AD-A140 710 EVALUATION OF STRATEGIES TO ENHANCE DEPARTURE SEQUENCING(U) ARINC RESEARCH CORP ANNAPOLIS MD D TILLOTSON ET AL. MAR 84 1378-11-9-3244 1/1

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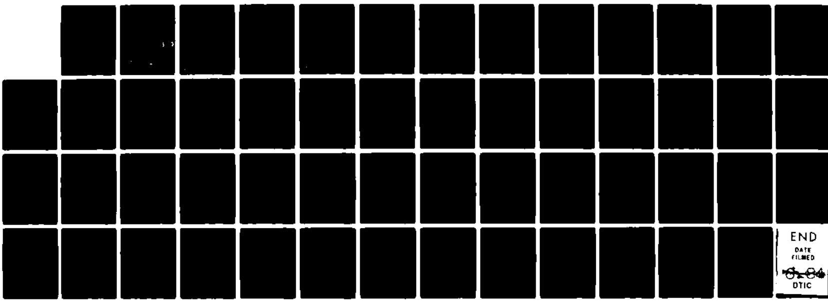

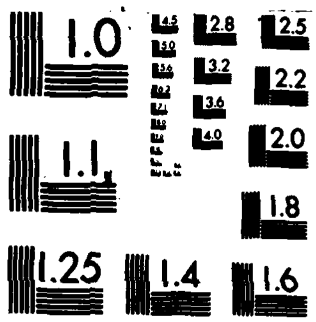

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U.S. Department of Transportation
Federal Aviation Administration
Systems Studies Program
Washington, D.C. 20591

Evaluation of Strategies To Enhance Departure Sequencing

D. Tillotson
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March 1984

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

EVALUATION OF STRATEGIES TO ENHANCE DEPARTURE SEQUENCING

5. Report Date

March 1984

6. Performing Organization Code

7. Author(s)

D. Tillotson, K. Markin

8. Performing Organization Report No.

1378-11-9-3244

9. Performing Organization Name and Address

ARINC Research Corporation
2551 Riva Road
Annapolis, Maryland 21401

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

DTFA01-80-C-10030

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Federal Aviation Administration
Systems Studies Program
Washington, D.C. 20591

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report assesses a departure enhancement strategy that will reduce the delays caused by the departure sequence of a series of aircraft. Data were collected at three airports to characterize the existing delays caused by the "first-come, first-served" departure sequencing strategy. The data were then used to define a simple alternative departure sequencing strategy. The alternative strategy was evaluated to determine the benefits available from departure resequencing. The evaluations indicated that possible reductions in fuel usage and possible increases in airport capacity could be achieved. However, the estimated benefits are not of sufficient magnitude to recommend implementation of the proposed strategy.

17. Key Words

Airport Capacity, Flow Control, Traffic Management System, Departure Resequencing

18. Distribution Statement

Unlimited

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	53	

ACKNOWLEDGMENT

The Federal Aviation Administration's Systems Engineering Service provided the overall guidance for this study. The data used in the preparation of this report were collected with the cooperation of the FAA's Air Traffic Services. Particular acknowledgment and appreciation are extended to the air traffic controllers and supervisors at the Baltimore-Washington International tower, the Las Vegas McCarran International tower, the Philadelphia International tower, and the Phoenix Sky Harbor International tower for their valuable contributions and assistance.

SUMMARY

This report documents the work performed by ARINC Research Corporation under contract to the Federal Aviation Administration to determine if implementable operational guidelines could be developed that would significantly enhance the efficiency of current Air Traffic Control (ATC) system departures. The purpose of this study was to develop strategies for resequencing departing aircraft to reduce inherent departure delays caused by the departure sequence. A strategy was developed after collecting data at three airports related to the responses of pilots to air traffic controllers' instructions, the takeoff performance of each aircraft category, and the delays caused by the departure sequence of pairs of aircraft. The conclusions reached in this report are based on the data collected at the three airports.

The data collected were reduced and reviewed for each individual airport. The individual data sets were then combined to form a data set that was used in subsequent analyses. From the combined data, a sample model was developed for resequencing a departure queue. The proposed resequencing model is simple and does not require the use of a microcomputer, programmable calculator, or handbook. This minimizes the effect of resequencing on the controller's workload. The model is defined by the five rules listed below:

1. Two or more aircraft of the same category should be grouped together and depart sequentially.

2. Faster aircraft should depart before slower aircraft, but this does not apply to the heavy turbojet aircraft such as the Boeing 747, the DC10, and the Lockheed L1011.

3. When a heavy aircraft is one of the aircraft in a departure queue, it should depart after the other aircraft.

4. A resequencing operation should not result in any aircraft being displaced more than three departure slots.

5. An aircraft should be moved no more than once.

The model was analyzed to determine the benefits associated with using the five rules to resequence a departure queue. The analysis indicated that the time required to launch a series of four aircraft could be reduced by resequencing. However, the magnitude of this time savings may be reduced when the departure queue is larger than four aircraft because the resequencing of the first group may delay the departure of the second group. The time savings possible improves the efficiency of a given runway and provides a small increase in airport capacity. The magnitude of the benefits that can be achieved by implementing this resequencing strategy are marginal when departure resequencing is the sole means of improving departure efficiency. The benefits may become larger when resequencing is combined with departure metering.

The analyses performed during this study indicate that there are benefits from the resequencing of departing aircraft. However, the estimated benefits associated with departure resequencing are not sufficient to recommend either widespread implementation of the proposed strategy, or the formal modification of the first-come, first-served philosophy through a change to the air traffic control handbook.

CONTENTS

CONTENTS (continued)

LIST OF TABLES

CONTENTS (continued)

LIST OF TABLES (continued)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The continuing growth of commercial and general aviation aircraft operations has increased the level of traffic congestion throughout the National Airspace System (NAS). The resulting increases in traffic delays coupled with rising fuel costs place operational and economic burdens on the Air Traffic Control (ATC) system and the NAS users. In response, the Federal Aviation Administration (FAA) has created the Traffic Management System (TMS) Program to establish a flow management concept that will provide an efficient and coordinated flow of aircraft throughout the ATC system and minimize user delays.

A second objective of the TMS Program is to improve the efficiency of the ATC system and thus increase its capacity. One area in which the TMS program addresses improved system efficiency is traffic management within the terminal area. The management of departure traffic must be addressed before a terminal area traffic management system can be defined. This study addresses the operational problem associated with delays related to the sequence of departing traffic.

Delays in departure traffic are related to airport departure capacity, departure separation requirements, and the mix of various aircraft categories within the departure sequence. The departure sequence is a function of either the order in which the aircraft reach the departure runway or report being ready for departure. Each aircraft in the departure sequence is separated from the preceding departure by either a specified time or specified distance. The magnitude of the separation is dependent on the category of both aircraft, the departure routing, and the meterological conditions at the airport. The sequence of some departures could be altered to reduce the amount of separation required and thereby improve the departure flow efficiency.

The FAA has contracted with ARINC Research to characterize the relationship between departure delays and the sequence of departing aircraft and to identify a departure sequencing enhancement strategy that will minimize the departure delays due to the sequence of departing aircraft.

1.2 PURPOSE

The purpose of this study is to determine if implementable operational guidelines can be developed that will significantly enhance the departure efficiency of the ATC system beyond the current practice of first come, first served. The study will also quantify any changes in fuel usage and delay times associated with the proposed enhancements to departure strategy.

1.3 SCOPE

This study assesses the departure delays resulting from the existing departure strategy of first come, first served. The delays resulting from the departure sequence are assessed by departure pairs, according to the category of each aircraft. After reviewing the delays generated by the existing strategy, a departure enhancement strategy is recommended that will reduce this type of departure delay. The savings of time and fuel resulting from reduced delays are quantified.

1.4 TECHNICAL APPROACH

Departure traffic data were collected at three different airports to quantify the delays resulting from the sequence of departing aircraft. Data were collected during peak departure times to ensure that data were available on delays caused by aircraft of various categories waiting to depart after aircraft of the same and different categories. The data were evaluated to characterize the relationship between departure delays and a particular sequence of departing aircraft. The data also provided a data base on the response of pilots to a controller's instruction, the takeoff performance of each category of aircraft, and the effects of airport layout on departure delays. From the relationship between aircraft categories and departure delays, a departure sequence enhancement strategy was identified. The data base on aircraft performance and pilot response was used by a computer simulation to provide information on overall time savings and changes in fuel usage for each aircraft when the alternative strategy is used. The computer simulation verified the improvement in overall delay times and the changes in fuel usage and led to a recommendation to implement the new strategy at selected airports for further evaluation.

1.5 REPORT ORGANIZATION

Chapter Two defines the terms used in this report and discusses the assumptions made during the collection and analysis of the departure data.

Chapter Three details the objectives of the data collection and describes the procedures used. It also discusses the criteria used in the selection of the three airports where data were collected.

Chapter Four presents the techniques used to reduce the collected data. It also discusses the combination of data from the three airports into a single data set.

Chapter Five describes an alternative departure-sequencing strategy and the constraints associated with that strategy.

Chapter Six reviews the techniques used to assess the effectiveness of the alternative departure-sequencing strategy, and Chapter Seven presents the conclusions and recommendations.

The appendix lists the references used in the preparation of this report.

CHAPTER TWO

DEFINITIONS AND ASSUMPTIONS

2.1 DEFINITIONS

The following definitions explain operational and air traffic control terms used in this report. The Air Traffic Controller's Handbook (Reference 1) was the source of definitions of those items related to ATC operations.

- Traffic Management System -- Traffic flow planning that is related to the volume of traffic, expected and unexpected constraints, contingency plans, system efficiency, and stability under current and predicted operating conditions.

- Departure Sequence -- The order in which a series of two or more aircraft depart from a given runway. The present air traffic control system usually sequences departure traffic in a "first-come, first-served" order.

- Air Traffic Control System -- The part of the FAA responsible for the safe conduct of aircraft operations within the National Airspace System.

- Aircraft Category -- Four aircraft categories used by ATC controllers to determine separation minima between two departing or arriving aircraft. For the purposes of this study, an additional aircraft category (category IIIP) was included to accommodate the diverse performance characteristics of aircraft weighing between 12,500 pounds and 300,000 pounds.

  -- Category I aircraft are single-engine, propeller-driven aircraft.

  -- Category II aircraft are twin-engine aircraft with a maximum gross weight not over 12,500 pounds.

  -- Category IIIP aircraft are propeller-driven and turboprop-powered aircraft with a maximum gross weight between 12,501 and 300,000 pounds.

-- Category III aircraft are turbojet aircraft with maximum gross weights between 12,501 and 300,000 pounds.

-- Category IIIH aircraft are turbojet aircraft operating at gross weights in excess of 300,000 pounds.

- Air Carrier -- An aircraft operator holding a Certificate of Public Convenience and Necessity issued by the Civil Aeronautics Board to conduct scheduled services over specified routes and a limited amount of nonscheduled operations.

- Air Taxi -- An aircraft operator that (1) performs at least five round trips per week between two or more points and publishes flight schedules that specify the times, days of the week, and places between which such flights are performed; or (2) transports mail by air pursuant to a current contract with the U.S. Postal Service.

- Instrument Flight Rules (IFR) -- Rules governing the procedures for conducting instrument flight.

- Instrument Operation -- An aircraft operation in accordance with an IFR flight plan or an operation in which IFR separation between aircraft is provided by a terminal control facility or air route traffic control center.

- Visual Flight Rules (VFR) -- Rules that govern the procedures for conducting flight under visual conditions. The term "VFR" is also used in the United States to indicate weather conditions that are equal to or greater than minimum VFR requirements. It is also used by pilots and controllers to indicate a type of flight plan.

2.2 ASSUMPTIONS

The following sections detail the assumptions that determined the scope of the problem investigated by this study.

2.2.1 Data Collection from a Single Runway

The data collection process that will be described in Chapter Three was designed to evaluate departures from a single runway. A single runway was selected for two reasons. First, the operational guidelines had to be straight-forward enough to permit the controller to implement them spontaneously and without extreme analysis of the control problem or automation support. Second, most terminal departure processes can be reduced to a single-runway problem. For example, widely spaced independent parallel runways can be considered as two or more single runways. Narrowly spaced dependent runways can be considered as a variation on a single runway. Crossing runways are similar to two or more single runways with diverging departure courses. The consideration of aircraft interactions at the runway crossings or within the departure airspace is rarely a trivial exercise and would normally require extreme analysis and automation support to determine if a resequencing action would be beneficial.

Delays associated with operations from other runways, or caused by the departure routes of preceding aircraft, were noted and considered in the analysis in order to factor out their effect on the single runway. The consideration of the traffic flow of other nearby airports, airspace restrictions, departure control restrictions, en-route flow restriction, and Central Flow Control restrictions will be integral functions of other Traffic Management System (TMS) program development efforts.

2.2.2 Effect of Delays Generated Away from the Airport

Departure delays can be caused by en-route or terminal area weather; capacity limitations of en-route ATC facilities, destination airports, and terminal area ATC facilities; or runway closures due to weather or accidents at destination or departure airports. Departure delays of those types are not considered by the resequencing procedures described by this report.

2.2.3 Fuel Costs

Average fuel costs were used for this analysis. Air carriers generally buy fuel in large enough quantities to receive a discount from the retail price. Several airlines reported that $1.00 per gallon was a valid fuel cost for use in the analysis. That price was used for all Category III and Category IIIH aircraft. The Category IIIP, Category II, and Category I aircraft are used by both air-taxi and general aviation operators. The fuel price used for those categories was the February 1983 national average. The jet fuel (Category IIIP) price was $1.83 per gallon and the 100 octane (Categories I and II) price was $2.01 per gallon (reference 2).

2.2.4 Fuel Flow at Idle

Average fuel flow figures were used in determining the effectiveness of the alternative sequencing strategy. The fuel flow values at idle power or thrust used in the analysis were obtained from discussions with various aircraft owners and pilots. The value used for each category is shown below:

Category I	3 gallons per hour
Category II	6 gallons per hour
Category IIIP	7 gallons per hour
Category III	600 gallons per hour
Category IIIH	966 gallons per hour

CHAPTER THREE

DATA COLLECTION OBJECTIVES AND PROCEDURES

3.1 OBJECTIVES

The collection of data had two objectives:

- Develop a data base recording the time required for a pilot to respond to a controller's instructions and the takeoff performance of each aircraft category

- Characterize the departure delays resulting from an aircraft of a given category departing after an aircraft of any other category

The data required to satisfy the two objectives were collected by means of the procedures defined in the following sections.

3.2 DATA COLLECTION PROCEDURES

The data collection procedures were developed after considering the objectives of Section 3.1. The following sections describe the airport selection criteria, the data collection form, and the procedures used at the airports while collecting data.

3.2.1 Airport Selection Criteria

Each airport has unique characteristics that may affect the departure delays experienced by its users. The effects of these characteristics may contribute to the departure delays and must be evaluated and considered before developing a new departure-sequencing strategy. Because of this, it was necessary to identify several airports having different characteristics. The primary consideration was that the airport have one or more periods each day during which the amount of departure traffic resulted in an airport-generated departure delay. Further consideration was given to the mix of aircraft categories operating at the airport, the traffic volume at the airport, and the runway configuration of the airport. After visiting the Baltimore-Washington International (BWI) airport and observing little or no traffic congestion, it was decided to use the traffic activity at BWI as a lower limit. During fiscal year (FY) 1981, there were 203,000 primary instrument operations at BWI (Reference 3). (FY 1981 data were used because the FY 1982 air traffic activity data were not available when the selection was made.) To eliminate airports whose operations did not provide a good mix of aircraft categories, the following two limitations were set:

- The percentage of general aviation (GA) and air carrier primary instrument operations should be greater than 25 percent and less than 75 percent of the airport's total primary instrument operations.

- The percentage of all air taxi operations (VFR and IFR) should be greater than 10 percent.

The final criterion was that the airport should have three or less runways. That requirement eliminated airports that might reduce departure delays by segregating instrument operations from other operations.

Using the above criteria, the following three airports were selected:

- Philadelphia International Airport (PHL)

- Las Vegas McCarran International Airport (LAS)

- Phoenix Sky Harbor International Airport (PHX)

Those three airports provided a wide variety of traffic mixes and operating conditions, permitting the data collected to be used to define a "generic" airport that can be used to construct a resequencing model. That model can be applied to a large number of airports without having to tailor the model for each airport.

3.2.2 Data Collection Method

Because the study was interested only in the departure delays caused by a sequence of departing aircraft, a method was developed to allow the isolation of those delays from delays due to weather, ATC, or other facilities. A form was developed that allowed the recording of the aircraft type, the departure sequence, and the time that six discrete events occurred during the departure of each aircraft: (1) when the aircraft entered the departure queue, (2) when the aircraft was cleared onto the runway, (3) when the aircraft was aligned with the runway centerline, (4) when the aircraft was cleared for takeoff, (5) when the aircraft began the takeoff roll, and (6) when the aircraft lifted off the ground. The form also provided a means of recording events that affected the objectives of the data collection, such as an arrival preceding a departure or a departure from a second runway. The data were collected in the cab of each airport's air traffic control tower facility. A stopwatch was used to provide the required time information and the tower's local control frequency was monitored so we could hear the clearances issued to departing aircraft. The information recorded during the data collection visits is described in the following paragraphs. The data collection form is shown in Figure 3-1.

FIGURE 3-1
DATA COLLECTION FORM

Number	Aircraft Type	Time Entering Queue / Number of Aircraft in Queue	Cleared Onto Runway	Aligned with Centerline	Date: Airport: Runway: Cleared for Takeoff	Initial Local Time: Takeoff Roll	Liftoff	Time of Preceding Event	New Controller	Preceded by Event	Rolling Takeoff	Clearance Delay	Resequenced	Comments

The data were collected while each airport was operating under VFR conditions, although the operations consisted of both VFR and IFR operations. Because of the VFR conditions, the controller had some flexibility in applying the minimum separation requirements. The flexibility was implemented by turning the VFR traffic off the runway heading as soon as practical to allow the departure of the next aircraft. Another observed operation was the application of visual separation between two departing aircraft. When two aircraft are separated by visual standards, the pilot of the trailing aircraft is responsible for maintaining the separation. This clearance can be issued for both VFR and IFR operations. Both of the above procedures reduce departure delays, but airspace limitations at some airports prohibit early turns off the runway heading, and there are conditions under which a pilot may choose not to accept a clearance for maintaining visual separation. When either of those procedures cannot be implemented, both VFR and IFR departures are delayed until the required minimum separation distance is established.

The data were collected under visual separation conditions, when early turns were performed by both VFR and IFR traffic, and when neither of those two methods were used. Because of the mix of IFR and VFR operations and the use of visual separation and early turns for some operators, the data represent the wide range of normal operations at a busy airport. This range of data allows the definition of a resequencing model that is valid for a large number of airports.

The data were collected during observations of the operations at the selected airports to record the time that each of six events occurred. From the tower cab, it was possible to monitor the movement of all aircraft on the ground as they taxied to the runway and to monitor the instructions issued by the local controller. When the aircraft reached the departure runway the time was recorded. The second event to occur was a clearance by the local controller: the aircraft was either instructed to "taxi into position and hold" or was "cleared for takeoff." The time that the instruction was issued was recorded. When the instruction was "cleared for takeoff," the same time was recorded in the column reserved for the "taxi into position and hold" instruction. After receiving either of the above clearances, the aircraft was authorized to taxi onto the runway. While that was happening, it was necessary to monitor the time required for the pilot to taxi onto the runway and align his aircraft with the runway centerline. If the aircraft had not yet been cleared for takeoff, it would have remained "in position" until the traffic conditions permitted the "cleared for takeoff" clearance to be issued. The time of the "cleared for takeoff" clearance was recorded, as was the time at which the takeoff roll began. The final time recorded was the time at which the aircraft became airborne.

The length of a departure delay is also affected by other airport activities such as arrivals on any runway and departures from a second runway. When such an event occurred, the time of the departure or arrival was recorded to allow an assessment of how this increased the departure delay. (This increase was removed during the data reduction process.) For this same reason, any delays caused by en-route or destination airport considerations were also recorded.

3.2.3 Data Collection Sites

Using the criteria defined in Paragraph 3.2.1, PHL, LAS, and PHX were sel cted to provide a wide range of traffic mix and runway configurations. Each airport provided unique operating conditions and limitations to be evaluated. The following paragraphs describe the traffic mix and the unique aspects of each.

3.2.3.1 Philadelphia International

PHL has two parallel east/west (09/27) runways that serve as the primary runways for air carrier and air-taxi operations. There is a third runway (17/35) that is perpendicular to the two parallel runways and is used by most of the general aviation traffic and some air-taxi traffic. Because of the distance from the tower to the departure end of runway 17, it was difficult to observe all the movements of small aircraft. For that reason, no data were taken from that runway. The two parallel runways allow the departure traffic to be segregated from the arrival traffic. That improves the departure efficiency of the airport because there are no delays caused by arriving aircraft.

The traffic at PHL is made up primarily of air carrier and air-taxi operations. The data collected at PHL concentrated on the category II, IIIP, III, and IIIH aircraft. During FY 1981, there were 336,000 primary instrument operations at PHL. Of these, 35 percent were air carrier, 41 percent were air-taxi, and 24 percent were general aviation.

3.2.3.2 Las Vegas McCarran International

LAS has two parallel runways (01/19) that are used primarily for general aviation and air-taxi operations and a third runway (07/25) used for air carrier operations. Data were collected on both runway 25 and runway 19L. Runway 19R was used for approximately 95 percent of the general aviation and air-taxi arrivals. Because of that, the general aviation and air-taxi arrival traffic had no effect on the runway 19L departures. There were some departure delays for runway 25 operations as a result of arriving traffic.

Aircraft of all five categories operate at LAS, and data were collected on a wide variety of departure sequences. The runway 19L data related primarily to category I and II operations with an occasional category III operation. The runway 25 operations involved only category III and IIIH aircraft. There were 320,000 primary instrument operation at LAS during FY 1981. Of those, 40 percent were air carrier operations, 18 percent were air-taxi operations, and 42 percent were general aviation operations.

3.2.3.3 Phoenix Sky Harbor International

PHX has two parallel runways (08/26), both of which are used for arrivals and departures. The airport has only one taxiway between the runways, which prevents the segregation of arrivals and departures.

The aircraft operations consist of air carrier and general aviation operations on the north runway (08L/26R) and air carrier and air-taxi operations on the south runway. Because of the mixing of arrivals and departures, some additional departure delays are induced that must be accounted for when the data are evaluated.

The operations on runway 08L/26R provided data on the mixing of Category III aircraft with Category I and II aircraft. The runway 08R/26L data had a concentration of a mixture of Category III and IIIH aircraft with Category II and IIIP aircraft. PHX had 330,000 instrument operations during FY 1981. Thirty-three percent of those operations were air carrier operations, 28 percent were air-taxi, and 56 percent were general aviation operations. Military operations made up the remaining 8 percent.

CHAPTER FOUR

DATA REDUCTION TECHNIQUES AND RESULTS

4.1 DATA REDUCTION TECHNIQUE

The data obtained at the three airports were in the form of the time that six events occurred during an aircraft departure. The first step in the data reduction process was to convert the recorded event times into time differences by subtracting the time between two sequential departure events. For analysis purposes, six time differences were computed:

- Δt_0 is the time an aircraft remains in the departure queue. The value is calculated by subtracting the time the aircraft entered the departure queue from the time the aircraft is cleared to "taxi into position and hold."

- Δt_1 is the time required for the pilot to align his aircraft with the runway centerline after being cleared to "taxi into position and hold."

- Δt_2 is the time between the ATC clearances of "taxi into position and hold" and "cleared for takeoff."

- Δt_3 is the time required for the pilot to initiate the takeoff roll after receiving the "cleared for takeoff" clearance.

- Δt_4 is the duration of the takeoff roll. It is calculated from the approximate time of brake release to the time the main landing gear leaves the ground.

- Δt_5 is the time between the lift-off of one aircraft and the clearance of the succeeding aircraft to take off.

After the first five time differences were calculated for each aircraft and Δt_5 was calculated for the appropriate aircraft pairs, the values were separated into two groups. The two groups are discussed in the following paragraphs.

4.2 PILOT RESPONSE AND AIRCRAFT PERFORMANCE

Throughout the early stages of the data reduction, the individual data sets from each airport were kept separate. A data set contained time measurements for a single runway over a three- to five-hour time period. After computing values for Δt_0 through Δt_4 for each aircraft, each data set was segregated into five subsets corresponding to the five aircraft categories. Using statistical techniques, the mean value, the standard deviation, and the kurtosis were calculated for the distribution of each subset of time differences. The mean value for each subset provides an indication of pilot response to a controller's instructions as well as a measure of the takeoff performance of each category of aircraft. The standard deviation provides a measure of the dispersion of the data used in the mean value calculation, and the kurtosis provides a measure of the distribution type.

After calculating the statistical values of the five time differences for each data collection period, the data were analyzed to determine which data sets could be combined. The goal of the analysis was to calculate a single value for each time difference that could be used in evaluating the effectiveness of any alternative sequencing strategy.

The first step was to combine the individual data sets collected at each airport into a single data set for each airport. The second step was to assess how well each individual data set matched the combined data set. That was accomplished by comparing the statistical characteristics of each individual distribution with those of the combined distribution.

Combining the data yielded a data set that would be found at a generic airport. However, since any airport has unique operating conditions and limitations, it was necessary to compare the data from each of the three data collection airports to the data set for the generic airport. This comparison showed a close correlation between the mean values at each airport and the generic airport.

With the exception of the Category III and IIIH aircraft, the distributions for Δt_1, and Δt_4 were closely correlated between the generic airport and each data collection airport. The discrepancy for the category III aircraft is attributed to the variations in aircraft weight and meteorological conditions at the three airports. Variations in these conditions cause changes in aircraft takeoff performance. Another factor that may have caused the variation between the distributions is that different air carriers have different ground operating procedures. Pilots may also differ in such matters as taxi speed. The lack of correlation for Category IIIH aircraft is attributed to the small amount of data for those aircraft at the three airports.

There is also little correlation between the distributions of Δt_3 at the generic airport and the data collection airports. Since this was true for all aircraft categories, the difference is attributed to variation in pilot behavior. When an aircraft is cleared for takeoff, each pilot responds differently. While some are ready to begin the takeoff roll immediately, others may delay the completion of some check list items until the clearance is received. The data collection method may have also contributed to the variations in distribution -- no discrete point was specified as the initiation of the takeoff roll. The value recorded for the initiation of the takeoff roll was based on observing movement of the aircraft along the runway centerline. When the takeoff roll was begun without holding in position, the recorded time could have been in error.

When the statistical characteristics of the three airports were compared to the combined statistical characteristics, some differences were noted in the data distributions. However, the mean values for Δt_1, Δt_3, and Δt_4 at each airport closely approximated the mean values for the generic airport. Because of this, it was concluded that the mean values of Δt_1, Δt_3, and Δt_4 calculated for the generic airport could be used in defining a resequencing model that could be applied at numerous airports.

The mean values, standard deviations, and kurtosis for the generic airport are shown in Table 4-1 and the values for the three airports are shown in Tables 4-2, 4-3, and 4-4.

4.3 Aircraft Separation

The second group of data measured was the observed separation beween two successive departures. A single time difference, Δt_5, was calculated for each departure pair. Since the objective of the study was to evaluate only those delays caused by the sequence of departing aircraft, it was necessary to review the values of Δt_5 and eliminate those that would incorrectly influence the results of the study The eliminated data were those resulting from a landing between the twc departures on the same or intersecting runway, a departure from another runway, an ATC clearance delay, or other aircraft movements on the ground. One or more of those conditions were observed at each of the three airports and as a result the number of valid Δt_5 data points was reduced.

The same method described in Section 4.2 was used in combining the values of Δt_5. However, the correlation between the distributions of the combined values and the distributions of the individual data sets is less than that shown for the pilot response and aircraft performance data. This can be attributed to the smaller sample size (see Table 4-5) of certain category pairs. The mean value, standard deviation, and kurtosis for the combined data set are shown in Table 4-6. Those values can be compared to the same values for each individual airport shown in Table 4-7 through Table 4-9. Since it was known that no individual airport would exactly correlate to a generic model, the differences between the combined distribution and each individual airport distribution were analyzed to determine the cause of the differences. In all cases, the differences between the distribution of the combined data and the distribution of each airport could be attributed to the influence of limited data points at one or more airports on the combined distribution. While there was a difference in the data distributions at each airport, the mean value of Δt_5 at each airport closely approximates the mean value calculated from the combined data from all three airports. Since the mean values were approximately the same, it was decided that the total mean values could be used in defining an alternative sequencing strategy and evaluating the effectiveness of any such strategy.

Table 4-6 shows that statistical values for Δt_5 were not computed for seven of the 25 departure category pairs defined for this study. The seven pairs were II-IIIP, II-IIIH, IIIP-I, IIIP-IIIH, IIIH-I, IIIH-II, and IIIH-IIIH. Each of these seven category pairs was evaluated to determine if a mean value could be assigned to allow the completion of the analysis. Five of the missing values were assigned by use of the data available for other pairs. The remaining two values were assigned by using the rules defined in reference 1.

a. II-IIIP - After reducing the valid Δt_5 data, there were no data available on this departure sequence. There were limited data available for the I-IIIP pair. Since the initial climb speed of an average Category I aircraft is only slightly slower than that for a Category II aircraft, the 17.67 second mean value for a I-IIIP pair provides a conservative approximation for the II-IIIP pair.

b. II-IIIH, IIIP-IIIH, and IIIH-IIIH - A Category IIIH aircraft will operate at approximately the same initial climb speeds as the Category III aircraft. For this reason, the mean values for II-III, IIIP-III, and IIIH-III pairs were used.

c. IIIP-I - All Category IIIP aircraft will have an initial climb speed that is much faster than that of the Category I aircraft. While a Category I aircraft is somewhat slower than a Category II aircraft, the value of a IIIP-II pair was used.

d. IIIH-I and IIIH-II - No data were available on either a Category I or Category II aircraft departing after a Category IIIH (heavy) aircraft. The air traffic controller's handbook requires two minutes of separation between a heavy jet departure and a succeeding departure to minimize the effects of wake turbulence. Although a pilot may waive this requirement, the two-minute separation is valid for this analysis.

TABLE 4-1

VALUES FOR MEAN TIME, STANDARD DEVIATION, AND KURTOSIS FOR GENERIC AIRPORT

Category	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I				173
Δt_1	26.49	8.96	3.13	
Δt_3	10.13	7.00	5.79	
Δt_4	21.11	6.09	3.21	
II				227
Δt_1	28.93	9.96	2.92	
Δt_3	9.28	6.56	5.89	
Δt_4	26.95	6.50	2.82	
IIIP				41
Δt_1	39.48	13.33	3.87	
Δt_3	9.47	6.11	3.93	
Δt_4	26.78	7.56	3.03	
III				480
Δt_1	47.10	15.74	3.21	
Δt_3	13.18	8.77	6.80	
Δt_4	37.15	6.75	3.30	
IIIH				39
Δt_1	55.70	18.51	3.07	
Δt_3	14.34	9.86	7.79	
Δt_4	35.52	5.82	2.26	

TABLE 4-2

VALUES FOR MEAN TIME, STANDARD DEVIATION, AND KURTOSIS FOR PHILADELPHIA INTERNATIONAL AIRPORT

Category	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
II				28
Δt_1	30.85	13.10	1.95	
Δt_3	7.00	5.49	2.60	
Δt_4	23.58	7.62	2.56	
IIIP				41
Δt_1	38.28	13.80	3.97	
Δt_3	8.44	6.21	4.24	
Δt_4	26.54	6.26	2.37	
III				96
Δt_1	46.75	16.44	2.58	
Δt_3	11.37	8.60	11.37	
Δt_4	35.19	5.14	2.77	
IIIH				27
Δt_1	55.23	16.21	2.76	
Δt_3	11.70	6.80	8.29	
Δt_4	34.33	5.47	1.85	

TABLE 4-3

VALUES FOR MEAN TIME, STANDARD DEVIATION, AND KURTOSIS FOR LAS VEGAS McCARRAN INTERNATIONAL AIRPORT

Category	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I				70
Δt_1	28.16	8.70	3.01	
Δt_3	8.74	6.74	7.12	
Δt_4	23.80	5.90	3.70	
II				128
Δt_1	28.42	8.21	[illegible].57	
Δt_3	9.91	6.63	4.82	
Δt_4	28.32	5.73	3.48	
III				203
Δt_1	47.68	16.16	4.28	
Δt_3	13.93	8.18	4.46	
Δt_4	38.59	7.22	2.93	
IIIH				3
Δt_1	72.00	13.14	1.50	
Δt_3	30.50	14.38	1.80	
Δt_4	40.40	2.24	3.06	

TABLE 4-4

VALUES FOR MEAN TIME, STANDARD DEVIATION, AND KURTOSIS FOR PHOENIX SKY HARBOR INTERNATIONAL AIRPORT

Category	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I				103
Δt_1	25.37	9.16	3.32	
Δt_3	10.38	8.01	6.16	
Δt_4	19.18	5.54	2.89	
II				71
Δt_1	29.31	11.24	2.95	
Δt_3	9.14	6.59	8.59	
Δt_4	22.60	7.76	2.97	
III				181
Δt_1	46.85	14.22	3.88	
Δt_3	13.91	9.19	6.40	
Δt_4	36.99	6.69	3.60	
IIIH				9
Δt_1	31.50	26.58	1.89	
Δt_3	15.29	7.36	3.95	
Δt_4	37.40	5.75	3.14	

TABLE 4-5

DATA COLLECTION SAMPLE SIZE

Departure Pair (By Category)	Total Sample Size
I-I	31
I-II	17
I-IIIP	3
I-III	6
I-IIIH	2
II-I	16
II-II	36
II-IIIP	--
II-III	17
II-IIIH	--
IIIP-I	1
IIIP-II	3
IIIP-IIIP	6
IIIP-III	9
IIIP-IIIH	--
III-I	14
III-II	20
III-IIIP	15
III-III	95
III-IIIH	9
IIIH-I	1
IIIH-II	1
IIIH-IIIP	5
IIIH-III	10
IIIH-IIIH	1

TABLE 4-6

STATISTICAL VALUES FOR SEPARATION TIMES, GENERIC AIRPORT

Category Pair	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I-I	6.75	11.92	2.65	27
I-II	26.53	15.74	1.96	16
I-IIIP	17.67	7.93	1.50	3
I-III	58.80	30.79	2.85	6
I-IIIH	24.00	14.00	1.00	2
II-I	6.87	11.30	3.34	4
II-II	8.28	9.92	3.46	35
II-IIIP	--	--	--	--
II-III	25.64	8.14	2.59	9
II-IIIH	--	--	--	--
IIIP-I	--	--	--	--
IIIP-II	21.00	5.35	1.50	3
IIIP-IIIP	25.50	11.79	2.06	6
IIIP-III	42.43	14.16	2.15	7
IIIP-IIIH	--	--	--	--
III-I	-10.46	12.70	2.00	14
III-II	6.75	10.98	2.77	20
III-IIIP	3.67	14.08	4.28	15
III-III	7.35	14.49	2.36	96
III-IIIH	20.67	17.59	1.80	10
IIIH-I	--	--	--	--
IIIH-II	--	--	--	--
IIIH-IIIP	75.80	15.32	2.67	5
IIIH-III	90.30	19.31	1.88	10
IIIH-IIIH	--	--	--	--

TABLE 4-7

STATISTICAL VALUES FOR SEPARATION TIMES, PHILADELPHIA INTERNATIONAL AIRPORT

Category Pair	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I-I	--	--	--	--
I-II	--	--	--	--
I-IIIP	--	--	--	--
I-III	--	--	--	--
I-IIIH	--	--	--	--
II-I	--	--	--	--
II-II	--	--	--	--
II-IIIP	--	--	--	--
II-III	--	--	--	--
II-IIIH	--	--	--	--
IIIP-I	--	--	--	--
IIIP-II	21.50	6.50	1.00	3
IIIP-IIIP	25.50	11.79	2.06	6
IIIP-III	48.40	11.79	1.91	5
IIIP-IIIH	--	--	--	--
III-I	--	--	--	--
III-II	3.75	8.84	3.06	8
III-IIIP	6.46	11.74	7.31	13
III-III	15.80	12.79	2.56	20
III-IIIH	28.14	15.15	2.29	7
IIIH-I	--	--	--	--
IIIH-II	--	--	--	--
IIIH-IIIP	75.80	15.32	2.67	5
IIIH-III	89.17	17.47	1.96	6
IIIH-IIIH	--	--	--	--

TABLE 4-8

STATISTICAL VALUES FOR SEPARATION TIMES, LAS VEGAS McCARRAN INTERNATIONAL AIRPORT

Category Pair	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I-I	8.25	8.23	2.50	8
I-II	23.22	15.82	1.94	9
I-IIIP	--	--	--	--
I-III	--	--	--	--
I-IIIH	--	--	--	--
II-I	--	--	--	--
II-II	8.48	10.14	3.83	26
II-IIIP	--	--	--	--
II-III	--	--	--	--
II-IIIH	--	--	--	--
IIIP-I	--	--	--	--
IIIP-II	--	--	--	--
IIIP-IIIP	--	--	--	--
IIIP-III	--	--	--	--
IIIP-IIIH	--	--	--	--
III-I	--	--	--	--
III-II	--	--	--	--
III-IIIP	--	--	--	--
III-III	7.05	13.77	2.51	38
III-IIIH	--	--	--	--
IIIH-I	--	--	--	--
IIIH-II	--	--	--	--
IIIH-IIIP	--	--	--	--
IIIH-III	--	--	--	--
IIIH-IIIH	--	--	--	--

TABLE 4-9

STATISTICAL VALUES FOR SEPARATION TIMES, PHOENIX SKY HARBOR INTERNATIONAL AIRPORT

Category Pair	Mean (Seconds)	Standard Deviation (Seconds)	Kurtosis	Sample Size
I-I	4.16	11.50	2.41	19
I-II	31.00	13.23	1.59	7
I-IIIP	--	--	--	--
I-III	60.25	34.27	2.16	4
I-IIIH	--	--	--	--
II-I	5.75	3.35	2.29	4
II-II	8.56	8.90	2.34	9
II-IIIP	--	--	--	--
II-III	23.00	8.11	2.48	9
II-IIIH	--	--	--	--
IIIP-I	--	--	--	--
IIIP-II	--	--	--	--
IIIP-IIIP	--	--	--	--
IIIP-III	--	--	--	--
IIIP-IIIH	--	--	--	--
III-I	-5.90	11.43	1.54	10
III-II	9.60	12.57	2.17	10
III-IIIP	--	--	--	--
III-III	3.71	14.45	2.68	38
III-IIIH	--	--	--	--
IIIH-I	--	--	--	--
IIIH-II	--	--	--	--
IIIH-IIIP	--	--	--	--
IIIH-III	--	--	--	--
IIIH-IIIH	--	--	--	--

CHAPTER FIVE

DEFINITION OF ALTERNATIVE DEPARTURE-SEQUENCING STRATEGY

5.1 EXISTING ONE-RUNWAY SEQUENCING STRATEGY

With a few exceptions, the departure sequence from any runway is determined by the order in which the departing aircraft arrive at the runway. The exceptions to this method usually result from an ATC need to allow the departure of a certain aircraft during a fixed time window. This fixed window is dictated by en-route or destination airport traffic conditions or ATC-imposed flow restrictions. During the data collection visits, this type of resequencing was observed on numerous occasions.

Resequencing was also observed when an aircraft in the departure queue was ready for departure before the first aircraft in the departure queue. When this occurred and there was enough room available on the taxiway, the aircraft were generally resequenced.

A third form of resequencing occurred when the ground controller was able to adjust the departure sequence to enhance operational efficiency. This was observed when the resequencing could be accomplished as an integral, unbiased part of ground flow management. This third form of resequencing would appear to have potential efficiency and airport capacity benefits through an increased, but bounded, ATC authority for resequencing departure aircraft.

5.2 GUIDELINES FOR ALTERNATE STRATEGY

Any new sequence-enhancement strategy will benefit some users and have the opposite effect on others. Because of these potential effects, it was necessary to define guidelines that will limit the negative effects. The guidelines used in developing the alternative sequencing strategy are described in the following paragraphs.

5.2.1 Required Time Savings

The data collected shows that the total time required to launch all the aircraft in some departure queues can be reduced by resequencing the order of departure. This time savings improves the rate of departures and may increase the airport capacity. However, it is possible that the time saved by resequencing a departure queue may be cancelled by the time required to perform the resequencing, especially if the resequencing is done by the local controller.

For example, consider a four-plane departure queue and assume that the optimum departure sequence requires that the third aircraft in the queue depart first. To accomplish this, the third aircraft must taxi past two other aircraft and then taxi into position. Table 4-1 showed that a Category IIIH aircraft requires an average of 56 seconds to taxi into position after being cleared to do so by the controller. That value represents the time required for a Category IIIH aircraft to taxi into position when the aircraft is the first aircraft in the departure queue. Using this observed worst-case value, a minimum time savings required for resequencing was derived.

The worst-case average value of Δt_1 (see Section 4.2) was used as the starting point. Additional time must be added for an aircraft maneuvering past one or more aircraft to reach the first slot in the departure queue. No data were taken on the time required to complete this maneuvering, so the additional time required was estimated to be 15 seconds. Therefore, the minimum total time savings needed to benefit from resequencing a departure queue is 72 seconds. This value was used only while assessing the validity of the departure-enhancement strategy and was not defined as a rule in the resequencing model.

5.2.2 Allowable Induced Departure Delays

When aircraft are resequenced, one or more aircraft must be delayed. Depending on the type of aircraft in the queue, the delay may range from less than 20 seconds to more than 200 seconds for an individual aircraft. This delay must be recognized and limited to ensure that no single user is unduly penalized by the resequencing. Using the data described in Chapter Six, it was decided that any resequenced aircraft must not be displaced more than three departure slots during the resequencing.

5.2.3 Controller Workload

The most crucial constraint in defining a departure-enhancement strategy is its effect on the air traffic controller's workload. The desire was to define a strategy that would provide additional flexibility to a controller without dramatically increasing his workload. For this reason, the defined strategy must be simple enough to be implemented without requiring a controller to consult a handbook or operate a mathematical model on a microcomputer or programmable calculator. Because of this, the departure-enhancement strategy was defined as a set of general guidelines available to the controllers for application either spontaneously, ad hoc in some combinations, or not at all as the tactical traffic situation warrants.

5.3 DEPARTURE-ENHANCEMENT STRATEGY

5.3.1 Rules for Departure-Enhancement Strategy

The controller workload constraint discussed in Paragraph 5.2.3 was the major consideration in defining an alternate strategy. After analyzing the data presented in Sections 4.1.1 and 4.1.2, the following rules were formulated for use in resequencing a departure queue:

1. When a departure queue contains two or more aircraft of the same category, they should be grouped together and depart sequentially.

2. With the exception of a Category IIIH aircraft, a faster aircraft should depart before a slower aircraft.

3. When any category of aircraft is following a Category IIIH aircraft, the total time required to launch both aircraft can be reduced by allowing Category I, II, IIIP, or III aircraft to depart before the Category IIIH aircraft.

4. A resequencing operation should not result in any aircraft being displaced more than three departure slots. Since there is no way to generalize the time involved in resequencing a series of aircraft, a controller will have to evaluate the time that can be saved by resequencing on the basis of the controller's knowledge of the aircraft and the operators involved.

5. An aircraft should be moved no more than once. For the purposes of this rule, an aircraft is considered to have been moved whenever any aircraft in a queue of four (or less) aircraft has been resequenced.

These are general guidelines and there are some aircraft combinations for which these rules may not produce the optimum departure sequence. Chapter Six discusses several examples that illustrate the benefits associated with resequencing.

The rules discussed above should provide a minimum time to launch a sequence of departing aircraft and, in turn, help improve the flow of traffic in the terminal area. However, rule 3 may result in a significant fuel burn penalty for a heavy aircraft if it is preceded by three departures (after resequencing) when it would have been the first aircraft to depart. The approximate fuel burn penalty is quantified in Chapter Six, but a detailed analysis of fuel penalties is outside the scope of this study.

5.3.2 Resequencing Implementation Criteria

Before a controller can implement any resequencing strategy, an assessment should be made to determine if there are any benefits available from resequencing. From a controller's point of view, the largest benefit is a reduction in the time to launch a departure queue, while a user is most concerned with the costs savings or losses resulting from resequencing. Because the controller will be implementing any proposed resequencing strategy, broad guidelines were developed to provide guidance on when resequencing will benefit the departure flow.

Resequencing can be implemented when there are two or more aircraft in the departure queue. As the number of aircraft in the queue increases, the queue should be divided into a series of smaller queues that may contain up to four aircraft. (A four-aircraft queue is used as a result of rule 4 in Section 5.3.1). Each smaller queue is then resequenced independently of other smaller queues. Since the number of aircraft in any departure queue (not yet divided into smaller queues) is changing, the controller must decide at which point he wants to start dividing the queue into the smaller queues. Once the controller decides where the initial division is to occur, rule 5 of Section 5.3.1 will limit the further division of the queue. Once a series of aircraft is included in a small queue and the small queue is resequenced, none of the aircraft can be resequenced again; the division of a large queue is fixed. The proposed resequencing strategy does not define the point at which the controller must begin dividing a large queue into a smaller subqueues. The controller is allowed the flexibility of deciding when resequencing would be beneficial to either the ATC system or to the users involved. Consider the seven-plane departure queue shown below:

III	I	IIIH	II	III	II	III
1	2	3	4	5	6	7

This queue should be divided into two or three smaller queues before resequencing begins.

$$\underbrace{\begin{array}{cccc} \text{III} & \text{I} & \text{IIIH} & \text{II} \\ 1 & 2 & 3 & 4 \end{array}}_{\text{Queue 1}} \qquad \text{and} \qquad \underbrace{\begin{array}{ccc} \text{III} & \text{II} & \text{III} \\ 5 & 6 & 7 \end{array}}_{\text{Queue 2}}$$

or

$$\underbrace{\begin{array}{c} \text{III} \\ 1 \end{array}}_{\text{Queue 1}} \qquad \text{and} \qquad \underbrace{\begin{array}{cccc} \text{I} & \text{IIIH} & \text{II} & \text{III} \\ 2 & 3 & 4 & 5 \end{array}}_{\text{Queue 2}} \qquad \text{and} \qquad \underbrace{\begin{array}{cc} \text{II} & \text{III} \\ 6 & 7 \end{array}}_{\text{Queue 3}}$$

Resequencing provides the maximum time reduction when a Category IIIH aircraft is in the departure queue. Therefore, a queue should be resequenced whenever a Category IIIH aircraft is in one of the subdivided queues. The Category IIIH aircraft may incur a fuel burn penalty as a result of being resequenced.

Resequencing should also be implemented when a Category III aircraft is one of the aircraft in a subdivided queue. The overall departure time can be reduced, although the reduction in time is not as great as the reduction when a Category IIIH aircraft is involved.

Resequencing does not provide a significant time reduction when more than two aircraft of the same category are in a four-aircraft departure queue.

Resequencing provides minimum time savings when a subdivided departure queue contains only Category I, Category II, and Category IIIP aircraft. Under those circumstances, the current departure strategy of first come, first served should be followed.

CHAPTER SIX

ANALYSIS OF ALTERNATIVE SEQUENCING STRATEGY

6.1 ANALYSIS OBJECTIVE

The objective of the analyses described in this chapter was to assess how much time and fuel could be saved by resequencing a departure queue compared to the current application of first come, first served. The following paragraphs describe the techniques used in this analysis and presents several examples of the savings that can be realized from using the rules of Chapter Five to resequence a departure queue.

6.2 DEPARTURE RESEQUENCING MODEL

A simple computer model was developed to analyze the benefits of resequencing a series of departing aircraft. To limit the number of possible departure sequences, a four-plane departure queue was used. When any four-aircraft sequence is entered into the model, the model systematically reordered the sequence to generate all 24 possible combinations. For each permutation, the model calculated the total time required to launch all four aircraft, the time each aircraft remained in the queue, the amount of fuel burned by each aircraft while in the queue, and the cost associated with this fuel burn.

The times used by the model in this analysis are the values discussed in Chapter Four of this report (see Tables 4-1 and 4-6). The fuel flow and fuel cost for each aircraft category are defined in Chapter Two.

The model assumed that there were four aircraft in the departure queue, with the first aircraft waiting at the departure end of the runway, behind the hold short line. Further, it was assumed that all four aircraft could depart with no delays caused by arriving aircraft or aircraft departing from a second runway. Under this assumption, an aircraft can always be in position ready for departure when the required separation from the preceding departure is established. This type of operation represents the most efficient method of launching a departure queue and was observed (when traffic conditions permitted) at all three airports where data were collected.

The model calculated the total time required to launch all four aircraft and the time each aircraft remained in the departure queue. The total time was the sum of the time required for each aircraft to leave the departure queue, taxi onto the runway, and take off. Using the time differences defined in Chapter Four, this sum can be expressed mathematically by the following expression:

$$\text{Total Time} = \left(\Delta t_{1_1} + \Delta t_{3_1} + \Delta t_{4_1}\right) + \left(\sum_{i=2}^{4} \Delta t_{3_i} + \Delta t_{4_i} + \Delta t_{i-(i-1)}\right)$$

The above expression is separated into two terms because of the assumption that the departure of the four aircraft is not interrupted by an arrival or another departure. This assumption means that an aircraft can be cleared to "taxi into position and hold" while the preceding aircraft is on its takeoff roll.

The time that each aircraft remains in the queue is dependent on how long it takes for the aircraft ahead of it to depart. Therefore, this time is computed from when an aircraft enters the departure queue until it is cleared for takeoff. For the first aircraft in the queue, this time is zero because all four aircraft are assumed to be in the queue at time zero and the first aircraft is cleared for takeoff at time zero. The time each aircraft remains in the queue is used to calculate the fuel burned by each aircraft while in the queue.

A second computer model was developed to determine the benefits or costs of resequencing a dynamically changing queue. Departure sequences that were observed at the data collection airports were entered and the model performed the resequencing operation. Several runs were made in which the original departure queue was subdivided into a series of subqueues with four aircraft in each queue. In addition, several runs were made in which the operator could resequence the original queue by applying the resequencing model to selected subqueues of two to four aircraft. The second model used the same algorithms described above and produced the same information.

6.3 RESEQUENCING EXAMPLES

The following examples demonstrate the potential benefits from enhancing the departure sequence by using the resequencing strategy defined by this study. Each example defines an initial ATC departure sequence, the optimum departure sequence, and the sequence that would be generated by the rules defined in Chapter Five. For those examples where the optimum sequence is different from the sequence generated by the Chapter Five rules, the causes of the differences are discussed. The optimum sequence was determined by generating all possible permutations of the initial ATC sequence and calculating the time required to launch all the aircraft. The optimum sequence was then defined as the sequence requiring the least amount of time to launch.

Each example presents the time required to launch each departure sequence and addresses the overall time savings and the time savings or losses for each aircraft resulting from resequencing. There are additional cost savings or penalties associated with a change in the time any aircraft remains in the queue. This analysis does not attempt to quantify the maintenance costs, crew costs, or other time-related costs nor does it attempt to minimize the costs or maximize the benefits of any individual user. It simply presents the increase or decrease in time the aircraft remains in the departure queue and the overall changes in departure times and fuel use.

6.3.1 Example One

This example assesses the time that can be saved by grouping aircraft of the same category and allowing all other aircraft to depart before the Category IIIH aircraft.

Initial ATC Sequence

The initial departure sequence is shown in Table 6-1. This sequence was observed at PHX, runway 08L, on 9 August 1983. The table shows the time that each aircraft remained in the queue and the fuel burned while in the queue. The total time required to launch the four aircraft was 400 seconds.

TABLE 6-1

EXAMPLE ONE, INITIAL ATC SEQUENCE

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)
1	Ia*	0	0	0
2	III	125	48.13	48.13
3	IIIH	196	75.46	75.46
4	Ib*	364	0.51	1.02

*The a and b are added to show how each aircraft moves during resequencing.

Total Time for Four Departures = 400 seconds
Average Time in Queue = 91 seconds

Optimum Sequence

The optimum departure sequence is shown in Table 6-2. The total time required to launch this sequence of four aircraft is 273 seconds.

TABLE 6-2

EXAMPLE ONE, OPTIMUM SEQUENCE

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)	Change in Time (Seconds)
1	III	0	0	0	-125
2	Ia	87	0.12	0.24	+87
3	Ib	130	0.18	0.36	-234
4	IIIH	225	86.63	86.63	+29

Total Time for Four Departures = 273 seconds
Time Saving = 127 seconds
Average Time in Queue = 56.25 seconds

Discussion of Results

The rules of Chapter Five were applied to resequence the initial departure queue. The model first placed the two Category I aircraft together and then placed the fastest aircraft (Category III) into the first departure slot. Finally the heavy aircraft was placed in departure slot four. This resequencing resulted in a reduction of 127 seconds in the time required to launch all four aircraft and an overall fuel savings of 13.26 gallons. This fuel savings results in a fuel cost reduction of $13.47. While there was an overall reduction in launch time and fuel used, two of the four aircraft were negatively affected by resequencing and remained in the departure queue for a longer period of time. The first Category I aircraft (Ia) remained in the queue 87 seconds longer after resequencing and thus burned an additional 0.12 gallon of fuel. The Category IIIH aircraft remained in the queue an additional 29 seconds after resequencing and burned an additional 7.78 gallons of fuel. These effects were offset by a 125-second reduction for the Category III aircraft and a time savings of 234 seconds by the second Category I (Ib) aircraft. The average time in the queue was reduced by 34.75 seconds.

6.3.2 Example Two

This example assesses the benefits realized by having the heavy aircraft depart in the fourth departure slot.

Initial ATC Sequence

The initial departure sequence is shown in Table 6-3. This sequence was observed on runway 08R at PHX on 5 August 1983. The total time required to launch all four aircraft was 343 seconds.

TABLE 6-3

EXAMPLE TWO, INITIAL ATC SEQUENCE

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)
1	I	0	0	0
2	IIIH	125	48.13	48.13
3	IIIP	249	4.26	7.79
4	II	307	0.85	1.71

Total Time for Four Departures = 343 seconds
Average Time in Queue = 76.75 seconds

Optimum Sequence

The optimum departure sequence is shown in Table 6-4. The total time required to launch all four aircraft is 268 seconds.

Discussion of Results

This optimum departure sequence deviates from rule two of Section 5.3.2 by allowing the Category I aircraft to depart before the Category II aircraft. This deviation is a result of the longer time required between a Category I and a Category IIIH departure than that required for a Category II-Category IIIH pair.

If rule 2 had been followed, it would have required 284 seconds to launch all four aircraft. That would still save 59 seconds over the initial sequence (see Table 6-5).

TABLE 6-4

EXAMPLE TWO, OPTIMUM SEQUENCE

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)	Change in Time (Seconds)
1	IIIP	0	0	0	-249
2	I	98	0.14	0.27	+98
3	II	161	0.45	0.90	-146
4	IIIH	220	84.70	84.70	+95

Total Time For Four Departures = 268 seconds
Time Saving = 75 seconds
Average Time in Queue = 55 seconds

As in example one, two of the four aircraft remain in the queue longer and thus burn additional fuel. The comparison between the initial sequence and the sequence generated by the rules of Chapter Five show that the Category I aircraft incurs an additional 141-second delay after resequencing and burns an additional 0.20 gallon of fuel. The Category IIIH aircraft has an additional 111 seconds of delay and thus burns an additional 29.79 gallons of fuel. Because of this increase in the Category IIIH fuel burn, the resequencing results in an overall increased fuel use of 25.15 gallons. This increase occurs in spite of an overall reduction in total dispatch time of 59 seconds. The additional fuel cost resulting from this resequencing is $21.23, even though the average time in the queue was reduced by 17.75 seconds.

6.3.3 Example Three

Rules Applied

This example demonstrates the case for which there are little or no benefits associated with resequencing. Note that there are no Category III or Category IIIH aircraft in this example.

TABLE 6-5

EXAMPLE TWO, SEQUENCE GENERATED WHEN ALL CHAPTER FIVE RULES ARE USED

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)	Change in Time (Seconds) from Initial Sequence
1	IIIP	0	0	0	-249
2	II	98	0.27	0.55	-209
3	I	141	0.20	0.39	+43
4	IIIH	236	90.86	90.86	+111

Total Time For Four Departures = 284 seconds
Time Saving = 59 seconds
Average Time in Queue = 59 seconds

Initial ATC Sequence

The initial departure sequence is shown in Table 6-6. This sequence was observed on runway 08L at PHX. When this sequence is used, 221 seconds are required to launch the departure queue.

Optimum Sequence

The optimum departure sequence is shown in Table 6-7. The optimum sequence requires 209 seconds to launch the four aircraft. The departure sequence generated by the rules of Chapter Five is shown in Table 6-8, and it requires 220 seconds to launch the four aircraft.

Discussion of Results

This example shows that resequencing a departure queue is not always beneficial. The comparison between the initial sequence and the departure sequence generated by the resequencing strategy shows that only one second is saved in the total launch time and that only 1.36 gallons of fuel are saved. Therefore, it would be impractical to attempt to resequence this departure queue. The example also demonstrates that the benefits of resequencing are slight unless there is a Category III or Category IIIH aircraft waiting in the departure queue.

TABLE 6-6

EXAMPLE THREE, INITIAL ATC SEQUENCE

Departure Slot Number	Aircraft Category*	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)
1	Ia	0	0	0
2	IIIP	84	1.44	2.63
3	II	142	0.39	0.79
4	Ib	185	0.26	0.52

*The letters a and b are added to show the movement of each aircraft during resequencing.

Total Time For Four Departures = 221 seconds
Average Time in Queue = 46.25 seconds

TABLE 6-7

EXAMPLE THREE, OPTIMUM SEQUENCE

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons)	Fuel Cost (Dollars)	Change in Time (Seconds)
1	II	0	0	0	-142
2	IIIP	72	1.23	2.25	-12
3	Ia	130	0.18	0.36	+130
4	Ib	173	0.24	0.48	-12

Total Time For Four Departures = 209 seconds
Time Saving = 12 seconds
Average Time in Queue = 43.25 seconds

TABLE 6-8

EXAMPLE THREE, SEQUENCE GENERATED
BY CHAPTER FIVE RULES

Departure Slot Number	Aircraft Category	Time in Queue (Seconds)	Fuel Used (Gallons	Fuel Cost (Dollars)	Change in Time (Seconds*)
1	IIIP	0	0	0	-84
2	II	98	0.27	0.55	-44
3	Ia	141	0.20	0.39	+141
4	Ib	184	0.26	0.51	-1

*Referenced to Initial Sequence.

Total Time For Four Departures = 220 seconds
Time Saving = 1 second
Average Time in Queue = 46 seconds

6.3.4 Example Four

This example is representative of the departure queues observed during a peak departure period. The example shows the changes in departure times and fuel used when the queue of aircraft is divided into a series of four aircraft subqueues. The original sequence is shown on the left side and the resequenced queue on the right side of Table 6-9.

The results of the resequencing operation are summarized at the bottom Table 6-9. The results also show the average cost to each aircraft, as well as the average time spent in the queue and the total launch time decreases. However, the possible savings are reduced by the departure combinations generated between subqueues by the resequencing operation. These departure combinations generated by the resequencing operations demonstrate the importance of the controller in the resequencing operation. As the results show, the benefits are small when departure resequencing is performed strictly within continuous groupings of four aircraft.

TABLE 6-9

EXAMPLE FOUR, SHOWING BOTH ORIGINAL AND RESEQUENCED ORDER

Original ATC Sequence			Resequenced				
Category	Time in Queue (Seconds)	Fuel (Gallons)	Category	Time in Queue (Seconds)	Fuel (Gallons)	Δt	Δ Fuel
III	0	0	III	0	0	0	0
III	104	17.34	III	104	17.34	0	0
III	208	34.67	III	208	34.67	0	0
III	312	52.00	III	312	52.00	0	0
I	319	0.27	III	316	52.67	-108	-18.00
III	424	70.67	III	340	56.67	-108	-18.00
III	448	74.67	III	411	68.50	-108	-18.00
III	519	86.50	I	631	0.53	+312	+0.26
I	526	0.44	III	510	85.00	-108	-18.00
III	618	103.00	III	569	94.83	-108	-18.00
III	677	112.83	II	640	1.06	-108	-0.18
II	748	1.24	I	823	0.69	+297	+0.25
III	736	122.67	III	737	122.83	+1	+0.17
I	708	0.59	III	611	101.83	-132	-22.00
III	743	123.83	II	610	1.01	-107	-0.18
II	717	1.19	I	902	0.76	+194	+0.17
I	689	0.58	III	582	97.00	-107	-17.83
III	689	114.83	III	561	93.50	-107	-17.83
III	668	111.33	IIIP	547	1.04	-107	-0.20
IIIP	654	1.24	I	1010	0.89	+321	+0.27
III	654	109.00	III	650	108.33	-4	-0.67
I	616	0.52	IIIP	521	0.99	-99	-0.19
IIIP	620	1.18	I	724	0.61	+108	+0.09
I	593	0.90	I	567	0.47	-26	-0.03
IIIP	582	1.11	III	447	74.50	-130	-21.67
III	577	96.17	III	331	55.17	-218	-36.33
II	566	0.94	IIIP	777	1.48	+195	+0.37
III	549	91.50	II	635	1.05	+69	+0.09

Average Fuel = 47.53 gallons
Average Wait = 545.14 seconds
Launch Time = 2890 seconds

Average Fuel = 40.19 gallons Δ = -7.34 gallons
Average Wait = 538.43 seconds Δ = -6.71 seconds
Launch Time = 2839 seconds Δ = -51 seconds

6.3.5 Example Five

This example is also representative of the departure queues observed during a peak departure period. In this example, the simulation operator was able to observe the departure queue as aircraft entered and departed and then selectively apply the resequencing strategy.

The results of this resequencing operation are summarized at the bottom of Table 6-10. As demonstrated in Example Four, there are both time and fuel benefits when the resequencing strategy is applied. A comparison between Examples Four and Five shows that the selective use of resequencing by a controller generally provides more benefit than resequencing within continuous groupings of four aircraft.

TABLE 6-10

EXAMPLE FIVE, SHOWING BOTH ORIGINAL AND RESEQUENCED ORDER

Initial ATC Sequence			Resequenced			
Category	Time in Queue (Seconds)	Fuel (Gallons)	Category	Time in Queue (Seconds)	Fuel (Gallons)	Δ Fuel (Gallons)
I	0	0	I	0	0	0
IIIP	79	0.15	IIIP	79	0.15	0
III	169	28.17	III	169	28.17	0
II	223	0.37	II	163	27.17	-14.67
III	251	41.84	II	327	0.54	+0.17
IIIH	339	90.95	IIIH	325	87.20	-3.75
III	431	71.85	III	417	69.51	-2.34
III	450	75.02	III	436	72.68	-2.34
III	459	76.52	III	445	74.18	-2.34
II	478	0.80	II	464	0.77	-0.03
II	466	0.78	II	452	0.75	-0.03
IIIH	469	125.83	II	350	0.58	-0.43
II	606	1.01	IIIH	528	141.66	+15.83
IIIP	584	1.13	IIIP	516	1.00	-0.13
II	567	0.94	II	499	0.83	-0.11
IIIH	539	143.54	II	347	0.58	-0.51
II	657	1.09	I	299	0.25	-0.26
I	609	0.51	IIIH	649	174.13	+30.59
IIIH	614	164.74	IIIH	501	134.43	-30.32
I	626	0.52	III	323	53.84	-45.35
IIIP	605	1.18	III	287	47.84	-45.35
III	595	99.190	IIIP	654	1.27	+0.09
III	559	93.18	I	882	0.73	+0.21
I	501	0.42	I	410	0.34	-0.08
IIIH	486	130.39	IIIP	239	0.46	-0.57
IIIP	529	1.03	IIIP	122	0.23	-0.96
IIIH	489	131.20	IIIH	602	161.52	+31.13
IIIP	612	1.19	IIIH	499	133.88	+2.68

Initial ATC Sequence	Resequenced	Δ
Average Time in Queue = 463.86 Seconds	Average Time in Queue = 392.29 Seconds	Δ = -71.57 Δ = -2.46
Average Fuel Used = 45.84 Gallons	Average Fuel Used = 43.38 gallons	Δ = -2.38 minutes
Launch Time = 3409 seconds = 56.82 minutes	Launch Time = 3266 seconds = 54.43 minutes	

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The current strategy used to sequence a series of departing aircraft is based on the principle of first come, first served. With limited exceptions, the air traffic controllers are forced to comply with this strategy and have relatively little authorized flexibility in rearranging the sequence to improve the departure flow. This lack of flexibility can result in aircraft being delayed on the ground while waiting for the minimum separation interval between departing aircraft to be established.

Departure sequence-enhancement strategies can be defined that provide more flexibility to the controller and may reduce the time required for a series of aircraft to depart. The enhancement strategy proposed by this study consists of the five following rules:

1. Two or more aircraft of the same category should be grouped together and they should depart sequentially.

2. Faster aircraft should depart before slower aircraft. This does not apply to Category IIIH aircraft.

3. When a Category IIIH aircraft is one of the aircraft in a departure queue, the Category IIIH should depart after the other aircraft.

4. A resequencing operation should not result in any aircraft being displaced more than three departure slots.

5. An aircraft should be moved only once.

These rules provide a simple model for resequencing a series of departing aircraft. They may not provide the optimum departure sequence for all combinations of aircraft, but the results presented in Chapter Six demonstrate that both fuel and time savings are possible when the five rules are applied. The model does not require a controller to consult a handbook or operate a microcomputer or programmable calculator before implementing the resequencing operation. The proposed strategy does not dictate when a controller should use the strategy, but offers guidelines for when the most benefits can be achieved. Although data were collected at only three airports, the operating conditions and traffic mixes observed were diverse enough to define a model that could be implemented at a large number of airports. The time saved by resequencing a departure queue can be used by the controller to allow another departure or to accept an arrival. This increases the traffic capacity of an airport and thus may allow additional operations or reduce congestion during peak departure periods.

The purpose of resequencing a departure queue would be to increase airport capacity by reducing the departure delays caused by the sequence of departing aircraft. This increase in capacity has no value when there are no aircraft waiting to depart. In light traffic situations, when the departure delays are small or zero, there is no point in resequencing the departing aircraft. There will be little or no benefit to the aircraft involved since there are no appreciable delays involved. Furthermore, since delays are small, it is unlikely that there are aircraft waiting that would take advantage of an increase in departure capacity.

When a queue becomes larger, the proposed resequencing strategy will yield some benefits to both the airport and to the users. The controller's judgment, based on his experience, is an important factor in determining the magnitude of the benefits. However, the estimated benefits, derived from the computer models, associated with departure resequencing are not sufficient to recommend either widespread implementation of the proposed strategies, or the formal modification of the first come, first served philosophy through a change to the air traffic control handbook. Since departure resequencing is a part of the overall TMS program, the effects of departure resequencing may prove more beneficial when the proposed strategies are combined with the departure metering component of the TMS development program.

APPENDIX

REFERENCES

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6