output but also requires a high level of detailed input information [5, 1]. For the purposes of this thesis, this level of detail is unnecessary and overly complex. Another airport capacity model is the Runway Simulator (rS) also developed by MITRE for internal use. This simulator was designed to bridge the gap between simulations such as ACM and those such as SIMMOD [1, 15]. The

runway capacity simulation developed for this thesis is most similar to the Runway Simulator, as it bridges the gap between allowing user flexibility, while not requiring detailed inputs.

CHAPTER III

BACKGROUND, MOTIVATION AND INSPIRATION

The motivation for the development of the regulator is the prevalence of CPSRs that are found at nineteen of the thirty-five busiest airports in the United States. Furthermore, at seven of these so-called OEP airports, there are multiple sets of closely spaced parallel runways [6]. Delays at these airports are one of the drivers for delays in the national airspace system (NAS), so increases in capacity at these airports will help decrease delays throughout the NAS.

3.1 Background

The first of these closely-spaced parallel runways were built in the 1950s when aviation was expanding at a rapid rate and there was a great need for increased capacity but the close proximity of airports to city centers meant that this capacity needed to achieved within the relatively tight confines of existing airport boundaries. Thus, in an era when aircraft operations would cease at the first sign of bad weather, the addition of CSPRs provided increased capacity in good weather or in visual meteorological conditions (VMC), while not significantly increasing the airport footprint.

3.2 Current Closely Spaced Parallel Runway Operations

There are two main configurations used for closely spaced parallel runways. One configuration is to use both runways for arrivals or both for departures. This configuration is frequently used at San Francisco International Airport (SFO). The other configuration, the configuration considered by this thesis, is to dedicate one runway to arrivals and the other to departures. This configuration is the more common of the two

and is frequently used at, among others, Hartsfield-Jackson Atlanta International Airport (ATL), Los Angeles International Airport (LAX), Newark Liberty International Airport (EWR), and Dallas-Fort Worth International Airport (DFW). Arrivals and departure clearances are currently determined by applying three sets of rules: arrival-arrival separation rules, arrival-departure separation rules, and departure-departure separation rules. These three sets of rules are described below.

3.2.1 Same Runway Arrival-Arrival Separation

For two successive arrivals on the same runway in IMC, the minimum allowed separations are listed in Table 1. These minima are found in Section 5-5-4 of the FAA Order JO7110.65T [9]. The required minima are determined from the four wake turbulence classes: small, large, Boeing 757, and heavy. For the minimum spacing of 2.5 nautical miles, arrivals must have, on average, a runway occupancy time of less than 50 seconds [9]. This requirement is often met by the use of high speed runway exits, as is the case for the airports considered in this thesis. For Atlanta, this assumption was validated by using ASDE-X data from the week of April 25 to May 1, 2011 to determine that the average runway occupancy time for the two standard arrival runways, 8L/26R and 9R/27L, is 43.3 and 43.0 seconds, respectively. The cumulative probability plot of arrival runway occupancy time for this week is shown in Figure 1. As seen in this plot, for the two main arrival runways, approximately only ten percent of aircraft have a runway occupancy time of more than 50 seconds.

Table 1: Minimum Separation between Arriving Aircraft [9]

		Trailing Aircraft			
	(nmi)	Small	Large	B757	Heavy
Leading Aircraft	Small	2.5	2.5	2.5	2.5
	Large	4	2.5	2.5	2.5
	B757	5	4	4	4
	Heavy	6	5	4	4
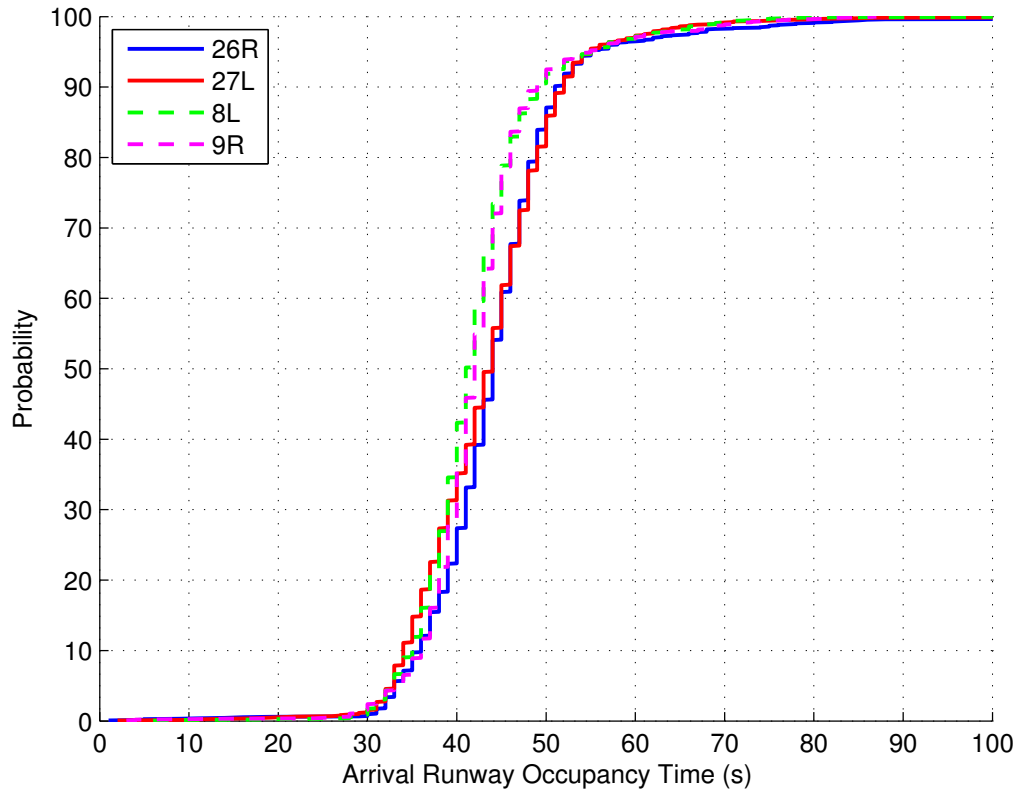
Figure 1: Cumulative probability plot of arrival runway occupancy times at ATL for April 25-May 1, 2011.

3.2.2 Arrival-Departure Separation

In VMC, arrivals and departures are allowed to operate independently on a pair of closely spaced parallel runways. However, in IMC, a departure's takeoff clearance depends upon the location of the arrival approaching the parallel runway. Section 5-8-4 of JO7110.65T [9] states that when radar separation are used, as under IMC, the departure is not allowed to be cleared for take-off when an arrival is within 2 nautical miles of the departure runway [9]. The departure must have begun takeoff roll by the time the arrival is within 2 nautical miles [9]. Once the arrival is within 2 nautical miles, the departure cannot be cleared until the arrival has touched down. In poor visibility conditions, the arrival touchdown time is often determined by using the ASDE-X display at airports equipped with such capabilities [13].

3.2.3 Departure-Departure Separation

For departure types considered in this study, before a trailing departure can begin its takeoff roll, the previous departure must be at least 6000 ft down the runway and airborne, as stated in Section 3-9-6 of JO7110.65 [9]. This same section also requires that when the leading departure is a heavy jet or a Boeing 757, the trailing aircraft must wait at least 2 minutes before beginning its takeoff roll [9]. Also, departures must be sufficiently spaced to ensure proper separation in the TRACON area. When departure courses diverge immediately after departure by at least 15 degrees, departures only need to be spaced by 1 nautical mile [9], as required by Section 5-8-3 in JO7110.65T. Otherwise, the minimum separations between departures along the same course within 40 miles of the radar antenna are listed in Table 2. These separation requirements are found in Section 5-5-4 of JO7110.65T.

Table 2: Separation Between Departures [9]

		Trailing Aircraft			
	(nmi)	Small	Large	B757	Heavy
	Small	3	3	3	3
Leading Aircraft	Large	3	3	3	3
	B757	5	4	4	4
	Heavy	5	5	4	4

3.3   Motivation

Closely spaced parallel runways, like the pair found at Newark Liberty International Airport as shown in Figure 2, have effectively double the capacity of a single runway in VMC as the arrival and departure runways are allowed to operate independently of one another. This fact allows for a constant stream of arrivals and departures with CSPRs whereas, with a single runway, arrivals and departures would have to spaced between each other.

However, the capacity gain is greatly reduced in instrument meteorological conditions (IMC) as arrivals and departures are once again coupled. A departure's takeoff
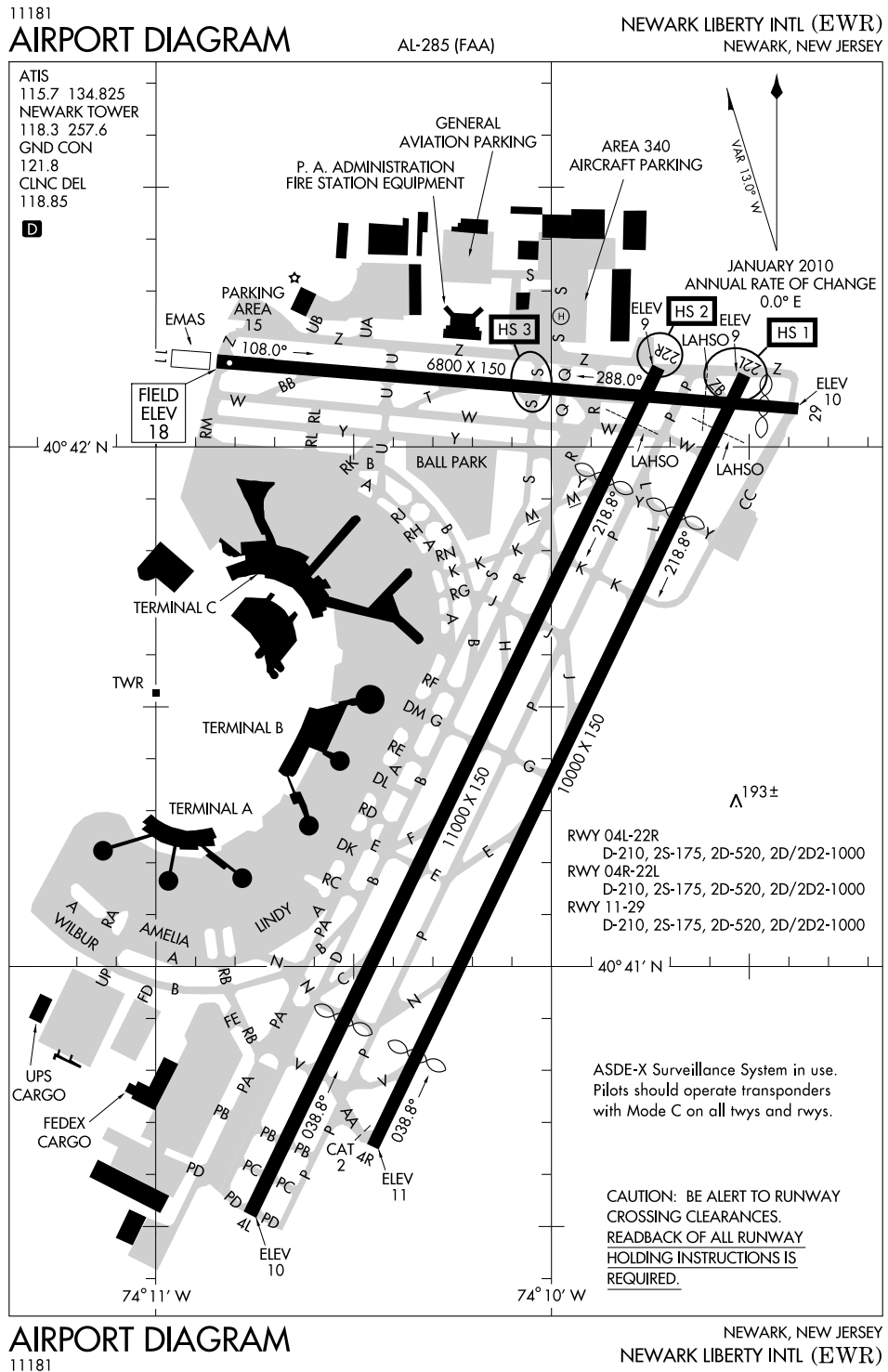
Figure 2: Runway Diagram of Newark Liberty International Airport [10]

clearance is restricted by the proximity of arrivals. Yet, CSPRs still provide advantages over a single runway in IMC. That is, in the case where an arrival is followed by a departure, the departure can be cleared for takeoff as soon as the preceding arrival has landed. For a single runway, the departure would have to wait until the arrival has landed, decelerated, and exited the runway. Additionally, the reduced visibility in IMC typically results in increased conservatism on the part of air traffic controllers. Specifically, they often add time buffers to account for any possible time lags on the part of pilots. The net result is a large decrease in capacity in IMC.

The regulator is designed to mitigate this loss of capacity by using improved sensing and automated clearances to clear a departure waiting for takeoff on one runway once an arrival landing on the other parallel runway has descended below its decision height.

A sample of airports with CSPRs is listed in Table 3 with the number of hours that each airport operated in IMC for the year of 2009. Only hours where the runway configuration had arrivals on one parallel runway and departures on the other were considered. Also included in this table is the average departure demand and the average departure rate. The numbers in this table were compiled using Aviation System Performance Metrics (ASPM) data for selected airports for all of 2009. ASPM data is collected by the FAA for the purpose of measuring the performance of airports.

Table 3: 2009 IMC Statistics at Sample Airports

Airport	Hours under IMC	Mean Departure Demand	Mean Departure Rate
ATL	2005	72.4	54.5
DFW	1601	39.5	36.5
EWR	1573	35.1	21.8
LAX	1829	29.3	28.5
PHX	34	28.2	21.2

As seen in the table, the number of hours in IMC varies greatly from one airport to another, as does the average departure demand and departure rate. At Phoenix,

where IMC conditions are relatively rare, there is little benefit to be gained from a runway regulator for improving capacity in IMC. However, at Newark and Atlanta airports there is both a large gap between the departure demand and the departure rate as well as a significant amount of time in IMC. Therefore, at both airports, significant gains could be made when operating in IMC.

3.4 Inspiration

The inspiration for the regulator came from the realm of track and field, specifically the differences between the 4x100 meter relay and the 4x400 meter relay. In both types of relays, the runners must exchange the baton within an exchange zone that is 20 meters in length, as seen in Figures 3 and 4. In the 4x400 meter relay, the outgoing runner must begin moving from a stationary position inside the exchange zone, as seen in Figure 3. In the 4x100 meter relay however, the runner receiving the baton has an acceleration zone of 10 meters prior to the exchange zone, as seen in Figure 4. The outgoing runner uses this additional 10 meters to accelerate and attain the same traveling speed of the incoming runner.

This difference results in exchanges at high speed in the 4x100 meter relay, whereas the exchanges in the 4x400 meter relay occur at comparatively lower speeds. As a result, the times for the 4x100 meter relay are faster than the sum of the individual runners times, while the same cannot be said for the 4x400 meter relay.
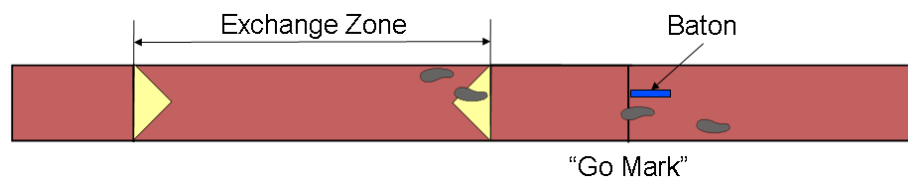
Figure 3: 4x400 Meter Relay Exchange Zone Diagram

The 4x400 meter relay is analogous to the current situation with CSPRs. When a departure on one runway follows an arrival on the other runway, the departure must wait for the arrival to touch down and thus has no acceleration zone. Consequently,

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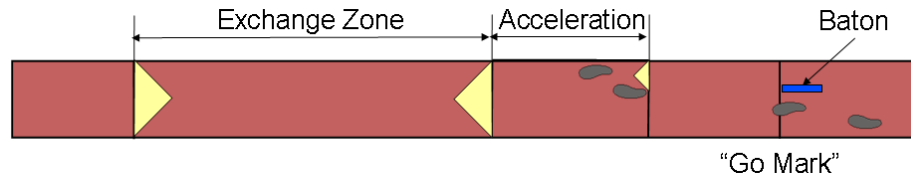
Figure 4: 4x100 Meter Relay Exchange Zone Diagram

the exchange between the two aircraft (which begins when the arrival is first adjacent to the departure and ends when the arrival is last adjacent to the departure) occurs at relatively low speed. The regulator creates a situation similar to the 4x100 meter relay by allowing the departing aircraft to begin its takeoff roll before the arrival touches down, effectively creating an acceleration zone for the departure. As a result, the exchange occurs at a higher average speed.

CHAPTER IV

CONCEPT OF OPERATIONS

With the goal of increasing the capacity of CSPRs, the regulator is conceived to have the following preliminary concept of operations. The local controller (who operates from the airport control tower) will instruct the departing aircraft to line up and wait on the departure runway. Then, if sufficient separation exists between the current departure and the previous departure, the regulator will issue an automated or semi-automated clearance once the arrival on the adjacent runway has descended below its decision height. The automated takeoff clearance may take the form of an automated voice clearance and/or a visual signal using lights on the runway. In the case of a semi-automated clearance, the controller would be provided a signal by a decision support aid indicating that the arrival on the adjacent runway has descended below the decision height.

4.1 Decision Height

The decision height is the altitude at which a pilot must be able to see the runway and commit to a landing; otherwise, the pilot must execute a missed approach. The decision height varies based on the landing aids available on the aircraft and at the airport in question, the terrain and obstacles around the airport. These factors determine which category of ILS procedures may be followed at specific airports. For each category of ILS approach, the FAA has specified the minimum decision height relative to the runway threshold [8]. These heights are listed in Table 4.

For the purposes of the following analysis, for approaches with decision heights greater than 200 ft, it is assumed that the clearance is issued as soon as possible after the arrival has descended below 200 ft.

Table 4: Minimum Decision Heights

ILS Category	Minimum Decision Height
Cat. I	200 ft
Special Cat I	150 ft
Cat. II	100 ft
Cat. III	0 ft

4.2   Comparison of Current and Proposed Operations

Currently, as stated in Section 3.2.2, when radar separations are required, an arrival and a departure must be separated by a minimum of two miles and the separation must increase to three miles after takeoff before a departure clearance can be issued by the tower [9]. This requirement specifies that the separation must be determined at the time when the departure begins its take off roll. So a controller must ensure that sufficient time exists for a clearance to be issued and the pilot to respond and begin the takeoff roll before the arrival crosses the two mile boundary [9].

Once an arrival is within the two mile threshold, the departure can only be granted clearance after the arrival has touched down, provided that there is sufficient separation with the previous departure. Introduction of the regulator would not require relaxation of the two mile separation requirement, but it would require that the touchdown requirement be relaxed. Specifically, the departure clearance would be issued as soon as it is detected that the arrival has descended below the decision height and there is adequate separation between the current departure and the previous departure.

Figures 5 and 6 illustrate the reduction in the minimum inter-arrival gap required for a departure to takeoff due to the regulator. Shown in these two figures are the interactions between two arrivals and a departure with current IMC operations and IMC operations with the regulator. As seen in Figure 5, with current IMC operations, for an aircraft to be able to depart between two arrivals, the inter-arrival gap must be large enough that the time between the leading arrival touching down and the

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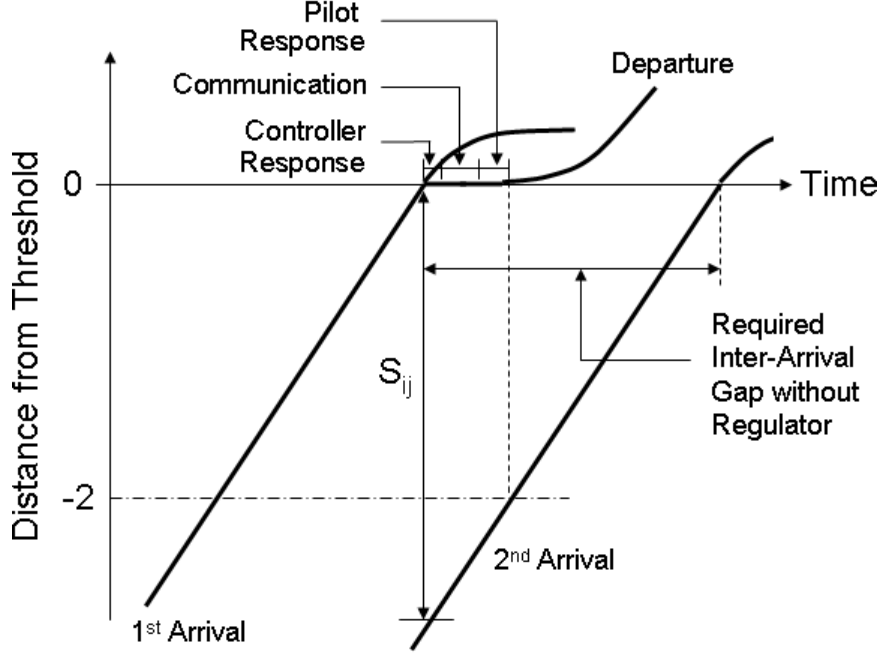
Figure 5: Diagram of Standard Operations at CSPRs under IMC

trailing arrival passing the 2 NM boundary is sufficient for the departing aircraft to begin its takeoff roll. For a departing aircraft to begin the takeoff roll, the controller must observe the leading aircraft touch down and then communicate the clearance to the departing pilot. The pilot must then communicate acknowledgement of the clearance, and then respond to the clearance by taking action to initiate the takeoff roll.

However, as seen in Figure 6, the inter-arrival gap necessary for an aircraft is smaller with the regulator. The regulator decreases the size of the gap by shifting the start of the takeoff procedure to an earlier point in time, namely the time when the leading arrival descends below the decision height. Therefore, the inter-arrival time can be shorter, while still allowing a departure to takeoff between the arrival pair.

The result of the smaller required inter-arrival gap with the regulator is that there is a greater probability that a sufficiently large gap will exist for a departure to be cleared for takeoff. In other words, the separation between a pair of arrivals, S_{ij}, can be less with the regulator and still allow for a departure to takeoff. Therefore, at a
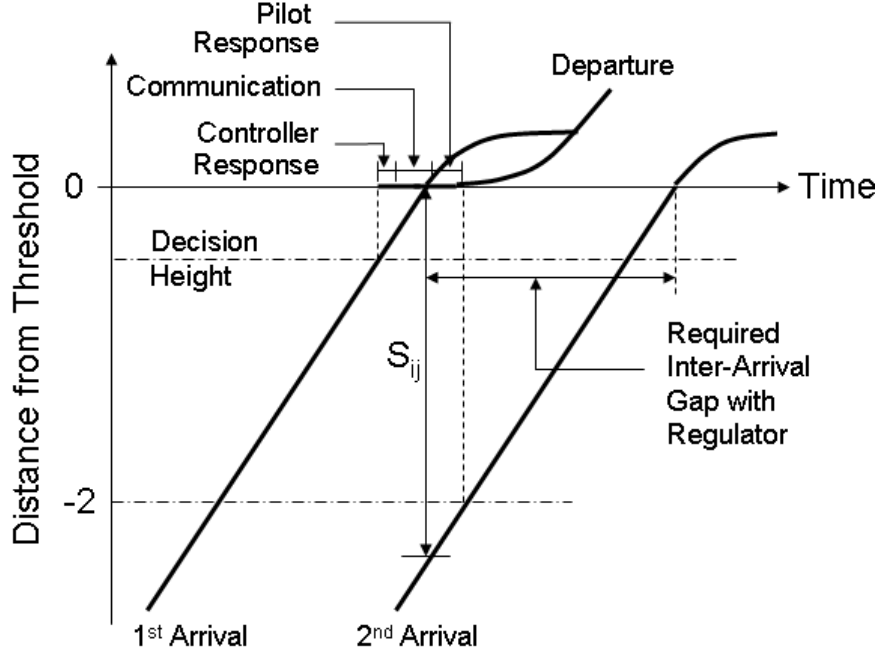
Figure 6: Diagram of Regulator Operations of CSPRs under IMC

given arrival rate, the departure rate will be greater when the regulator is implemented than when current standard separation requirements are applied.

Another advantage of the runway regulator is that it allows an arrival to cross the departing runway without having to wait until the departure has crossed the intersection as the departure will have already passed that taxiway intersection. With the regulator, as the arrival is slowing to exit the arrival runway, the departure is taking off, thereby clearing the departure runway. The arrival can then be immediately cleared to cross the departure runway if necessary, thereby helping to reduce congestion on the taxiways.

4.3 Clearance Methods

The departure clearance can be issued in either a semi-automated or fully automated manner. The semi-automated clearances would be issued by providing the controller with a decision support tool and the controller would issue the clearance as normal. The automated clearance could take the form of voice clearances generated by a

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computer based on the flight number and departure runway. The generated clearance would then be broadcast via existing HF channels. Alternatively, lights on or to the side of the runway could be used as visual cues to the pilot indicating clearance for takeoff. These runway lights would change from red to green when the arrival has descended below the decision height and the departure can be cleared. A visual cue could also be used in conjunction with voice clearances.

4.3.1 Semi-Automated Clearances

Of these three options, the semi-automated clearance, where the controller is notified and then issues the clearance, differs the least from current operations. In this form, the regulator would simply function as another decision support tool for controllers. The advantage of this clearance method is that it would be the simplest to implement as it would require the fewest changes to current regulations. It also would require no new training on the part of pilots. Possible disadvantages include added workload for controllers as the cue would be another source of information that requires monitoring.

4.3.2 Automated Voice Clearances

Using an automated voice clearance to clear departures would remove the controller response time from the clearance process thereby allowing departure clearances to be issued sooner. Also, this form of clearance would not require any additional training for pilots. However, this form of clearance would still require communication over current voice channels. Therefore, the clearance could still be delayed if the radio channel was occupied. This clearance method would also be more difficult to implement than semi-automated clearances. Any implementation of this method would have to be able to guarantee that other voice communications would not be overridden and that the automated clearance would fit into the flow of communication. Another implementation challenge would be recognizing a correct reply to the clearance.

4.3.3 Automated Visual Clearances

Using only the runway lights to issue the clearances departs the most from current operations. However, this method significantly cuts down on response time to a clearance being issued. Instead of listening to a clearance and then responding with confirmation to the clearance and then advancing engine throttles, a pilot only needs to respond to a visual signal, thereby greatly reducing the response time. An additional benefit to with this clearance method is that it frees the radio channel for other communications. This clearance form also avoids possible confusion that can arise with voice communications. Voice communications can be garbled or cut off by others trying to communicate on the same channel, thus requiring the controller to repeat a clearance, whereas issuing clearances visually would remove this risk.

One advantage of voice communications is that voice communications can relay additional information regarding specific departure procedures, such as which RNAV procedure to use. Such information could not be relayed with a visual cue. These procedures would have to specified when the departure is told to line up and await the automated clearance. Specifying the procedures during this communication would still allow for a read back confirmation of any specific departure procedure.

Multiple implementation difficulties are present with automated visual clearances. One disadvantage is that it differs considerably from current operations using voice clearance. However, precedent exists for using visual signals to clear departures. First, FAA JO7110.65T Section 3-2-1 defines the procedures for using light signals when radio communications cannot be employed. It specifies that a steady green light should be used to indicate a takeoff clearance and a steady red light should indicate a stop [9]. However, these procedures are designed for emergency situations if radio communications fail or for small facilities without radio communications. These procedures are not designed for normal operations at large airports. Secondly, runway entrance lights (REL) and takeoff hold lights (THL) also provide some precedent for

using runway lights to provide information to pilots [16], [7]. As stated previously, REL indicate when it is unsafe to taxi across a runway due to an arrival or departure and THL indicate when it is unsafe to takeoff due to surface vehicles crossing the runway. However, these two systems do not provide clearances; they can only prohibit aircraft movements. Thus, more validation would be required before implementation than what would be required with the semi-automated clearance.

This method would also required additional training for pilots. However, there are once again the precedents of REL and THL, a fact which would reduce the unfamiliarity of this clearance form.

Confusion between this light system with other runway light systems is another concern that would have to be addressed. Any implementation of the automated clearance lights would have to ensure that the departing aircraft, awaiting clearance, does not confuse any other lights with these departure clearance lights, in order to prevent an aircraft from beginning takeoff without clearance. Implementation of the departure clearance lights would also have to ensure that taxiing aircraft do not mistake these lights with REL and ensure that aircraft landing on the parallel runway do not confuse these lights with any approach lights.

CHAPTER V

SAFETY

With the regulator, two safety concerns exist that are not present with current operations. The first concern involves the case of a missed approach occurring below the decision height, after the departure clearance has already been issued and the departure has begun takeoff roll. The second concern is that the automated clearance could issue a departure clearance when there is an obstruction on the departure runway.

5.1 Missed Approach

Because, at the decision height, a pilot must be able to see the runway and be in the appropriate configuration and attitude for landing, the number of missed approaches executed once an arrival has descended below the decision height is extremely low. For example, at SFO there were 33149 arrivals during the months of January, February, and March in 2006. Of these, there were 143 missed approaches and go-rounds. Only 8 of the 143 occurred below 200 ft and all occurred above 120 ft. Given that SFO is equipped for CAT III landings on runway 28R and therefore approaches with a decision height of 0 ft are allowed, many of these missed approaches could have occurred above the decision height for the approach being flown and thus would not have even triggered the regulator to issue a departure clearance.

The risk associated with missed approaches is significantly mitigated by divergent headings for missed approaches. The majority of missed approaches procedures for a set of closely spaced parallel runways specify that the arrival executing a go-around fly a heading that diverges from the parallel departure runway heading. When, in

VMC, CSPRs with departures on one runway and arrivals on the other operate independently, missed approaches do occur. In these cases, arrivals follow the missed approach procedure and divert away from the departure runway. The arrival and departure maintain visual separation. In IMC, visual separation would not be necessarily be possible depending on the visibility and ceiling.

On the rare occasion where a missed approach is initiated below the decision height, an automated abort takeoff command will be issued to the departure. Because of the short time between the decision height being reached and the arrival touching down, the departing aircraft will not have reached V1 speed by the time the arrival initiates the missed approach. Recall that V1 is the speed at which a pilot must continue takeoff even in the case of engine failure. As such, it is the maximum speed from which a pilot can safely abort the takeoff.

As the decision height increases, the gain in capacity increases because the departure can begin takeoff roll sooner, as discussed later in Section 7.1. However, increasing the decision height also allows the departure to gain more speed before a potential missed approach. In order to study this trade off, a high fidelity departure simulator was used to generate departure profiles for a range of aircraft types at various weights and thrust settings. Figure 7 shows a plot of the maximum percentage of V1 reached by any departure assuming the given decision heights and the arrival speeds. This plot assumes the worst possible case of no delay between the arrival descending below the decision height and the departure beginning takeoff roll, as well as assuming that a missed approach occurs just before touchdown. This figure shows the maximum %V1 of all departure profiles generated at each point for this scenarios.

The worst case occurs with the highest decision height and the slowest arrival speed tested. This result is as expected as the combination results in a long time between the arrival clearing the decision height and the arrival starting a missed approach. In this case, the fastest departure actually reached a takeoff speed of 120%
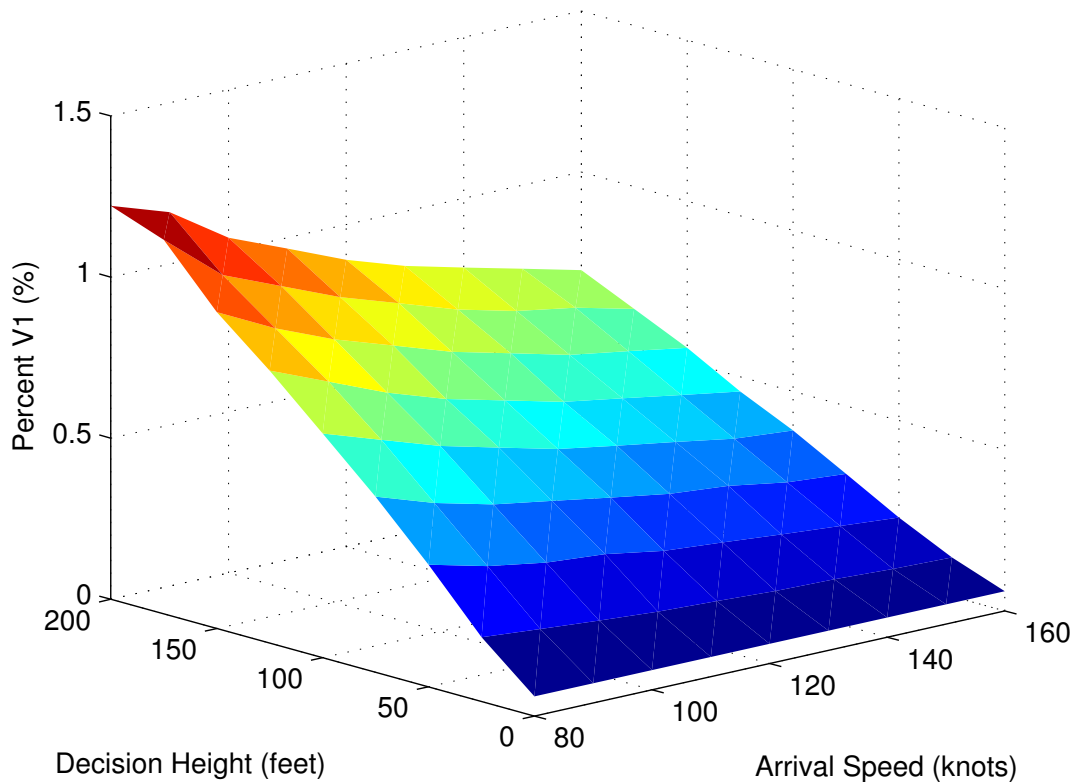
Figure 7: Effect of Arrival Speed and Decision Height on %V1 Reached by a Departure before Missed Approach with the Regulator

of V1. Therefore, that departure would be unable to abort takeoff, if required. Thus, any implementation of the regulator would have to consider the current decision height and current arrival's approach speed. The simplest fix would be to reduce height above the runway at which the departure clearance is issued. A more complex solution would be adjust the clearance height based upon the arrival's final approach speed and the acceleration rate of the departure. Either of these approaches would allow for increased safety margins with the departure regulator.

Further risk analysis is needed to ensure the safety of the regulator in the event of a missed approach. Nevertheless, given the rarity of missed approaches below the decision height and the limited time between the decision height and touchdown, the preliminary analysis indicates that the regulator can be implemented safely and still

provide increased capacity, even if the clearance height for the regulator must be lowered below the decision height.

5.2   Automation and Runway Incursions

Using any automated version of the departure regulator results in a shift of the responsibility of ensuring that the departure runway is clear before the takeoff clearance is issued. Currently, the controller is responsible for checking the departure runway before issuing the clearance. However, with the automated departure clearance the responsibility would be shifted, at least partially, to the departure regulator.

Before a departure clearance can be issued, the departure runway must be cleared of obstructions. Currently, this requirement is checked with visual observations and with surface surveillance radar, such as ASDE-X. However, an automated version of the departure regulator would only have access to the surface surveillance radar data. Detecting possible future runway incursions is also difficult without information about clearances issued to taxiing aircraft. A controller knows which aircraft have been cleared to cross a departure runway and which have been told to hold short of the departure runway. Therefore, when a controller observes a taxiing aircraft approaching a departure runway, the intent is known and decisions are made accordingly. However, the automated regulator would not have knowledge of the intent of taxiing aircraft. Therefore, it would be difficult for an implementation of the automated clearance to determine if an aircraft was taxiing across a departure runway or simply taxing into position to hold short.

The other safety concern involves the controller response when a runway incursion occurs. Currently the controllers responsibilities are issuing commands to the involved aircraft to resolve the situation. However, with an automated departure regulator, the controller would also have to override the regulator to ensure that the regulator did not issue a clearance while the incursion was present. This action would increase

the workload of controllers during an already stressful event.

Further study is needed to determine how an automated would affect a controller's workload. Future studies will also be needed to investigate the ability of an automated regulator to detect runway incursions while minimizing the number of false-positive runway incursion detections.

CHAPTER VI

SIMULATOR DESCRIPTION

A discrete stochastic simulation has been developed to determine the possible capacity gains due to the introduction of the regulator. This simulation generates capacity curves based on an input set of runways and conditions. A simplified flow chart of the simulation is shown in Figure 8. Random arrival and departure sequences are generated and iterated over to determine the maximum departure rate for a given arrival rate. The capacity curve is generated from repeated runs of the simulation, each run with a slightly lower arrival rate in order to guarantee that the range of arrival rates is fully traversed. The arrival rate is adjusted with the parameter, λ. The separation between all aircraft is determined from a set of rules, which are derived from the FAA standards, along with an additional random separation.
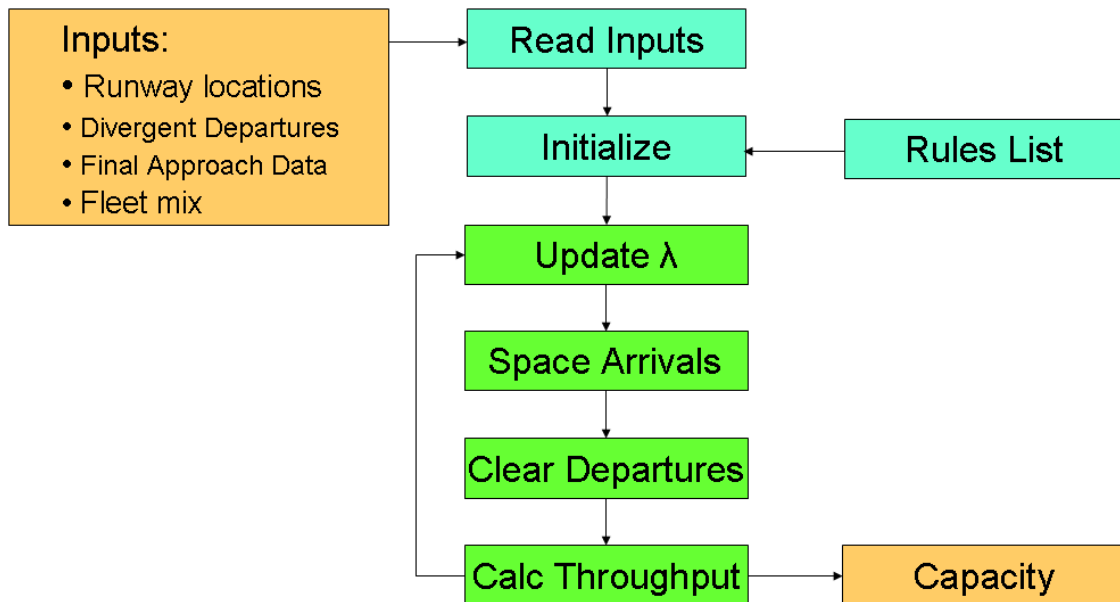

Figure 8: Simulation Flow Chart

6.1 Runway Interactions

At startup, the simulation reads in a user-created input file. The input file includes information on each runway, the fleet mix, and the other options necessary to run the simulation. The possible inputs are described and a sample input file is shown in Appendix A. As seen the example, each runway is defined by the latitude and longitude of its start and end. Also, each runway is categorized as being used for arrivals, departures, or a mix of both.

For each arrival runway, a final approach profile is created. The final approach profile is set based upon the length and the glide slope of the final approach path shared by all arrivals to the runway. Each arrival runway is assigned a decision height. The final approach length, the glide slope, and the decision height can be set separately for each runway in the input file. If these values are not set in the input file, they default to a final approach length of 10 nautical miles, a glide slope of 3 degrees and a decision height of 100 ft. The profile is currently defined as a set of points (the start of the final approach, the decision height, the threshold crossing, and touchdown) where more points could be added based upon actual final approach profiles.

After reading in the information about the runways, the simulator determines all possible pairings of runways and the configuration of each pair of runways. The list of possible configurations and their definitions are included in Table 5. A runway can be paired with itself, thus the identical configuration. The identical configuration exists so that aircraft on the same runway can be properly spaced as explained later in Sections 6.2.1 and 6.2.3. Crossing runways are distinguished from converging and diverging runways by the fact that crossing runways have an actually intersection point, while converging and diverging runways do not intersect.

Table 5: Runway Pair Configurations

Configuration	Angle Between	Separation
Identical	0°	0 ft
CSPR	< 15°	<= 2500ft
WSPR	< 15°	> 2500ft
Crossing	> 15°	NA
Converging	> 15°	NA
Diverging	> 15°	NA

6.2 Rules

Each pair of runways is linked to a set of applicable rules, which will be used later in the simulation to separate arrivals and departures. The runway pairs and rules are linked based upon the configuration of the pair and the specific combination of arrivals and departures on the runway pair.

A rule is defined as function that takes as input an independent aircraft, a dependent aircraft, and information about the runway pair. An independent aircraft is any aircraft which has already been scheduled and whose flight path has been fixed. A dependent aircraft is any aircraft being spaced or cleared. For example, when spacing arrivals, the leading arrival would be the independent aircraft and the trailing arrival would be the dependent aircraft, as the leading arrival's profile would already be fixed, but the trailing arrival's profile could still be adjusted.

A rule returns the time delay required for the dependent aircraft to satisfy the given rule. If the dependent aircraft already meets all of the requirements of the rule, no delay time is returned. The delay is then used to adjust the dependent aircraft's start time.

Currently, only three rules are present in the simulation. These rules cover the cases of separation between arrivals on the same runway, between an arrival and a departure on CSPRs, and between departures on the same runway. These three rules cover all use cases seen at the airports considered by this thesis. Additional rules could be easily created based on the current rule template to cover cases for other

configurations.

6.2.1 Same Runway Arrival-Arrival Separation

The first rule applies to the separation of two arrivals on the same runway. For this rule, the leading arrival is the independent aircraft and the trailing arrival is the dependent aircraft. The requirements listed in Section 3.2.1 are used determine what delay to apply to the trailing aircraft in order to ensure spacing between the two arrivals.

To calculate what delay, if any, is required to separate two arrivals on the same runway, the simulation first determines the minimum required separation between the two arrivals using Table 1. Then, the simulation iterates over all points in the leading arrival's profile. At each leading arrival point, the simulation finds the point, along the trailing arrival's profile, that is located the minimum separation from the current leading arrival point. If the trailing arrival crosses this point before the leading arrival reaches its currently considered point, the required delay is set to the delta between the two times at which the arrivals reach their respective points. The maximum such delay is returned as the time required to space the two arrivals.

6.2.2 CSPR Arrival-Departure Separation

The second rule covers the case of clearing a departure for takeoff on one runway based on the location of arrivals on a closely spaced parallel runway. For this rule, the arrival is the independent aircraft and the departure is the dependent aircraft. The requirements of this rule are listed in Section 3.2.2.

The simulation enforces this rule by checking if the arrival is within 2 nautical miles of the departure runway and has not touched down when the departure is set to start take-off roll. If so, the required delay to the departures start time is set to the difference between the current start time and the arrival's touchdown time. If the arrival is more than 2 nautical miles away or has touched down, the delay is set to

zero, as this rule is satisfied.

This rule is modified when the departure regulator is active. Instead of only being satisfied once the arrival touches down, this rule is satisfied once the arrival descends below the decision height.

6.2.3 Same Runway Departure-Departure Separation

The third rule ensures proper separation between departures on the same runway. For this rule, the leading departure is the independent aircraft and the trailing departure is the dependent. The requirements for the this rule are detailed in 3.2.3.

To determine what delay if any needs to be added to the trailing departure, the simulation first checks if the leading aircraft is a heavy or Boeing 757, the simulation adds enough delay to ensure that the second aircraft starts its takeoff roll at least 120 seconds after the first one. If the leading is a large or a small, the simulation then checks to see if the two aircraft are on diverging headings. If so, the delay is set so that the second departure will not be given clearance until the 6000 ft and airborne separation requirement is met, as this will also guarantee the 1 nautical mile separation rule for divergent headings. If the aircraft are not using divergent departure profiles, the departure profiles are used to ensure the separations listed in Table 2 are satisfied once the departure reaches the TRACON.

6.3 Arrival Sequence Generation and Spacing

Once all runway interactions have been determined and the runway pairs linked with the applicable rules, arrival sequences are initialized on all runways with arrivals. An arrival sequence is a queue of aircraft of predefined length. Each aircraft is of a randomized wake turbulence class, generated with a uniform random number generator using the input fleet mix.

Each arrival is then propagated over the final approach profile for its runway. The profile start times are initially all set to zero. The arrival is propagated assuming a

constant speed along the final approach path. The assumed aircraft speeds for each wake turbulence class are listed in Table 6.

Table 6: Average Arrival Speed [2]

Small	Large	B757	Heavy
90	130	130	150

After all of the arrival sequences have been set, these sequences are spaced out using the runway pairs and rules. All runway pairs that have arrivals on both runways are iterated over until all of the arrivals are spaced. Arrivals are spaced one at a time by applying all rules that deal with two arrivals that are linked to all runway pairs that include the arrival's runway. For any rules that are not satisfied, the required delay is added to the arrival's start time. In addition to the required delay, a randomized delay is added to the start time. This random delay has an exponential distribution with a probability density function as shown in Equation 1. With each run, λ is decreased to test the regulator over a range of arrival rates, from the maximum arrival rate to effectively no arrivals.

$$f(n) = \begin{cases} \lambda e^{-\lambda t} & \lambda \geq 0 \\ 0 & \lambda < 0 \end{cases} \tag{1}$$

For every arrival, after all the rules have been checked and any additional delays added in, all of the rules are checked again to ensure that by satisfying one rule another rule was not invalidated. If another rule was invalidated, the process is started over with the arrival at the new start time. This cycle repeats until the arrival is successfully spaced.

6.4 Modeling Controller-Pilot Interactions

For each arrival-departure pair, a total response and communication time is drawn from a set distribution. If the total response and communication time is greater than

the time available to start the takeoff roll, the departure is not given clearance. The available time is the time from either the leading landing aircraft descending below the decision height for the regulator or the leading landing aircraft touching down for current operations up to the time when the trailing aircraft reaches the 2 NM boundary.

The values used to model the response and communication times of the controllers and departing pilots are listed in Table 7. For each arrival-departure pair, a total response and communication time is calculated based on this table. If the total response and communication time is greater than the time available to start the takeoff roll, the departure is not given clearance. The available time is the time from either the leading landing aircraft descending below the decision height for the regulator or the leading landing aircraft touching down for current operations up to the time when the trailing aircraft reaches the 2 NM boundary.

For each communication or response time that is modeled as a normal distribution with a lower bound, if a time less than the lower bound is generated, the normal distribution is resampled until a time greater than the lower bound is generated.

Table 7: Response and Communiction Times

	Distribution	Minimum	Maximum
Controller Response	$N(1.0, 0.25)$	0.25 sec	NA
Controller Communication	$N(2.75, 0.6)$	1.6 sec	NA
Pilot Response to Voice	$\beta(3, 5.9)$	0.5 sec	30.0 sec
Pilot Response to Visual	$\beta(2.65, 5.55)$	0.5 sec	30.0 sec

The controller communication time distribution is based on observations of controllers issuing departure clearances at ATL for runway 8R. The pilot response to voice clearances distribution is a fit of observations of tower operations made by MITRE [4]. For the pilot response time, MITRE observed a mode of approximately 8.5 seconds. The pilot response to visual clearances was estimated by shifting the mode of the distribution to subtract out the mean controller communication time.

The controller response time is the time it takes for the controller to recognize either that an arrival has touched down or to observe the automated signal that the arrival has descended below the decision height. This response time is only used when modeling baseline conditions or the semi-automated regulator where the controller is cued to issue the clearance.

The controller communication time is the time required to verbally issue the departure clearance. This communication time is not included in any version of the simulations as it is included in the next response time. It is included here only for reference.

The pilot response time models the time from the start of a clearance being issued to the start of takeoff roll. This time includes the time it takes for the engine to spool up following throttle movement. The minimum pilot response time is less than the minimum controller communication time for two reasons. First, when a controller begins issuing a clearance, the pilot flying will sometimes begin the throttling up for takeoff as soon as the start of the clearance is heard. In this case, the pilot not flying will be the one to respond to the clearance as the aircraft is starting roll. Secondly, these measurements include operations where the departure is given clearance to taxi onto the runway and immediately takeoff.

To approximate the effect of the pilot response to visual clearances, the mode of the pilot response distribution was shifted to the left by the mean of controller communication time. The beta distribution shaping parameters were scaled to maintain a similar shape to the distribution of pilot response times to voice clearances. This distribution is used to generate the delay with the automated visual departure clearances.

These delays do not factor in congestion of the radio channel. A departure clearance may not be able to be issued as soon as possible due to other communication on the radio channel. However, departure clearances normally have priority over

ground traffic communications and even arrival clearances as departure clearances are generally more time critical than the other two types of communication.

6.5   Modeling Departures

The final step of the simulation is iterating over all of the arrival sequences and clearing a departure in every possible slot between arrivals. Every possible slot is filled so as to maximize the departure rate for the current arrival rate. Departure clearances are determined in a similar manner to the spacing between arrivals. The simulation uses the rules to determine what delays if any need to added to each departure's start of takeoff roll.

A list of departure runways is repeatedly iterated over. Each time a runway is iterated over, a new departure is created for this runway. This new departure is issued a clearance time by checking all rules that are linked to all runway pairs of which the current runway is part. An additional random clearance delay time is also added using the distributions listed in Section 6.4.

The departure runway list is iterated over repeatedly until the most recent departure begins take-off roll after the final arrival in any arrival sequence touches down. At this point, this run of the simulation is considered to have finished.

To accurately model departures, a aircraft departure simulator based on high fidelity aerodynamic data was used to generate departure tracks for a variety of aircraft models of weight classes large and heavy. For each aircraft, tracks were generated at range of takeoff weights and thrust settings. Based on these high fidelity simulation results, for the purposes of this capacity simulation, departures are assumed to accelerate at a constant rate until it reaches the wheels-off point.

Both the rotation speed and takeoff distance, i.e. the distance from the start of roll to wheels off, are randomly generated based on the results of the high fidelity simulation runs. Figure 9 shows the correlation between takeoff distance and the

rotation speed. To model this relationship, the takeoff distance, $d_{takeoff}$ is drawn from the range of 3500 ft to 7500 ft, using a uniform distribution. The rotation speed, v_R, is then calculated using the least squares curve fit plus a delta airspeed, which is randomly distributed, as shown in Equation 2. In Equation 2, v_R is in knots and $d_{takeoff}$ is in feet. Small aircraft are assumed to accelerate to 120 knots at a distance of 4000 ft down the runway and then rotate. After rotation, all aircraft are assumed to continue accelerating during climb until reaching 250 knots.

$$v_R = 128 + 0.00613 d_{takeoff} + u$$
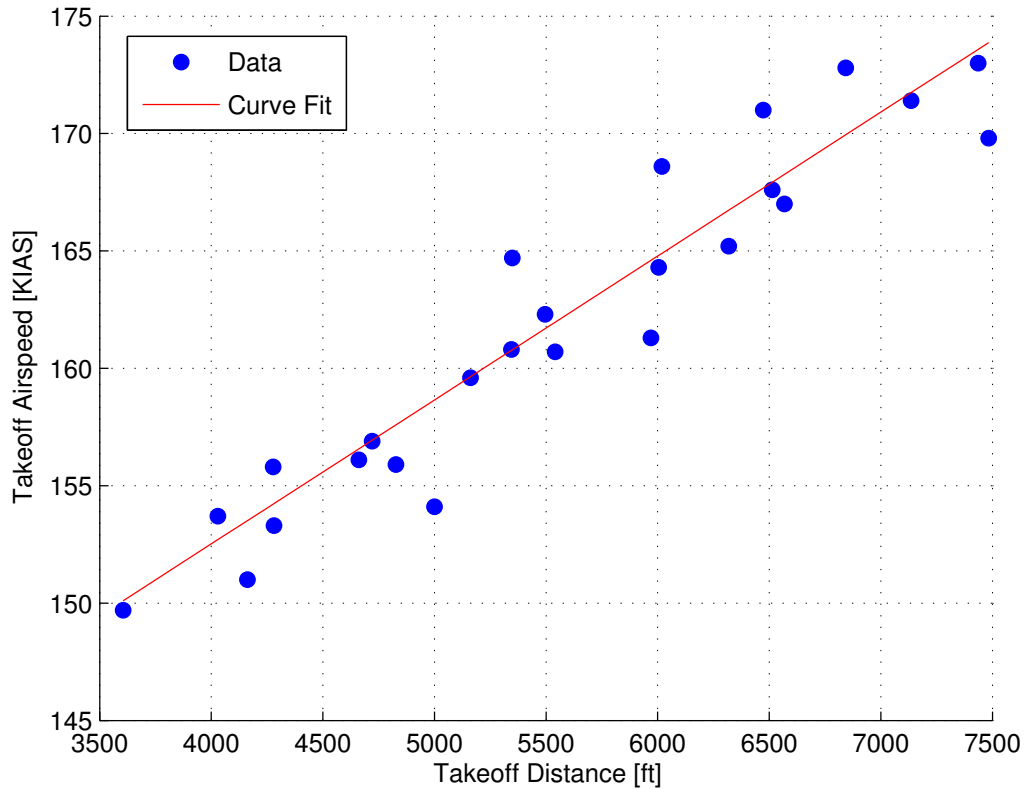$$u \sim N(0, 2)$$

(2)

Figure 9: Takeoff Distance and Airspeed for a Variety of Aircraft Types and Weights.

6.6 Analyzing the Results

Once the arrival queue has been properly spaced out and iterated through with a departure being allowed to takeoff in all allowable gaps, the throughput of the CSPR for each run of the simulation is calculated from the number of arrivals and departures, and the time of the final departure. Multiple runs of the simulation are made with varied distributions of the random arrival-arrival separation in order to calculate the maximum departure rate at a range of arrival rates.

CHAPTER VII

RESULTS

The simulation results indicate that there would be large capacity gains for CSPRs in IMC when operating with the proposed regulator. In Figure 10, the baseline curve represents the capacity of a set of CSPR under current operations in IMC. Also shown in Figure 10 are the capacity increases both with the two automated forms of the regulator as well as with the semi-automated form, where the controller issues clearances. In each of these plots, the decision height used by the regulator is 100 ft. The runway configuration at EWR was used for these results with arrivals on 4R and departures on 4L. See Figure 2.

All three forms of the regulator provide significant increases in capacity. These increases are the result of two phenomena. First, as was explained earlier (see Figures 5 and 6), the regulator effectively reduces the gap between arrivals that is required to insert a departure. The reduction in required gap provides gains in the total capacity, because the probability of finding a gap that enables at least one departure increases. The net result is that the departure rate decreases slower with increasing arrival rate compared to the baseline case. Second, as the arrival rate increases, the number of inter-arrival gaps that enable two or more departures decreases. At some threshold rate, the vast majority of the inter-arrival gaps will only enable one departure. Even though the gaps might be wider than the required gap for one departure, they are less than the required gap for two. The net result of this phenomenon is the unexpected behavior that the departure rate actually increases slightly with increasing arrival rate, because the regulator has synchronized the departures with the arrivals. In other words the arrivals and departures are executed in lock step with each other.
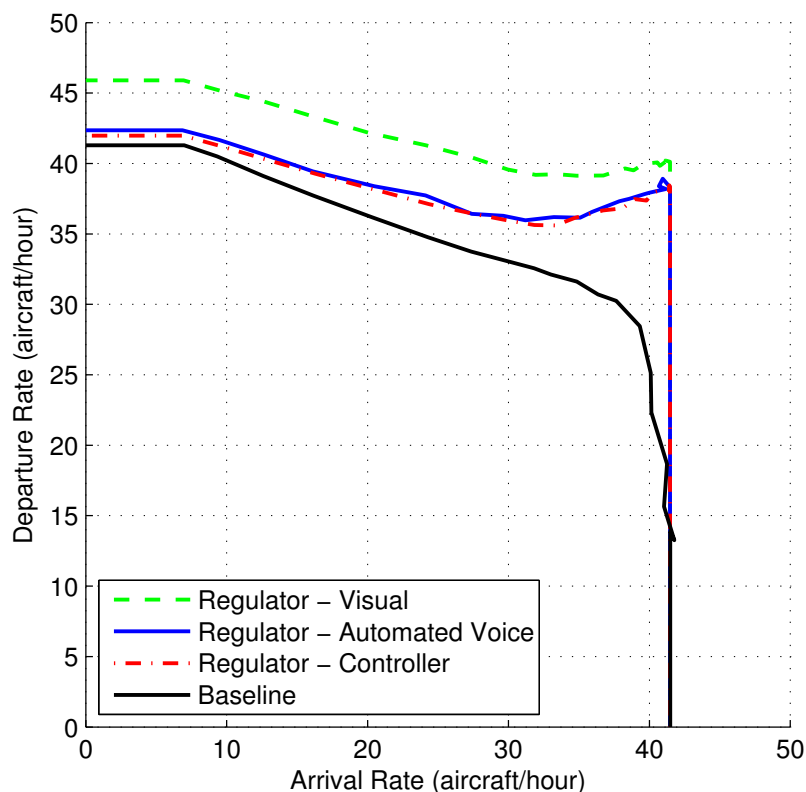
Figure 10: Capacity of CSPRs With and Without the Regulator.

This increase continues until the arrivals become too tightly spaced and the departure rate once again begins to decrease. The percentage increases in throughput when the set of CSPR has balanced operations, i.e. when the arrival and departure rates are equal, are listed in Table 8.

Table 8: Clearance Method Throughput Increases

Clearance Method	Throughput Increase
Visual	23%
Automatic Voice	14%
Controller	14%

The largest capacity gains occur when visual cues (runway lights) are used. This gain is greater than in the other two cases because controller response and the communication times are eliminated. There is a small capacity gain with automated

voice clearances over the controller issuing a clearance after receiving a visual cue. This gain occurs because with automated clearances there is no delay between the earliest time that a clearance can be issued and the time that the clearance is issued. However, this delay is minimal with this simulation; thus, the gains are small. That being said, it is important to determine what the true controller-pilot interaction delays would be through human-in-the-loop simulation or direct observations of current operations. Once the delays are known, the simulation can be used to derive revised capacity estimates.

Note that when controllers issue the clearances with and without the regulator, the capacities for both cases are very similar same when only departures are present. This result is expected as, under these conditions, the mean time for a clearance to be issued and a departure to begin takeoff roll is identical for both cases. As the arrivals are sparse, there are no gains to be achieved with the regulator.

7.1 Effects of Decision Height

As the decision height decreases, the benefits of increased capacity are decreased, as shown in Figure 11. The percent throughput increase with each decision height is listed in Table 9. The percent throughput is calculated when there are balanced operations on the runway. As can be seen, there are still significant benefits even with a decision height of 50 ft. The semi-automatic version of the regulator was used to generate these curves.

Table 9: Throughput Increases at Various Decision Heights

Decision Height	ThroughputIncrease
200 ft	17%
150 ft	14%
100 ft	13%
50 ft	8%

As discussed in Section 5.1, while the capacity gains increase with increasing
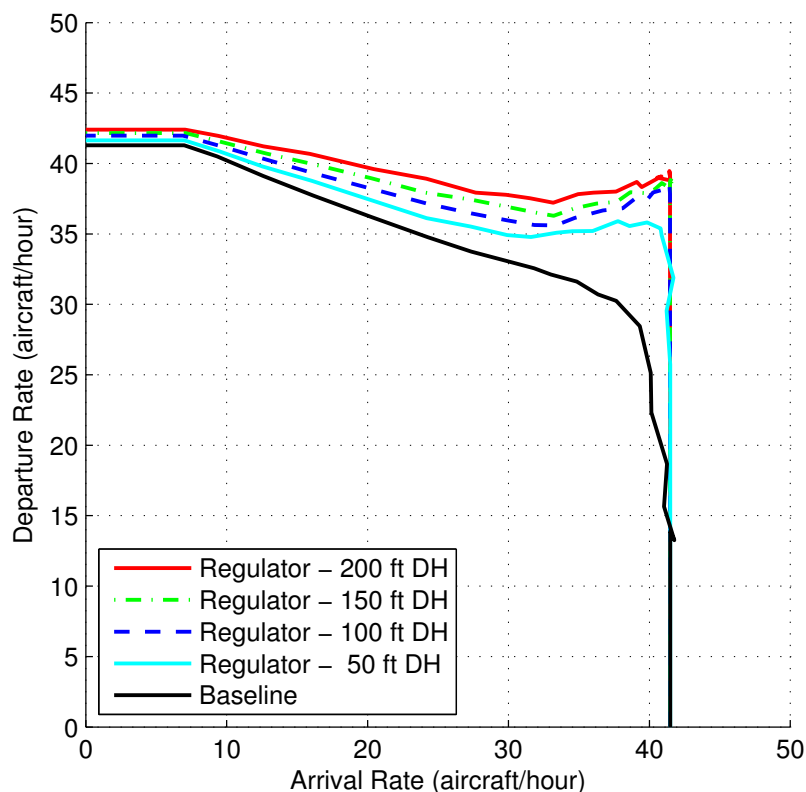
Figure 11: Effects of Decision Height.

decision height, the safety risks also increase. Therefore a trade off must be made between capacity and safety. As safety is by far the more significant interest, it is important to note that even if the clearance height for the regulator is lowered below the decision height, the regulator still provides significant increases in capacity. Thus, the regulator can be both effective and safe.

7.2 Airport Specific Results

The results presented thus far have been for Newark (EWR) with arrivals on 4R and departures on 4L, as shown in Figure 2. Figure 12 also includes capacity curves for Atlanta (ATL) and Los Angeles (LAX). The capacity curve for ATL was generated for west bound operations with arrivals on 26R and 27L and departures on 26L and 27R. The curves generated for LAX also assume westbound operations with arrivals

on 24R and 25L and departures on 24L and 25R. For each airport, the capacity curves with and without the regulator are shown. The higher capacity curve is always the capacity with the regulator. For these runs, the semi-automated regulator was used and the decision height was 100 ft.
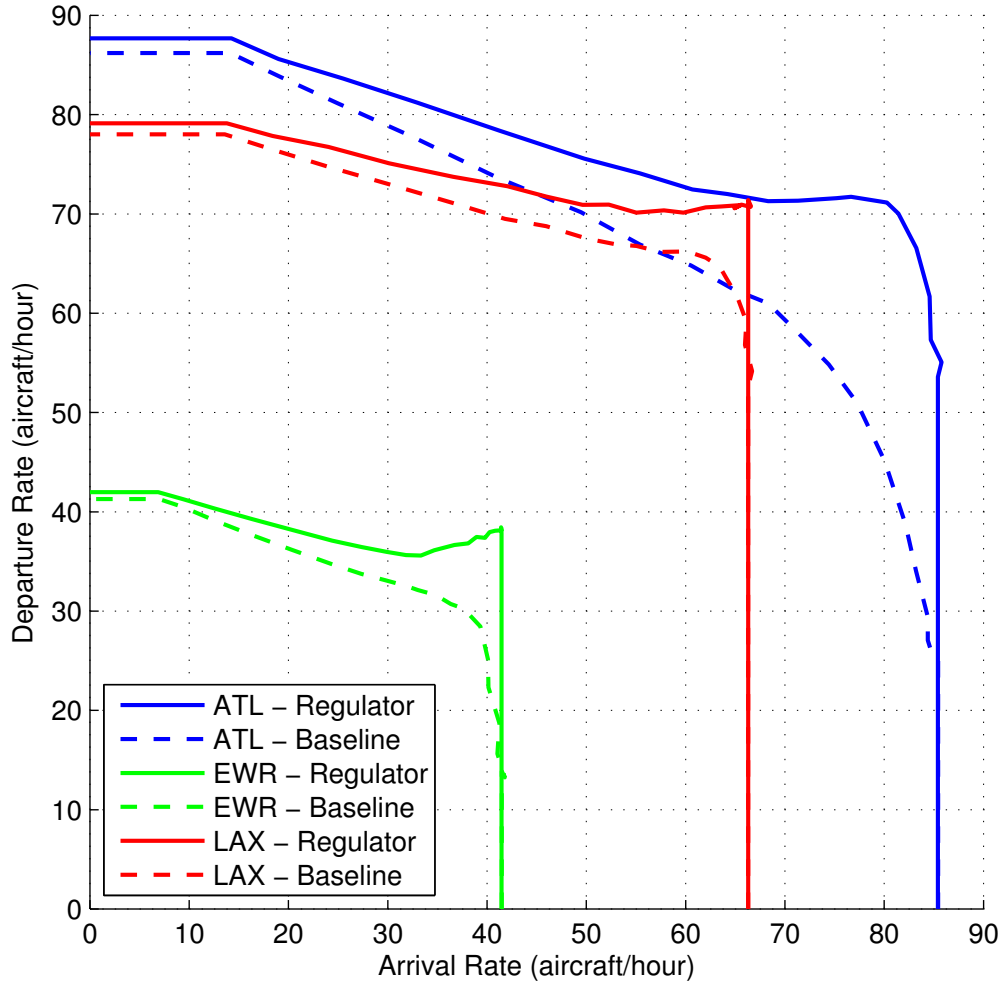

Figure 12: Capacity at Example Airports.

One reason for the differences seen in this figure is the fleet mix. The spacing between both arrivals and departures depends greatly on the aircraft weight classes. Thus, the capacity at an airport greatly depends on the percentage of each class that frequents that airport. Listed in Table 10 are the fleet mixes at Atlanta, Newark,

Table 10: Fleet Mix at Example Airports

	ATL	EWR	LAX
Small	1.7%	1.8%	10.2%
Large	78.8%	77.2%	62.0%
B757	13.3%	11.3%	12.0%
Heavy	6.2%	9.7%	15.7%

and Los Angeles during 2009 as calculated from ASPM data. These fleet mixes were used to generate these capacity curves. While both Atlanta and Los Angeles have two runways dedicated to arrivals, the maximum arrival rate at ATL is higher than at LAX due to the fact that there are less heavy and small aircraft at ATL. The larger number of heavy and small aircraft at LAX force larger separations between arrivals, therefore decreasing the arrival rate.

Atlanta has a larger benefit from the departure regulator than does Los Angeles due to a difference in the staggering of thresholds at Atlanta and at Los Angeles. As seen in Figure 13, both pairs of parallel runways at Atlanta are staggered, with the threshold of 26R being slightly under 1000 ft farther down field than the threshold for 26L and the threshold of 27L being 2000 ft farther down field than the threshold for 27R. However at Los Angeles, only runways 25L and 25R are staggered by 1000 ft, as shown in Figure 14. Because in all of these cases, the threshold of the arrival runway is farther down field than the threshold of the departure runway, the gaps in which a departure can be cleared are smaller. For example, for the case two large aircraft arriving at 27L at ATL flying the same speed and spaced 2.5 nautical miles apart, the available gap for clearing a departure is the time it takes for the trailing aircraft to fly 1000 ft. This small gap exists due to the fact that the when the leading arrival touches down the trailing arrival will only be 1000 ft from the 2 nautical mile separation distance from the departure. This small amount of time is usually not enough to clear a departure. The regulator significantly helps with this case by increasing the gap that a departure can be cleared in to a reasonable size. Therefore,

because the greater stagger at Atlanta, the departure regulator has a greater effect there than at Los Angeles.
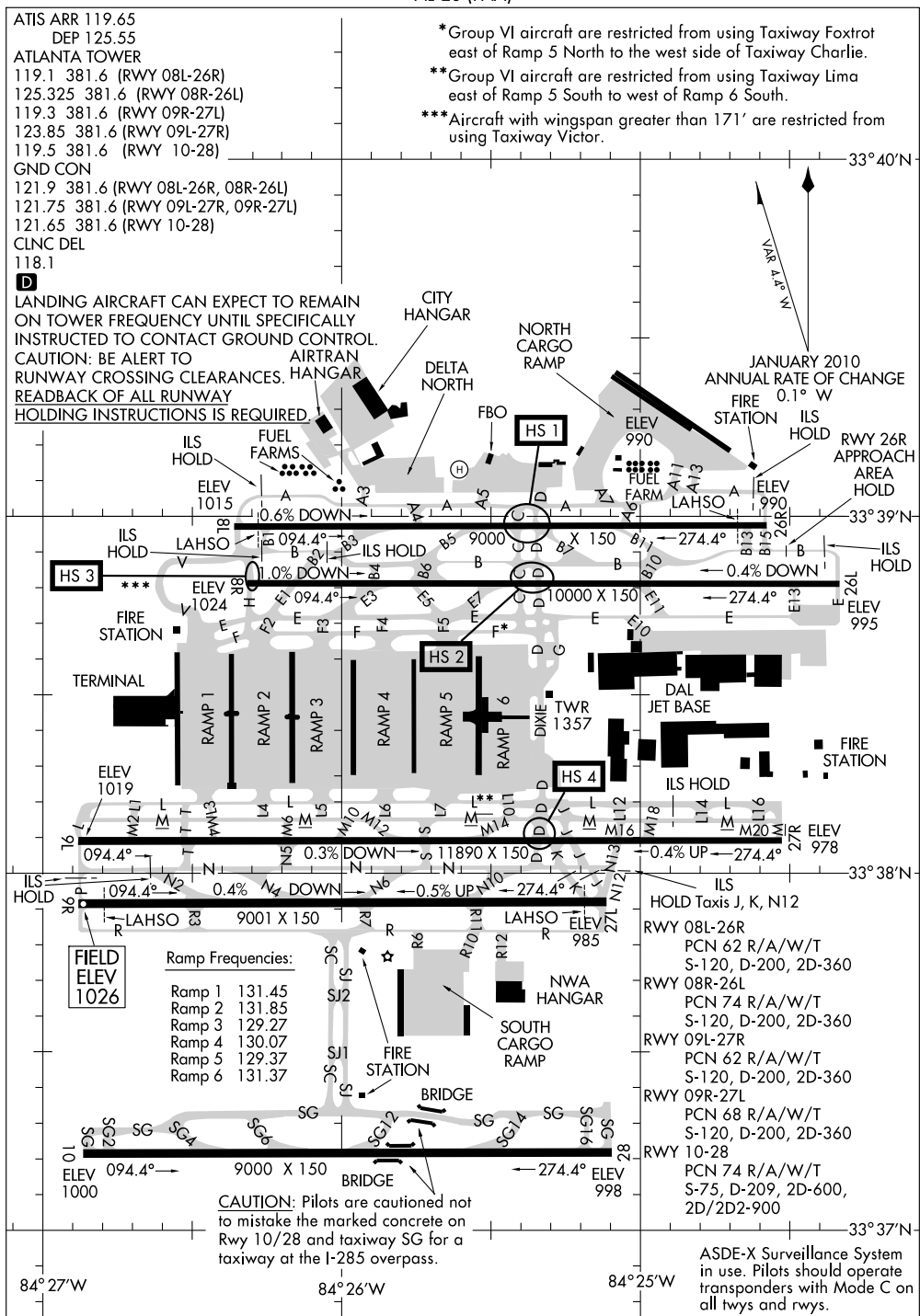
Figure 13: Runway Diagram of Hartsfield-Jackson Atlanta International Airport. [10]
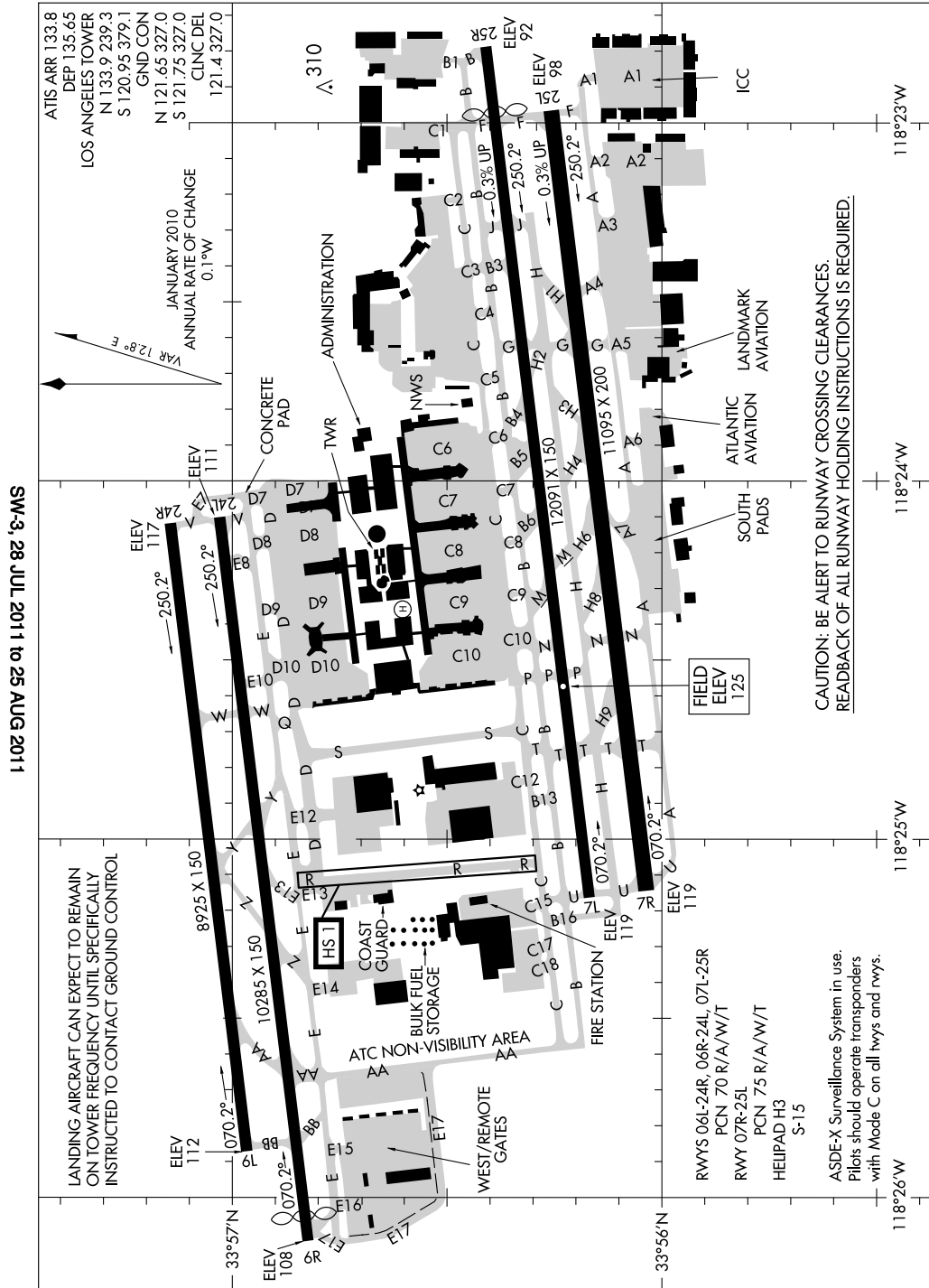
Figure 14: Runway Diagram of Los Angeles International Airport. [10]

CHAPTER VIII

FUTURE WORK AND CONCLUSION

8.1 Future Work

While this thesis has laid out the basic concept of operations for the departure regulator and has demonstrated capacity gains, future work is required to further develop the concept of operations, to ensure safe operations with the regulator, and to validate the capacity gains.

A basic concept of operations was developed in Section 4. For further development of the regulator, the concept of operations must be expanded upon to create a detailed order of operations for all types of semi-automated and automated clearances. A detailed understanding of the flow of information, aircraft, and communications is needed to be able to effectively evaluate the safety considerations associated with the departure regulator.

In concert with a detailed concept of operations, a thorough safety analysis of the departure regulator must be conducted before proceeding with the development. This safety analysis must consider the effects of missed approaches upon the departure regulator. When considering missed approaches, future work must investigate the ability of aircraft executing a go-around to fly a diverging heading and safely maintain separation in inclement weather. A trade study must be conducted to weigh the benefits of increased capacity with increased decision heights against the disadvantages of departures having higher speeds if a missed approach does occur below the decision height. Another safety consideration that must be examined in future work is the effect of distributing between the controller and the regulator the responsibility of detecting and accounting for runway incursions. Finally, consideration must be given

to the lay out of visual clearance lights to ensure that no confusion arises with other runway lights.

To better understand the effects of the departure regulator on capacity, a more accurate model of controller and pilot response times is required. These response times are important as they affect the effectiveness of the regulator and influence the safety considerations.

8.2 Conclusion

The initial results of the simulation have demonstrated the potential for large capacity gains through the use of the proposed departure regulator. The simulation model was designed to mimic current and proposed FAA regulations. Automated clearances using runway lights offers the greatest potential for gains in capacity, but this method departs the most from the current operating paradigm. Introduction of a decision support tool that cues the controller offers significant, albeit smaller, gains and has the added benefit that it fits well with the way runways are currently managed. The decision height plays a significant role in the capacity gains of the regulator, but even with low decision heights, significant gains in capacity are available. These gains are also present with a range of fleet mixes and runway offsets.

The large capacity gains with the regulator are due to the fact that the regulator allows a departure to takeoff in a smaller gap between arrivals. Thus, there are more gaps in an arrival stream allowing a departure to takeoff. The regulator creates the situation where the maximum departure rate possible increases with increased arrival rate, when the arrival and departure rates become approximately one-to-one. This gain in departure rate occurs near the peak arrival rate allowing for increases in capacity even under heavy demand.

APPENDIX A

SAMPLE INPUT FILE

Below in Listing A.1, a sample input file is shown. This input file is a working input file for Newark airport (EWR). As seen here, two runways are defined by their start and end latitudes and longitudes. Information about the final approach to a runway can also be set by the user. Each runway is assigned to arrivals, departures, or a mix of both. The total number of arrivals for each runway is also defined. The input file includes a flags to indicate if the departure regulator should be used and if the regulator should use controller, automated voice, or visual clearances. The user is also able to define what the fleet mix for the given airport.

```
 1   ##################################################################
 2   #
 3   #                        RunwaySim  Input  File
 4   #
 5   ##################################################################
 6
 7   airportName = Sample
 8
 9   ##################################################################
10   # Runways  Setup
11   ##################################################################
12
13   originLatLon = 40.692500,  −74.168667 # Degrees  Latitude ,  Longitude
14
15   numberOfRunways = 2
16
17   runwayName1   = 4L
```

```
18    runwayStart1 = 40.675381, -74.179450 # Degrees Latitude, Longitude
19    runwayEnd1   = 40.702558, -74.162175 # Degrees Latitude, Longitude
20    runwayUse1   = Departures             # Arrivals, Departures, or Dual
21    divergentHeadingFlag = true
22
23    runwayName2  = 4R
24    runwayStart2 = 40.677583, -74.174244 # Degrees Latitude, Longitude
25    runwayEnd2   = 40.702289, -74.158536 # Degrees Latitude, Longitude
26    runwayUse2   = Arrivals               # Arrivals, Departures, or Dual
27    glideSlope2  = 3                      # degrees
28    decisionHeight2 = 100                 # feet
29    finalApproachLength2 = 10             # nautical miles
30
31    ##############################################################################
32    # Simulation Variables
33    ##############################################################################
34
35    numberOfArrivals = 2000      # Number of Arrivals per Runway
36    numberOfRuns     = 20
37
38    useRunwayRegulator    = true     # Flag to turn the regulator on
39
40    clearanceForm = Controller    # Visual, Voice, Controller
41
42    ##############################################################################
43    # Fleet Mix Setup
44    ##############################################################################
45
46    fleetMixSource        = userDefined
47
48    smallPercent          =  5.0    # %
49    largePercent          = 85.0    # %
```

```
50   B757Percent           =   5.0     # %
51   heavyPercent          =   5.0     # %
```

Listing A.1: Sample Input File.

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