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Dual Lane Runway Study Final Report

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16. Abstract

The issues in the dual lane runway problem were investigated via computer real time (man in the loop) and fast time (no human input during the simulation run) simulations in order to identify a dual lane runway configuration and determine operation strategies.

The real time experiments were conducted using experienced ATC controllers and a pilot to observe the situation at interactive graphics CRT displays. Headsets and microphones were utilized to permit the normal controller/pilot interchanges. Flight strips as used in control tower cabs were employed to further simulate controller workload. Based on information gained during early real time controller experiments, a programmed controller concept (fast time) was adopted.

A series of dual lane runway computer simulation experiments were performed to investigate the pertinent dual lane issues: centerline spacing, arrival/departure preference, parallel taxiway, threshold stagger, and high speed exits.

In addition, time was spent analyzing operational high density airport terminal facilities. Airport administrative and operations personnel were interviewed to obtain their views on high density operations and the dual lane concept. Peak rush hour periods were sought out to determine control strategies employed indirecting peak period traffic. Air crews utilizing these high density airport terminals were interviewed in the course of their operations into and out of these major hub airports.

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DUAL LANE RUNWAY STUDY

1.0 INTRODUCTION

Both the Air Traffic Control Advisory Committee Report (ATCAC-1969) [1] and the Civil Aviation Research and Development Policy Study (CARD-1972) [2] recommended continued development and evaluation of the more promising approaches to increase airport traffic capacity. The high cost of construction of new airports and the increasing hostility to their tenancy because of noise, pollution, and ecological factors has led to the urgent requirement to maximize the utilization of existing airports and to increase their traffic handling capacity. The dual lane runway has been suggested as a cost-effective design to expand airport operating capability. Prompt resolution of the issues related to the design and operation of dual lane runway airports is needed. This report describes an investigation of the issues surrounding dual lane runways. It includes an overview of the critical issues, describes a computer simulation analysis, and summerizes the findings of surveys of operating facilities.

Tens of hours were spent analyzing operational high density airport terminal facilities. Airport administrative and operations personnel were interviewed to obtain their views on high density operations and the dual lane concept. ATC tower cab peak rush hour periods were sought out to determine control strategies employed in directing peak period traffic. Air crews utilizing these high density airport terminals were observed and interviewed while flying into and out of major hub airports.

Real time and fast time simulations were run on Lincoln Laboratory's TX-2 interactive graphics computer system. Real time experiments were conducted using a CRT display to present the situation to experienced ATC controllers and a pilot (Figure 1). The simulation program controlled the aircraft in flight while the pilot controlled aircraft ground movements in response to voice commands from the ATC controller. Headsets and microphones were utilized to permit the normal controller/pilot interchanges. Flight strips as used in control tower cabs were employed to further simulate a realistic controller workload. Based on information gained during early real time controller experiments, a programmed controller concept was adopted. A controller algorithm was programmed into the TX-2 and the simulations run in accelerated (fast) time, thus, allowing more data to be accumulated. A graphics display of the fast time algorithm directing traffic was available upon request by the simulation user for analysis.

1.1 Summary

A series of dual lane runway computer simulation experiments were performed to investigate the pertinent dual lane issues of runway centerline spacing, arrival/departure runway preference, runway threshold stagger, parallel taxiway, and high speed exits. A summary of these dual lane issues and findings of the simulation analyses follows.

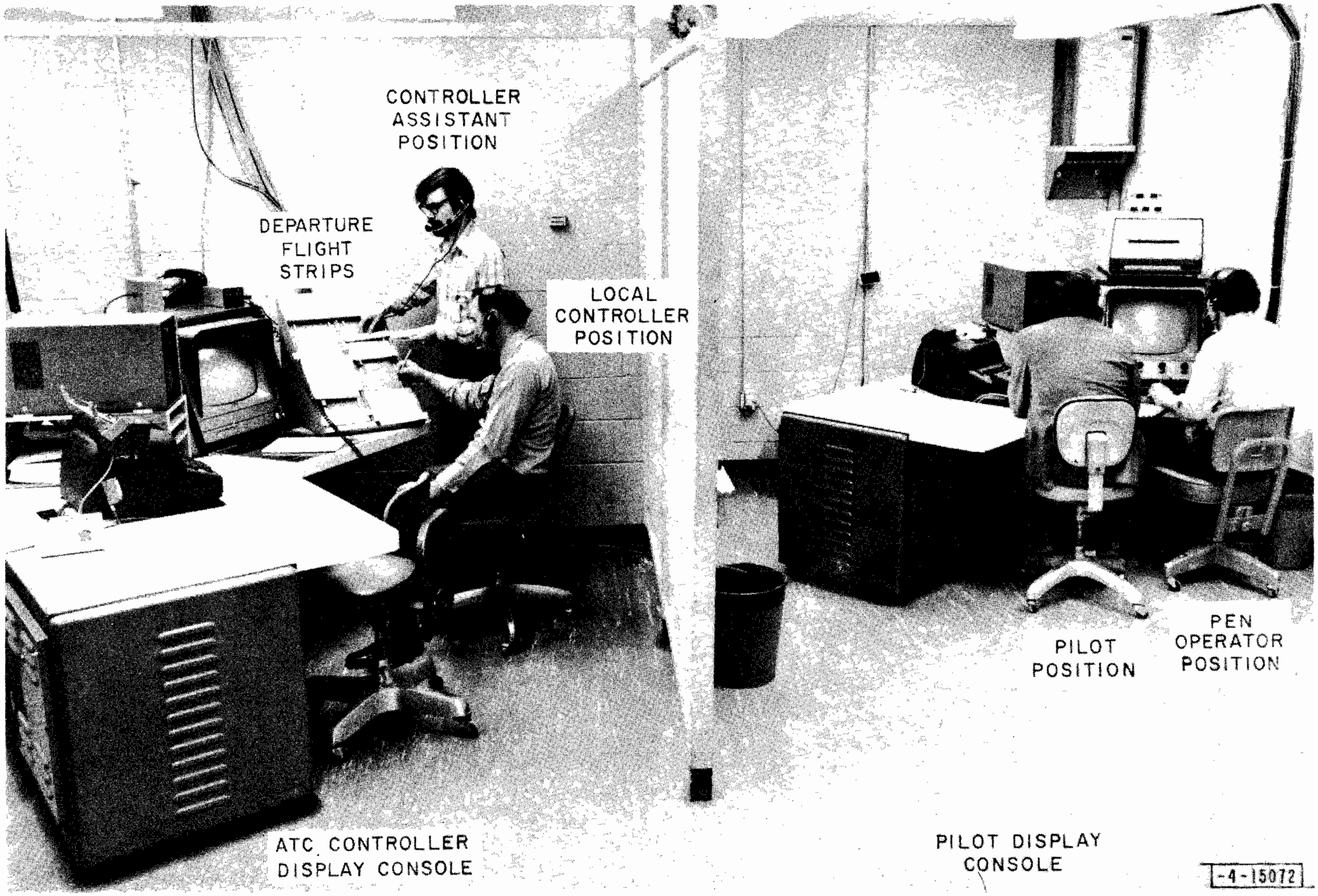

Fig. 1. Photograph of a real time experimental run in progress. Local controller and controller assistant are on the left console while the pilot and pen operator are seated at the right console.

1.1.1 Dual lane capacity

The dual lane runway configuration was found to substantially increase traffic handling capacity over a single lane runway for both VFR and IFR conditions. A 70 percent increase in VFR traffic over single lane traffic was found for the dual lane while at the same time, a slight increase in controller workload was observed. The 70 percent increase in VFR traffic was achieved by segregating arrivals and departures to separate runways, thereby, making the controller's task simpler than directing mixed traffic to a single lane. An additional 15 percent increase in VFR traffic was achieved by handling mixed traffic operations on both of the dual lane runways; however, this additional 15 percent increase was achieved only with a disproportately high increase in controller workload.

IFR traffic handling capacity was found to be sensitive to actual IFR weather conditions. The dual lane was found to increase IFR traffic handling capability by 60 percent over that of a single lane. This increase is dependent on weather conditions. Under the better IFR conditions (visibility just under 3 nmi or ceiling just under 1000 ft) the increase was found to be 60 percent while under poorer visibility and wet runway conditions, the additional lane provided more than 100 percent increase in IFR traffic handling capability.

1.1.2 High speed exits

Adding high speed exits (60 mi/h) to an arrival runway was found to decrease arrival runway occupancy time by 20 percent from conventional (40 mi/h) angled exit times. However, the addition of high speed exits to an arrival runway does not necessarily increase arrival capacity. Conventional angled exits will support the present 3 nmi minimum spacing of arrivals. Only when the minimum 3 nmi arrival spacing is reduced to approximately 2.5 nmi, or less, are high speed exits required. Pilot acceptance of high speed exits is essential to realize their full benefit. It was determined that high speed exits alone will not support a 2 nmi arrival stream of air carrier traffic due to variation in approach velocity, some form of speed control or other technique is needed.

When handling mixed VFR operations, high speed exits were found to allow an increase in operations by permitting consistent departures between 4 nmi spaced arrivals rather than the more conventional 5 nmi spacing employed with angled exits. Operational field data on high speed exit usage was not available to support the simulation findings.

1.1.3 Runway centerline spacing

A minimum adequate centerline spacing between two parallel runways is desired to reduce airport real estate needed for the dual lane runways. If airport real estate is not a constraint, increased centerline spacing allows greater operational flexibility. This is true until 5000 ft spacings are achieved where present regulations permit independent IFR operations to both runways.

The simulation found the number of operations achieved on a dual lane system did not change when centerline spacings varied between 1000 and 2499 ft. At a spacing greater than 2500 ft, the number of operations increase as a function of the number and distribution of heavy (>300,000 pounds) aircraft in the traffic mix due to the change in wake turbulence regulations affecting the adjacent runway.

At spacings less than 1000 ft, operations were impacted by two considerations. To consistently feed the outer (furthest from terminal) departure runway, adequate holding area for at least two aircraft was needed. If this holding area was not provided, the outer departure operations were curtailed from the 60 per hour otherwise achieved. It was established that to hold two aircraft between runway thresholds, at least 1000 ft centerline spacing was needed. The other consideration determining centerline spacing of 1000 ft or greater was the stopping distance for an aircraft executing high speed (60 mi/h) runoff between runways. It was calculated that 1000 ft was adequate to support aircraft exiting at high speeds into the area between runways.

1.1.4 Arrival/departure runway preference

ATC controllers directing a steady flow of traffic prefer to segregate arrivals to one runway and departures to the other to minimize their workload. When at least two aircraft could be held between thresholds, (i.e., centerline spacing $\geq$ 1000 ft) the number of operations the simulation achieved was the same when handling arrivals on either runway. However, arrival and departure delays were minimized when arrivals were directed to the inner runway (departures on outer runway). On the other hand, operating with arrivals on the inner (outer departures) may create ILS glide slope interference due to taxiing departure aircraft.

Jet blast effects must be considered when choosing a runway configuration. Modern heavy jets, when taxiing or breaking away from a stopped position, create jet blasts of sufficient intensity to cause hazardous situations involving other aircraft. Departures taxiing across an inner arrival runway to use an outer departure runway, can create this hazardous situation.

Operational experience indicates that outer arrivals and inner departures are the preferred strategy. Controllers feel the easiest workload situation is to clear arrivals across the inner departure runway while holding a departure in position on the runway. The other case of clearing departures across an arrival runway is considered to be a more demanding task by the controllers. The conclusion was that arrivals on the outer (departures on the inner) is the preferred strategy.

1.1.5 Inclusive parallel taxiway

Simulation experiments were performed to determine if a parallel taxiway placed between the two dual lane runways would offer increased operational flexibility. The addition of the taxiway in the simulation did not increase the number of operations. A strategy was employed where outer arrivals used the taxiway to taxi back toward the threshold and cross behind inner runway departures near the threshold. The number of operations was not increased but average departure delay can be reduced over those delays (time aircraft is not moving) incurred due to normal crossings. However, arrival taxi time will be increased in effecting this departure delay reduction. Utilizing the taxiway created conflicts between aircraft taxiing "against the grain" and outer arrival aircraft turning onto the taxiway. These conflicts increased controller workload and became potential hazards in IFR weather under poor visibility conditions. The taxiway was not needed as a high speed rollout area for outer arrivals.

1.1.6 Runway threshold stagger

The off-setting of one parallel runway threshold from another is referred to as threshold stagger. No increase in the number of operations was found due to stagger. However, if the real estate is available, by staggering thresholds such that the two runways are operated on a non-interference basis (no runway crossings made) both arrival and departure delays can be minimized. It was also found that a few thousand feet of stagger provided the operational flexibility to reduce arrival delays.

In summary, the dual lane runway was found to offer substantial increase in VFR and IFR capacity handling capability. Dual lane runway provided some reduction of controller workload by permitting segregated operations to achieve these capacity increases. Controller workload increased disproportionately to any capacity increase when mixed operations were introduced to one or both of the dual lane runways. High speed exits offered an additional gain by reducing arrival runway occupancy times such that reductions in interarrival spacings were supported. A 1000 ft centerline spacing was found to be adequate to achieve maximum operational flexibility for spacings less than 2500 ft. The handling of arrivals on the outer runway (inner departures) was found to be the preferred operational strategy due to the reduction of controller workload. This was true even though the reverse strategy of inner arrivals (outer departures) reduced arrival and departure delays. A parallel taxiway between closely spaced parallel runways did not increase capacity. It did cause conflict situations where controller intervention was needed to resolve them. Threshold stagger did not increase capacity. Providing sufficient threshold stagger minimized arrival and departure delays.

2.0 SIMULATION TECHNIQUES

The interactive graphic capability available on the TX-2 computer provided a base on which a real time (man in the loop) simulation of a dual lane runway system was developed. The simulation ran at a real time rate and utilized an experienced air traffic controller to direct the traffic. In addition, the system was designed so that an analyst or airport planner could input or modify an airport configuration in a matter of minutes and then rerun the simulation. An analyst can observe the operation of the system by watching traffic on the display while listening to the commands given by the controller and then compare that operation with observations made in an airport tower. This feature provides the analyst the capability required to design a realistic simulation and verify the realism by observation. The obvious disadvantage of the real time simulation is that the quantity of data that can be gathered is limited by time.

A second simulation effort evolved. A fast time programmed controller simulator was designed based on the observed controller actions and the aircraft modeling used in the real time simulation. The fast time simulation, which ran approximately 25 times real time, provided data required to quantitatively evaluate the dual lane runway system. A discussion of the operation of the real time and fast time simulation follows.

2.1 Real Time Controller Simulation

The real time runs were made with a controller, controller assistant, pilot, and pen operator; each seated at one of the two computer consoles (Figure 2). A

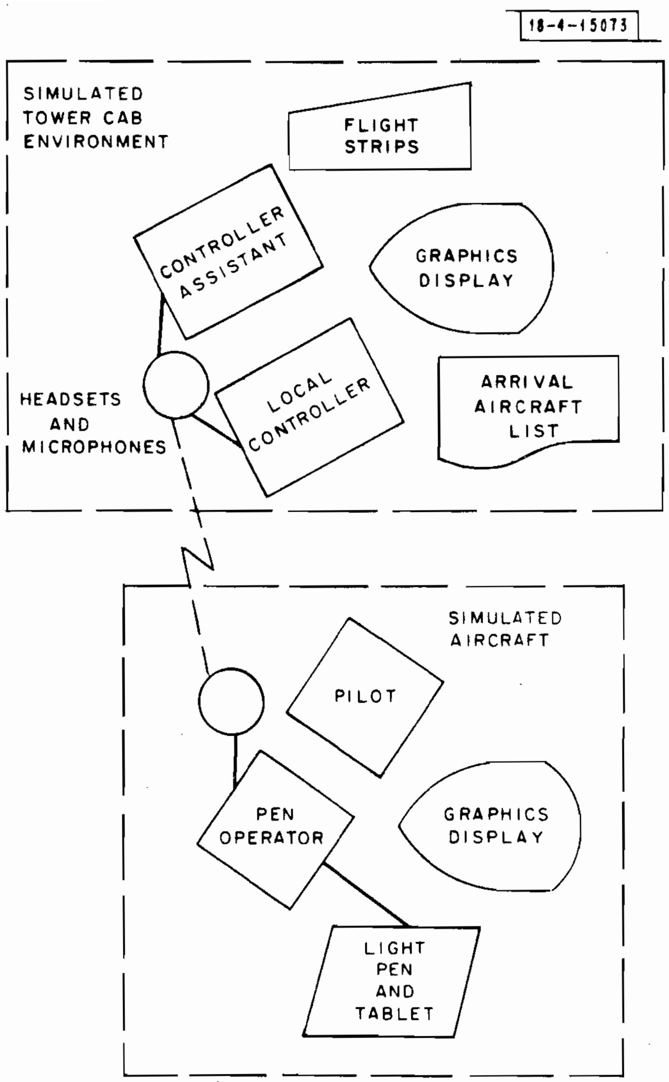

Figure 2. Block Diagram of the TX-2 Real Time Simulation.

visual presentation of the aircraft and runway/taxiway configuration was available on both concole CRT's. Figure 3 graphically illustrates the information found on the display. A typical CRT display is shown in Figure 4. The scale drawn at the top of Figure 3 shows a heavy (H) arrival about 3 nmi from runway threshold of the outer runway (below scale line). A split screen presentation with the upper scale depicting the extended centerlines of the runways from outer marker (A), to the missed approach decision points (X), to the runway thresholds is shown. Two parallel runways, various exits and taxiway are shown on the display. A medium* (M) aircraft is taxiing from the terminal area to the runway threshold. A large (L) aircraft has just landed on the outer runway (farthest from the terminal). Aircraft symbols change from a triangle for airborne aircraft to a plane symbol for aircraft on the ground. The simulation clock in the lower right hand corner indicates that the simulation has run for 5 min and 19 sec. When an aircraft is queried by using the "pen" to draw a symbol over it, a readout of its present speed (SPD), its target speed (S_T) and whether it is on a runway (RW) or taxiway (TW), is indicated at the bottom of the display. Data useful to the programmer is also displayed. The aircraft queried glows brightly to indicate which aircraft the data pertains to. The large aircraft landing on the outer runway is shown at 130 knots decelerating to its target speed of 52 knots or 60 mi/h which is the simulation exit speed for a high speed exit.

Each of the four simulation positions were provided headsets and push-to-talk microphones on the same communication frequency. The controller and controller assistant were seated at one graphic console while the pilot and his assistant (pen operator) sat at the second interactive computer terminal. During saturation demand traffic flows, we found it necessary to provide a pen operator position

*Medium is a simulation term and not an FAA designated aircraft class.

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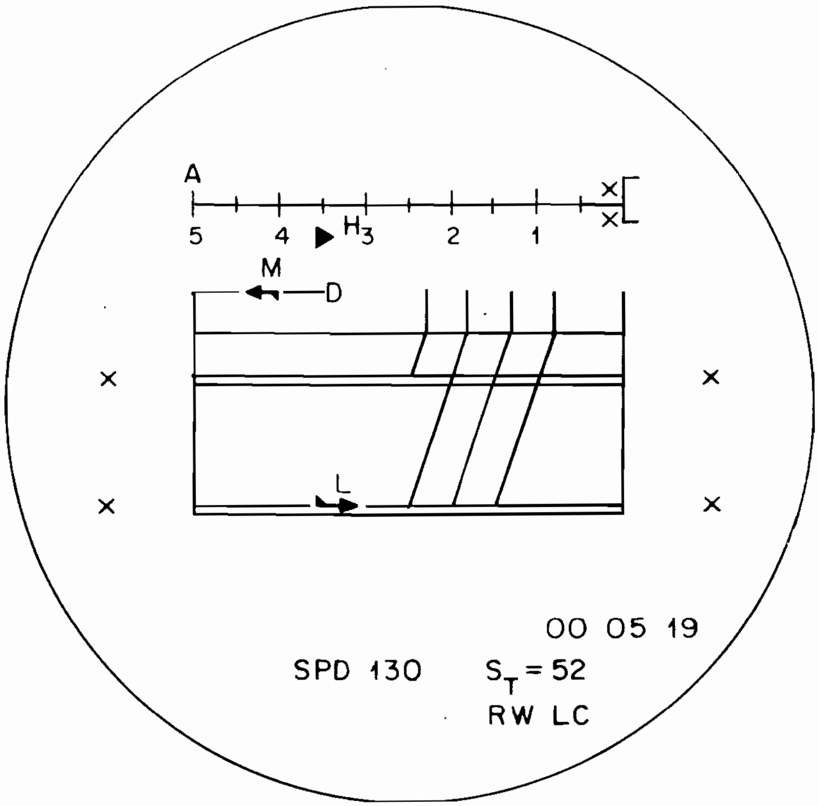


A – OUTER MARKER

× – MISSED APPROACH DECISION POINT

D – DEPARTURE FIX

L, M, H, G – AIRCRAFT TYPE
- L – LARGE (B707)
- M – MEDIUM (B727)
- H – HEAVY (B747)
- G – GENERAL AVIATION

SPD – AIRCRAFT SPEED (knots)

S_T – TARGET SPEED (knots)

RW-LC – QUERIED AIRCRAFT ON RUNWAY, LARGE CLASS AIRCRAFT

TW – TAXIWAY (symbol not shown)

Figure 3. TX-2 Dual Lane Runway Simulation Display.

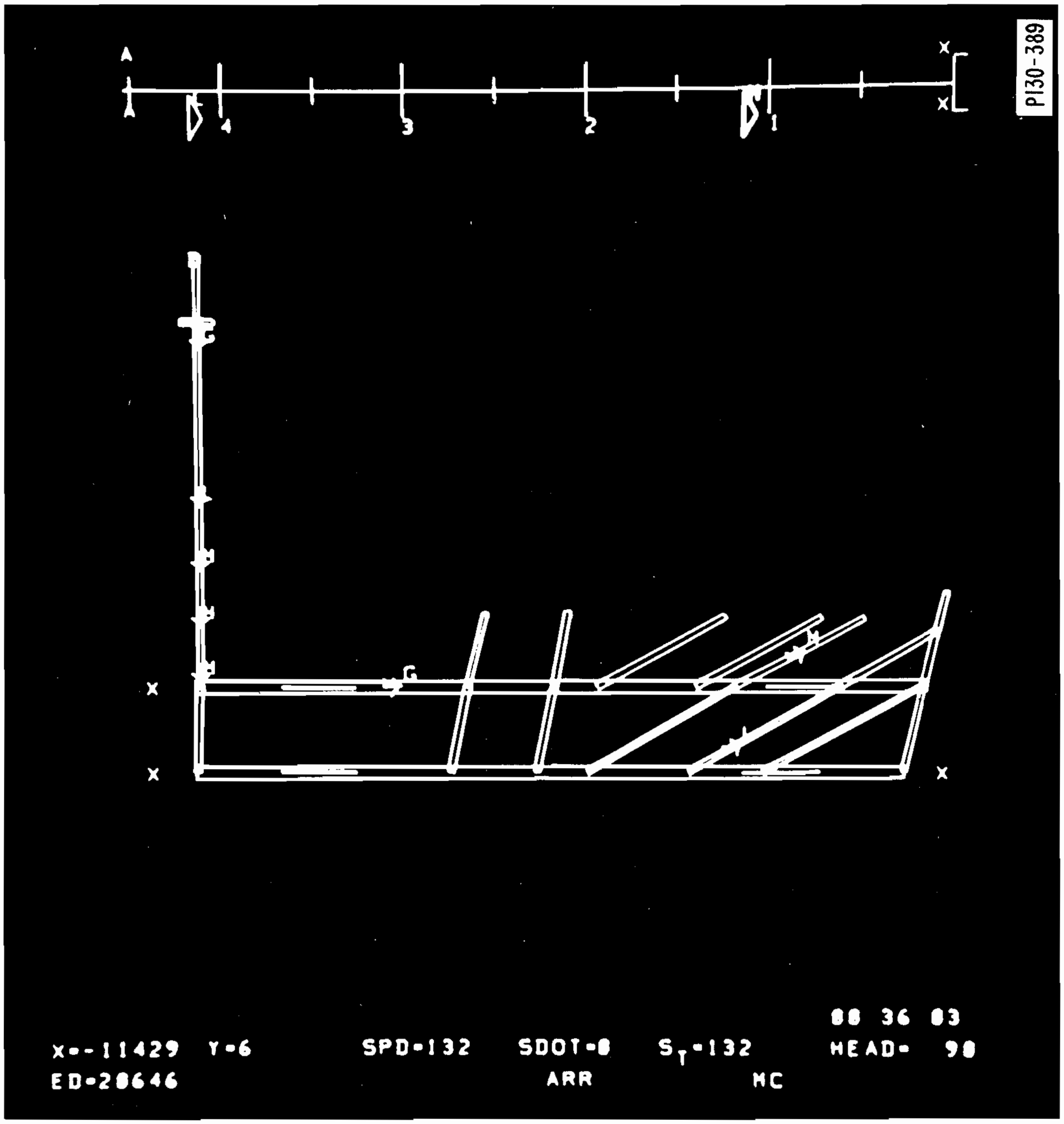


Fig. 4. Typical TX-2 Dual Lane Runway CRT Display.

(pilot assistant) in order to determine which aircraft the controller was addressing and have him issue the necessary command via a computer command using the pen and tablet input device. One pilot responded for all aircraft communicating with the controller and thus, did not have time to also determine the exact aircraft on the display the remark was addressed to.

The controller would give his instructions verbally to a particular simulated aircraft. The pen operator, utilizing the pen and tablet, gave the aircraft the intended command after locating the specific aircraft on his CRT. The pilot, listening to the controller and seeing the pen operator give the aircraft the command, would respond verbally to the controller. Part of the controller's task was manipulation of the departure flight strips and arrival identification list similar to the local controller in the tower cab at a major hub airport.

The procedure for arrivals had the pilot call out arrival aircraft identification over outer marker from lists of arrivals (one for commercial and one for general aviation). A typical pilot call out would be: American Airlines two thirty-heavy (AA230H) over outer marker for four right (4R)." The controller would see the aircraft with a heavy (H) symbol on his display (Figure 3), thereby, identifying the aircraft. He would record, in a list, the identification (e.g., AA230H) number and either clear the aircraft to land or have the aircraft continue its approach. Eventually, AA230H would either be cleared to land on 4R, asked to transition and land on 4L, or told to go around on a missed approach course. After the aircraft had landed, the controller would give the necessary commands in order to get the aircraft clear of the runways and into the apron area. These would be voice commands (e.g., "AA230H hold short of four left (4L)") which the pen operator would interpret and give to the aircraft using the pen and tablet. The pilot would respond over the voice channel acknowledging receipt and execution of the command after the pen operator executed the command.

A typical sequence of controller commands to a departure would be: "United two eighteen heavy (UA218H) cleared into position and hold on four left (4L)," and the pilot would respond: "United two eighteen (UA218) into position and hold four left (4L)." The controller would then give the command "United two eighteen-heavy (UA218H) cleared for takeoff on four left (4L)." The pilot would respond after seeing the pen operator give the takeoff command: "United two eighteen (UA218) rolling on takeoff." The controller would observe the take-off and when the aircraft was airborne as indicated by a change of symbol on the scope, the command: "United two eighteen-heavy switch to departure control on one hundred twenty point six (120.6), good day," was given. The pilot response would be: "UA218 switching to departure control on one hundred twenty point six (120.6) good day." The aircraft would disappear from the screen after a period of 60 sec from the start of departure roll.

Departure and arrival aircraft for a specific experiment were controlled in this fashion for approximately 40 min time. The first ten minutes were dropped to eliminate the start-up transient. The data was adjusted to obtain an hourly rate. The data available included (Appendix D), number of arrival/departure operations, number missed approaches, runway occupancy time, delay time, taxi time, and total time in system. The individual computer runs were stored on magnetic tape for playback and data reduction.

2.1.1 VFR controller experiments

A series of real time VFR TX-2 experiments were designed and ATC controllers scheduled to quantify the various dual lane configurations and procedures under investigation. The experiments included single lane (conventional angled exits and high speed exits), centerline spacing, and arrival/departure preference, parallel taxiway, threshold stagger and the specific dual lane configuration. The experiments were performed using a constant mix of traffic simulating traffic to a major hub airport. In separate experiments, the nominal spacing of arrivals was varied to simulate various densities of arrival traffic. Departures were scheduled to enter the departure taxiway segment at nominal 60 sec intervals for departures only and nominal 90 sec for mixed traffic. The strategy was to operate the runways in three basic modes:

(1) arrivals only;

(2) departures only;

(3) arrivals and departures (mixed).

The traffic to the simulated major hub airport configurations was high density. High density traffic generates an added burden on pilots and controllers. The controllers will normally "give the picture" to the pilots to insure their cooperation and anticipate their reactions. This consists of alerting the pilots to the controllers intention and in advising the pilots of immediate traffic in their area. The controllers refer to this as priming the pilots preparatory to issuing the actual commands. Close cooperation along with mutual trust and respect is required between pilots and controllers to direct high density traffic operations. These extra priming commands were not issued in the simulation. Cooperative pilots with normal reaction times were simulated.

Departure traffic was "generated" at departure fixes at nominal 60 and 90 sec intervals. When they are generated, the controller assistant would put the appropriate flight strip (already in its holder) on the flight strip board in its proper sequence and proper runway alignment. The controller observed the departure aircraft on the scope and associated them with their flight strip.

He normally cleared a departure into position on the runway and hold until the runway is cleared by a previous departure or arrival or a crossing aircraft. This was done only when the controller felt that there was no chance of causing a missed approach to a succeeding arrival aircraft.

2.1.2 IFR controller experiments

The IFR experiments were performed under conditions simulating 0.5 nmi visibility and 200 ft ceiling for the various dual lane criteria explored. It was assumed that the controller could not reliably see any portion of the dual lane runway due to stated weather conditions. This would be true if a control tower were over 200 ft high and/or the distance between the tower and the nearest portion of the inner runway was over one half nautical mile. The controllers view might be obscured under these weather conditions due to the presence of haze, smoke, or ground fog. It was further assumed that an airport surface detection equipment (ASDE) radar was not available to the controller, but that a bright radar indicator tower equipment (BRITE) television display system was available. This IFR situation was simulated by blanking out the runway/taxiway configuration by providing only the final approach scale (upper portion of Figure 3 display) to the local controller and controller assistant console display. Airborne departure aircraft were still displayed to the controller console by unblanking the right portion of the display. This provided the controller with the information that the departure had lifted off and was leaving the runway system. This approach simulated the information a tower local controller would have available on a BRITE display. Only a small number of the larger commercial airports have ASDE's available. Under these conditions, the controller was blind to events occurring on the dual lane runway system. The controller must rely on the pilots to provide the necessary information in order to direct traffic under these conditions. The controller needs to know when aircraft are clear of a runway in order to clear other aircraft to use the runways.

A typical sequence of commands issued by controller and accompanying pilot responses providing the necessary information follows: An arrival aircraft on final approach contacted the controller at the outer marker: "Eastern two eighteen (EA218) over outer marker for four right" (runway 4R). The controller responded: "Eastern two eighteen continue approach for four right, please advise when you have runway lights in sight." At approximately a half mile from threshold, when the runway becomes visible, the pilot called: Eastern two eighteen have runway lights in sight." The controller responded: Eastern two eighteen clear to land four right, hold short four left, please advise when clear of runway." Pilot responded: "Eastern two eighteen will hold short of four left and advise when clear four right." After the landing aircraft had cleared the runway, the pilot called: "Eastern two eighteen, clear four right." The controller responded: "Eastern two eighteen, hold short four left." The controller came back: "Eastern two eighteen, please advise when you see TWA B727 pass your position." The pilot: "Roger, will advise," The controller had cleared a TWA B727 for takeoff on runway four left (4L) and wanted to know when the departure passed the holding arrival aircraft position so he could clear the arrival across the runway four left. The pilot called: "Eastern two eighteen, departing jet has just passed our position." The controller: "Roger, Eastern two eighteen, clear to cross four left, please advise when clear of four left." The pilot: "Eastern two eighteen, clear four left." The controller: "Roger, Eastern two eighteen, switch to 121.9 for ground control." The controller will release a departure on four left when he is assured that a crossing is holding short of that runway or that a crossing aircraft has cleared the runway. The departure cannot be release on 4L if there is an arrival to 4R within 2 nmi of threshold, the rationale being that the controller does not want two aircraft in the air at once in the case of a missed approach by the arrival aircraft. Hence, the departure was not released until the arrival to 4R was at a position on the approach path where the pilot would normally have the approach lights in sight for the conditions simulated. At this time the pseudo-pilot informed the controller that the runway was in sight. It is only at this time that the controller has the confidence that the arrival aircraft will land and not execute a missed approach. The next departure was held when an arrival to 4R was within 2 nmi of the threshold until the arrival pilot calls the runway lights.

2.2 Programmed Controller Simulation

In order to obtain sufficient data for a quantitative comparison of candidate dual lane runway systems, it was necessary to program the control of all aircraft movements. Controller algorithms for fast time simulation of the dual lane runway systems were generated based on experience gained through observation of the real time simulation operation, interaction with the ATC specialists actively engaged in the real time simulations, and through discussions of control procedures with FAA personnel at a number of high density airports with parallel runway systems.

Early experiments suggested that controller workload, and delays to arrivals and departures offered the most sensitive areas for measuring quantitatively each configuration's performance under traffic saturation conditions. Fast time (programmed controller) simulation provided the output to capture the necessary statistics to indicate a configuration's capacity and delay profiles. Questions relating to controller workload were essentially answered during the real time simulation runs. Debriefing discussions with controllers after the completion of a number of fast time runs helped to assure the validity of the fast time approach.

Controller algorithms were incorporated into the existing interactive runway simulation implemented on the TX-2 computer to provide the "Hands off" capability needed for the fast time runs. Two options in program operations were available in the programmed controller simulation with selection made through a command inserted through the data tablet.

(1) Display blanked

(2) Display activated

With display blanked, the simulation time advanced limited only by the computation speed of the machine and the efficiency of the program and constitutes what we refer to as the "fast time" simulation. The fast time mode ran approximately twenty-five times real time providing the bulk of the data to quantify the effects of the dual lane runway parameters.

With the display activated, simulation time advanced at a rate selected by the analyst (generally, at the real time clock rate). This feature provided several benefits useful throughout the course of the study.

(1) At any point during a run, movements in the programmed controller simulation could be shown to the ATC specialists engaged in the real time experiments for their comments on realism.

(2) Periodic observation while the fast time runs progressed provided a degree of increased confidence in a particular experiment.

(3) Questionable results obtained after a fast time run could be observed in display mode to refine controller strategy to handle the offending situation more realistically.

(4) Rapid identification of program deficiencies.

Simulation output data was in the form of histograms extending over the duration of the simulation and were taken during all runs (real time and fast time) indicating each aircraft's runway occupancy time, taxi time, total time in the system, and delay time. Graphs were obtained for both arrivals and departures. These served to identify the trends, if any, developed by a traffic sample operating on each configuration and facilitated a meaningful comparison of the configurations. Additionally, instantaneous counts of departures and arrivals being serviced by the dual lane system were made at three minute intervals. The mean and standard deviation of each of the output parameters were calculated after the completion of each run and provided additional means to compare each configuration against the other. A sample output time graph representing partial output of one run is included in Appendix E.

Based on the results of early experience gained through real time simulations, it was determined that the questions relating to the criteria of dual lane systems are best answered by investigating their operation with one runway dedicated to arrivals and the other to departures. The effect of mixed operations to each runway of a dual lane runway was considered as part of a sensitivity analysis study performed to determine if mixed traffic changed any of the findings.

In practice, the demand for service by the air carrier and corporate jets remains approximately the same whether the weather conditions are VFR or IFR and constitutes the largest portion of the traffic at major hub airports. However, due to restrictions imposed during IFR conditions on independent operations in order to insure adequate separation between airborne aircraft, the delays experienced by all increase and the runway utilization decrease. A great interest in dual lane runway usage lies in its ability to increase IFR operations while complying with current ATC procedures. However, runway pavement usage during such periods is reduced to a minimum due to procedural restrictions. Delays then become primarily a function of the restrictions rather than a function of the pavement configuration. The dual lane system is most sensitive to variation in its characterizing parameters when subjected to heavy runway usage. In order to facilitate the identification of desirable features to incorporate into the design of a dual lane configuration not limited by imposed restrictions but rather by pavement, we first investigated the cases under VFR conditions and heavy demand. Having identified pavement limiting factors in this mode, attention was directed to IFR conditions in order to determine the effect of the restrictions which may or may not be relaxed at some later date.

As in the real time experiments, we assume efficient ATC terminal subsystems which can deliver and accept saturated queues of arrival and departure traffic. Likewise, the taxiway/apron/gate subsystems are similarly efficient in their ability to handle the aircraft movements. If conditions fall short of these assumptions (as they often do in practice), the dual lane runway criteria as established remains valid and is not expected to change. However, the delays experienced by both arrivals and departures and the capacity as established here, only reflect conditions modeled and can be expected to change proportionately as various assumptions change. A dual lane runway system is imbedded in both a specific terminal airspace environment incorporating the terminal airspace restrictions and a selected taxiway/apron/gate layout of unique design. Thus, the numbers presented in this report are not expected to be reproduced operationally.

The configurations were exposed to a number of VFR and IFR traffic demand levels in order to determine the sensitivity of each configuration parameter to traffic loading variations. The various levels correspond to saturation loading under; present radar separation requirements, decreased separation possible through assumed ATC system improvements and increased separation requirements based on deteriorating weather conditions. The fast time experiments were conducted according to the following grouping:

(1) VFR conditions with the nominal 3 nmi arrivals (current IFR radar separation minimum). Traffic with 4 nmi and 5 nmi arrival separation was also simulated.

(2) VFR conditions with nominal 2.5 nmi arrivals (decreased IFR spacing anticipated with improved ATC systems).

(3) IFR conditions with 3 nmi arrivals (current IFR radar separation minimum).

(4) Same as 3 above except for either improved or deteriorated assumed IFR weather conditions.

(5) IFR Conditions with 2.5 nmi arrivals (decreased IFR spacing anticipated with improved ATC systems).

(6) IFR conditions with 4 and 5 nmi arrivals (operations under IFR with increased spacing requirements due to increased runway occupancy times).

Related Sensitivity Studies

(7) Number of exits and exit class requirements to support saturation traffic.

(8) Sensitivity to aircraft type distribution operating on dedicated runways.

(9) Sensitivity to variations in the number of heavy jet operations to wake turbulent dependent and independent runway complexes.

A single traffic mix was used throughout the simulation experiments. The combination of maintaining constant demand on each configuration and the wide range of effects investigated throughout the course of the study necessitated the varying of arrival and departure spacings. Arrival and departure traffic samples using specific spacings were created and called scripts. A specific script was used for each of the above experiment groups. Ideally, the traffic script selected maintained a small queue to each runway on the most efficient configuration of the group. The resulting capacity, queuing and delay profiles could then be compared to those obtained on the remaining configurations.

The arrival scripts (IFR and VFR) generated aircraft at nominal interarrival separations ranging from 2.5 nmi to 5 nmi with a positive 10 to 20 sec uniform delivery error. The outbound traffic originated at a departure gate at periodic intervals ranging from 60 to 120 sec with a 10 sec delivery error. During VFR experiments, the requirements to constantly demand service to the departure runway for a dual lane system with runways maintained in the dedicated mode required a generation rate at the departure gate of one aircraft every 60 sec. Under the more restrictive IFR conditions, a generation rate of one aircraft every 90 sec was found to be adequate to load the system. The actual rate of departures from the simulated dual lane configuration was a function of the simulation dynamics.

3.0 DUAL LANE RUNWAY ISSUES/FINDINGS

3.1 Background

The study objective was to establish a standard dual lane runway configuration. This was accomplished by evaluating dual lane parameters and operational procedures through the use of:

(a) a real time interactive graphics airport simulation, and

(b) a programmed controller (fast time) airport simulation.

As pointed out in Section 2.0, the initial simulation technique chosen was real time interactive graphics. Input values for the simulation were selected based on report information (see bibliography), field observations, and measurements [3]. Visits to airports with operational dual lane runway systems were made (see Appendix C). Extensive observations of pilot and controller techniques were performed at Los Angeles and San Francisco Airports. Each airport had two sets of 750 ft centerline-spaced parallel runways; the Los Angeles pairs are parallel to each other while San Francisco had the pairs intersecting each other at about their mid points. Pilots were observed from the vantage point of the cockpit area and interviewed on several flights between major airport pairs. Data measurement programs were conducted at Logan Airport, Boston, and at Atlanta Airport; the data were reduced, analyzed [3], and incorporated into the simulation.

The dual lane airport interactive graphics computer program simulated aircraft traffic flying into and out of a pair of closely spaced parallel runways. The program handled arrivals from the outer marker to the terminal apron area and departures from the apron area to their transition over to departure control (Figure 5).

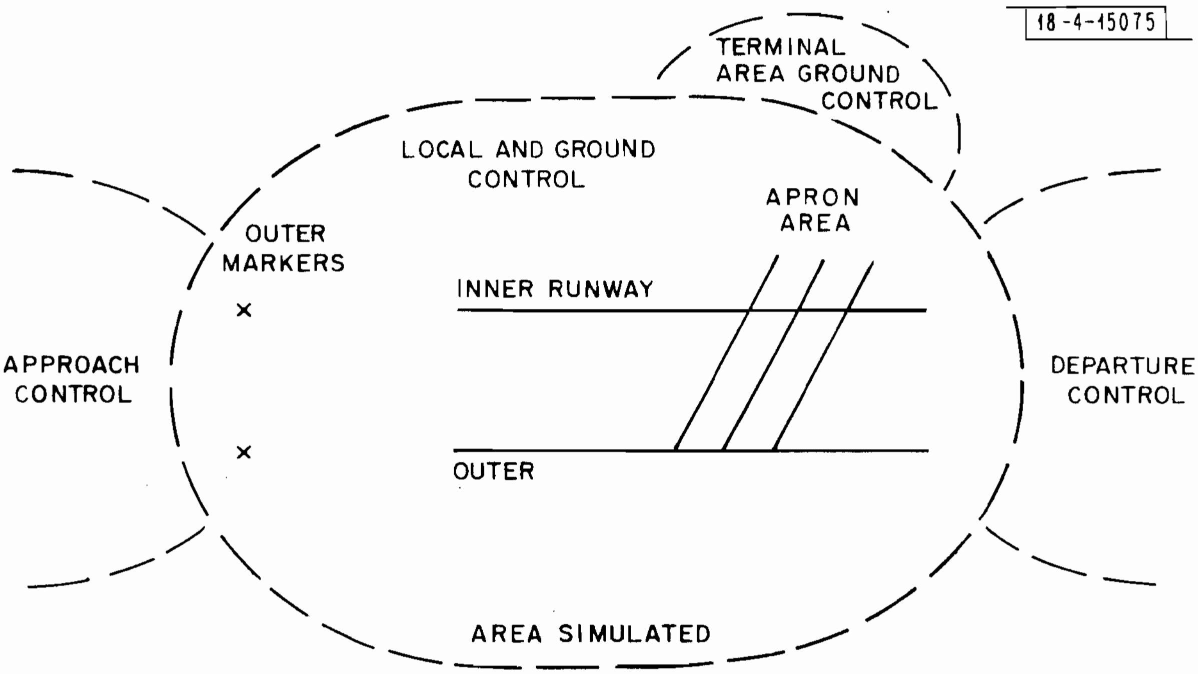


Figure 5. Simulation Boundary of the Airport Terminal Area.

A series of computer experiments were designed to perform an evaluation of candidate runway configurations. The experiments explored the impact of changes to the following dual lane runway parameters on ATC operations and capacity:

(1) High speed exit velocity/placement

(2) Centerline spacing

(3) Arrival/departure runway preference

(4) Runway threshold stagger

(5) Parallel taxiway placement

(6) End point vs mid point crossing.

Specific configurations and scenarios were selected for simulation and were designed to aid in the evaluation of the parameters listed above. A summary of configurations used is shown in Figure 6. Experiments were performed using these configurations both with the ATC controller directing traffic in real time (Section 5.1) and with a programmed controller concept (fast-time runs (Section 5.2)) on the TX-2 computer. Simulated traffic mix and the traffic distribution were standardized to obtain a measure of the key dual lane runway parameters. Two modes of operations for various arrival and departure traffic flow rates were used:

(1) Arrivals and departures routed to separate runways (segregated traffic)

(2) Arrivals and departures mixed on each runway (mixed traffic).

Four practicing air traffic controllers spent over a total of 200 hours at the computer console controlling and directing saturation traffic to the simulated dual lane runway configuration. Jointly, these simulation runs were used to "debug" the simulation, evaluate the experimental procedures, and test potential

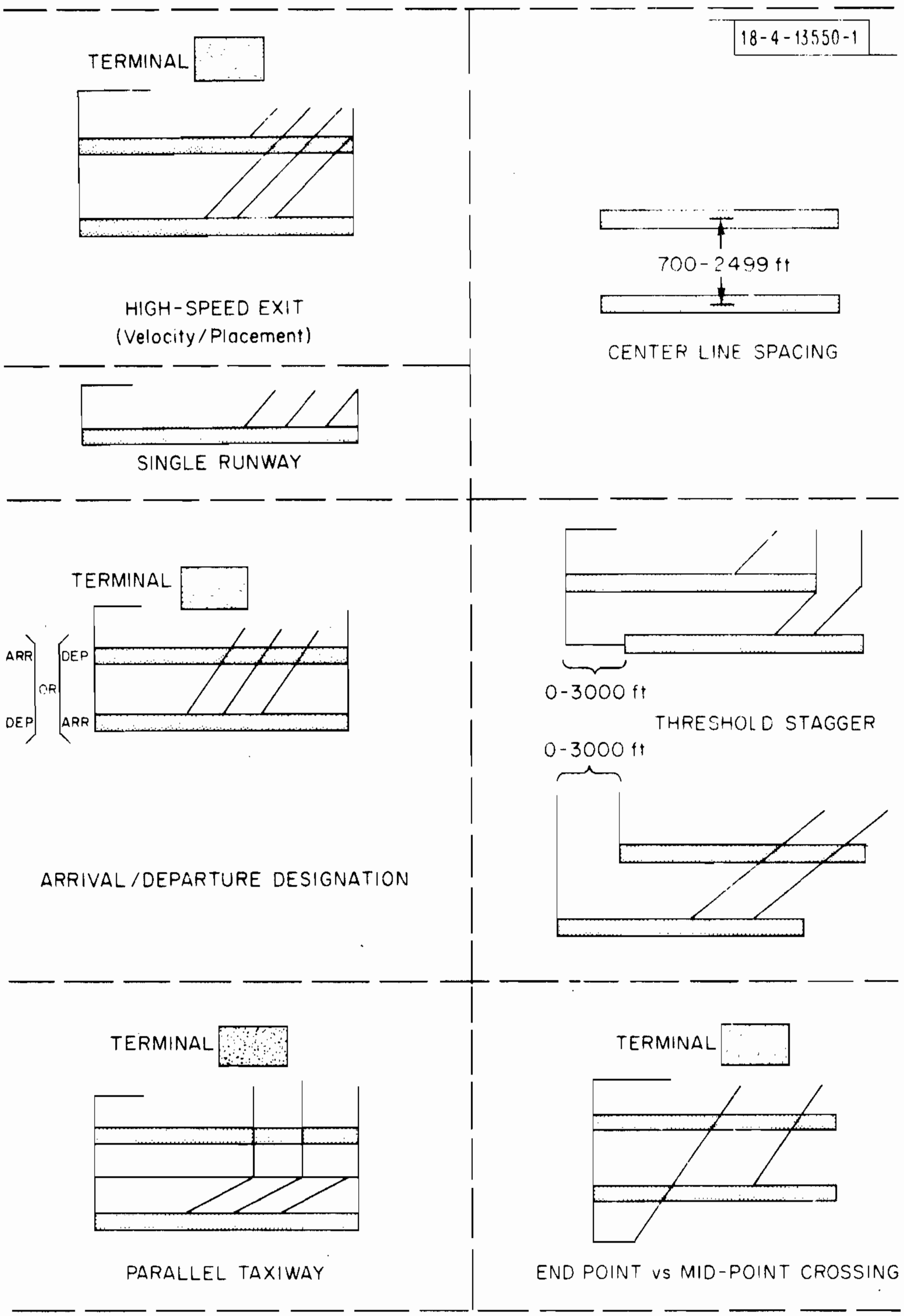


Figure 6. Summary of Dual Lane Parameters Investigated Through Simulation.

recommendations. The observations were also used to develop a set of general rules of control which were programmed into the TX-2 computer. The latter allowed traffic to dual lane configurations to be directed and controlled by the computer eliminating individual controller variations. The time consuming live simulation runs were used to verify the programmed controller findings. Over 400 hours of simulated traffic was run in fast time using the various dual lane configurations investigated. Observations were made during real time to determine alternate means of directing traffic to maximize traffic flow while attempting to lighten controller workload under saturated traffic conditions. For example, initial simulation runs were made with the controller directing traffic himself using the pen and tablet. This technique did not fully simulate the controller workload involved in actual tower operations; in fact, it simulated an automated environment with an automated tracking algorithm and data link. In order to better represent the present ATC tower control conditions, headsets and push-to-talk microphones and flight strips were employed at the operating consoles to permit the controller to issue voice commands. We then observed that the voice channel started approaching saturation when the number of mixed operations exceeded 90 per hour. This figure compares favorably with a recent report on voice communication channel loading [32].

Programmed controller experiments were conducted to provide the numerical data required to place the issues and findings of this report on a quantitative basis. The experiments were conducted using the following assumptions:

(1) Operations in both VFR and IFR conditions

(2) Current FAA operating procedures as relates to wake turbulence

(3) Traffic levels requiring use of both runways (continuous heavy demand)

(4) Various arrival/departure ratios

(5) Zero wind

(6) An inter-arrival spacing range of 2.5 to 5.0 nmi

(7) Aircraft type mix simulating commercial hub airport traffic

Heavy (747, DC-10, etc.)	20 percent
Large (707, DC-8, etc.)	40 percent
Medium* (727, DC-9, etc.)	30 percent
General Aviation	10 percent

The baseline dual lane runway configuration is characterized by a closely spaced pair of parallel runways of equal length with no threshold staggering. Simultaneous operations (Section 3.2.2) as well as IFR dependent operations (Section 3.2.1) involving commercial carrier aircraft are authorized with runway centerline separation greater than 700 ft [17]. This distance establishes the the minimum runway separation considered in this study. The parallel runways, surpporting simultaneous VFR operations, offer an attractive approach to increase substantially the number of airport operations possible over the number for a single lane system. Even under IFR conditions with runway activity restricted to dependent operations, maximum throughput remains higher than that possible for the single lane system.

As pointed out previously, the first effort emphasized the VFR mode of operations in order to subject the dual lane system to the greatest demand. IFR operations and additional operations under VFR conditions on a dual lane complex were subsequently investigated.

Preliminary analysis in this study were directed toward the task of uncovering the sensitivity of airport operations to variations in the basic parameters characterizing the dual lane system rather than an analysis of capacity of dual lane

*Medium is a simulation term and not an FAA designated aircraft class.

runway configurations. Comparative capacity and delay were utilzed as measures for the various configurations. Advantages and disadvantages of additional runway separation and threshold displacement (runway stagger) were analyzed. Likewise, the factors which influenced arrival and departure runway preference in a dual lane system were listed and discussed. Modifications to the basic runway configuration such as the addition of an inclusive parallel taxiway or a change in runway crossing strategies were considered. Although additional modifications (high speed turnons, staging areas, general aviation runway) were identified; they were not included as part of this investigation. We have attempted to identify the effects of all factors relevant to the dual lane system. Several factors were not directly modeled although their effects need to be considered in the final selection of the dual lane configuration. Economic and safety (effects related to blunders and wake turbulence) models were not developed as part of this simulation effort. Constraints related to safety were implicitly incorporated in the experiments by closely adhering to FAA procedures and regulations in the design and operation of the dual lane runway simulation. The conclusions are based on analysis of data and observations of controllers directing traffic during the dual lane runway simulations.

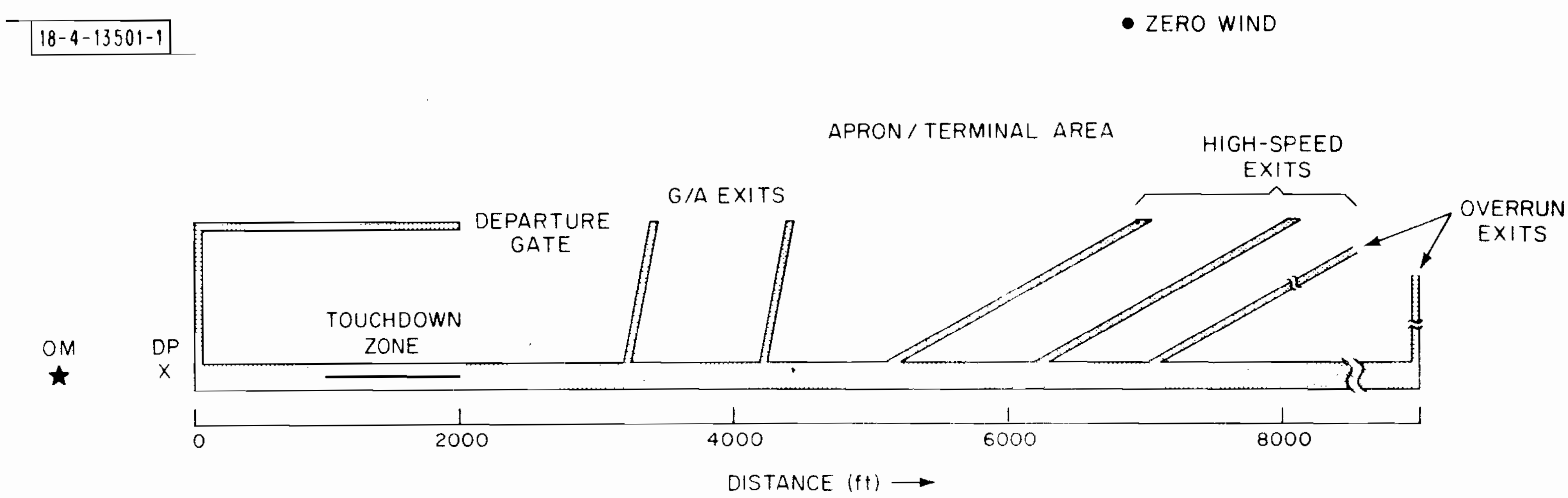
This section discusses the various parameters characterizing the dual lane system. The general format consists of a brief introduction followed by the description of the issues and the experimental findings for each parameter considered independently. For example, the effect of increasing centerline spacing or increasing threshold stagger were determined experimentally by adjusting one parameter while holding the other parameter constant. Then the procedure was alternated and the simulations repeated to arrive at the effect of the other parameter. To measure the effects of either the inclusive parallel taxiway or a midpoint crossing procedure, it was necessary to first establish a "standard" dual lane configuration against which effects caused by introducing these additional features could be compared.

All simulation experiments reflect zero wind conditions. It was decided that including wind would vary exit placements due to reduction in aircraft approach velocities but would not impact any of the other dual lane parameters. A nominal (simulation variable) interarrival spacing existed between successive arrivals when the first aircraft on final was over threshold. A stream of departures to one or both of the dual lane runways simulated heavy departure traffic demand.

Figure 7 illustrates all features characterizing the single lane runway. Number and location of exits represented are developed in Section 3.3. It also represents the standard arrival runway of a dual lane runway model. When the traffic level demanded arrivals and departures on both runways, two such standard arrival runways make up the dual lane configuration.

3.2 Operation Considerations

Airports using parallel runways generally designate one for arrivals and one for departures. This segregated operation reduced workload and was generally preferred by controllers over mixed operations to each of the parallel runways. The ILS localizer and glide slope are placed on the designated arrival runway. In periods of very light VFR traffic (occasional arrivals and departures), the controllers tend to utilize a single runway: generally the one closest to the terminal area. The level of traffic which indicates the use of both runways



HIGH-SPEED EXIT PLACEMENT (ft)	AIRCRAFT
4800	DC-9, 727, etc.
6100	DC-8, DC-10, 707, 747, etc
7000	HIGH-SPEED OVERRUN

★ OUTER MARKER (OM) TO THRESHOLD - 4.5 n mi

X DECISION POINT (DP) TO THRESHOLD

Figure 7. Diagram of the Single Lane Runway, Illustrating the Locations of the Touchdown Zone, G/A Exits, and High Speed (60 mi/h) Exits.

cannot be expressed as a number. Operational preferences are decisions based upon specific runway demand situations at a given airport. Each of the parallel runways may be used to handle mixed or segregated operations; it is strictly a function of the specific arrival or departure demand. However, the number of operations which one or both of the runways of a dual lane system can accommodate with segregated or mixed operations operating under VFR or IFR can be expressed quantitatively.

3.2.1 IFR considerations

Flight is conducted under rules designated as IFR (Instrument Flight Rules) in weather conditions when the visibility becomes less than 3 nmi and/or the ceiling becomes less than 1000 ft. Separation between all IFR aircraft is maintained by terminal and en route radar controllers. IFR procedures may be summarized as follows [17]. A 5000 ft runway separation is required to permit independent arrival operations to a pair of parallel runways. A 3500 ft runway separation is needed to permit independent departure operations or independent arrival/departure operations to a pair of parallel runways. At runway separations less than 3500 ft, dependent arrival/departure operations are permitted. Generally, traffic is segregated; that is, arrivals are serviced on one runway and departures on the other. The departure release is dependent upon the position of the approaching arrival. Departure takeoff clearance is withheld from the time an arrival is within 2 nmi of its runway threshold until the controller is assured that the arrival is committed to land. The intention is not to have two aircraft airborne in close proximity as may be caused by releasing the departure and having the arrival execute a missed approach procedure. The IFR simulation runs followed these procedures.

3.2.2 VFR considerations

Flight may be conducted within a terminal area under VFR (Visual Flight Rules) whenever the visibility is greater than 3 nmi and the ceiling is greater than 1000 ft [17]. However, commercial carrier aircraft are required to file and fly IFR flight plans regardless of the weather conditions. This means that commercial carrier aircraft spacings are maintained by radar controllers. VFR conditions permit a visual approach procedure where the controller transfers the responsibility to the pilot to maintain separation between his aircraft and the preceding one. Generally, the controllers have these aircraft transition to visual approaches somewhere outside the outer marker. The visual approach allows both air carrier and general aviation independent arrivals, independent departures, and unrestricted arrival/departure operations to runways spaced at least 700 ft apart. Simultaneous operations are here defined as side-by-side arrivals or departures.

When conditions warrant, controllers permit general aviation aircraft operating VFR to execute short final approaches and merge with the air carrier stream inside the outer marker. This allows controllers to fill gaps in the stream of arrivals, thereby, not restricting the stream flow.

The simulation followed the above procedures with the exception of permitting general aviation aircraft to execute short final approaches. The steady stream of arrival traffic simulated did not provide any convenient gaps to be filled in this manner.

3.2.3 Wake turbulence procedures

Wake turbulence procedures [25] are in effect when heavy jet aircraft are in the traffic mix. Heavy jet aircraft (> 300,000 pounds) create wake turbulence vortices [28] which can seriously affect the flight of following aircraft. All heavy jets in the simulation are treated alike.* Wake turbulence procedures apply only for arrival/arrival and departure/departure operations. There are no restrictions between arrival/departure operations to parallel runways.

3.2.3.1 Arrival

For the arrival of a heavy jet, the procedure requires at least a 5 nmi gap behind it for any following non-heavy aircraft. If the following aircraft is itself a heavy jet, the gap need only be 3 nmi. For two aircraft making parallel approaches to adjacent parallel runways, a 5 nmi gap behind a heavy jet must be maintained for a following non-heavy aircraft landing on the adjacent parallel runway. This wake turbulence dependence relationship between runways applies when runways are spaced less than 2500 ft apart.

3.2.3.2 Departure

A two-minute hold period behind departure of a heavy jet is required if the following departure is a lighter jet. If the following departure is itself a heavy aircraft, only the normal VFR 600 ft in-trail separation distance is required. When operating parallel departure runways, a two minute hold period after a heavy jet is necessary for any non-heavy aircraft departing the adjacent runway for spacings less than 2500 ft.

3.2.4 Controller workload

It is very difficult to adequately measure controller workload. Simulation cannot reproduce the airport environment and stress situations induced when human lives are in the balance. Controller workload, as referred to in this report, was derived from observations of controllers directing saturation traffic through the various dual lane configurations investigated in the real time simulation mode.

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* When these procedures were incorporated into the simulation, there was no distinction made between types of heavy jets as there is presently. The recent heavy tri-jet wake turbulence procedure recommends that all aircraft except the C5A and the B747 maintain at least 5 nmi in-trail separation behind the new heavy tri-jets (DC10 and L1011). The C5-A and B747 should maintain at least 3 nmi separation behind the heavy tri-jets.

3.2.4.1 IFR workload

Mixed VFR operations to one or both runways of a dual lane system is a valid concept. Mixed IFR operations on one or both runways, although valid, are not considered realistic. The number of IFR dependent operations supported by the dual lane complex depends upon the actual weather conditions. A departure is normally released when, in the controller's judgment, the arrival to the adjacent runway is committed to land and most likely will not execute a missed approach. The controller makes this judgment, in part, by observing the approaching aircraft's velocity, altitude, and position. Under poor visibility conditions, there are times when the controller cannot see the threshold end of the runway. Under these conditions, the controller must wait until he actually sees the aircraft on the runway or request the pilot to give him a call and state his progress.

The controller workload under these poor visibility IFR conditions was increased appreciably as the controller had to maintain the dynamic picture of the events taking place on the runway/taxiway complex in his mind. Also, the identification of each aircraft, along with its position, had to be maintained. The number of transmissions increases per aircraft so that the controller could constantly maintain the progress of all aircraft on the runway/taxiway configuration.

3.2.4.2 VFR workload

Mixed VFR operations to both dual lane runways was found to create a workload burden to the controller. The simulation revealed that a single local controller using an assistant, could not sustain this level of traffic for even a short period of time. The single voice channel was constantly in use.

In general, one of the most difficult decisions a local controller must make occurs when he is directing mixed traffic operations. The controller must determine whether he can permit a departure between two successive arrival aircraft. The decision becomes more difficult in peak traffic situations where interarrival spacings are reduced to increase traffic flow. Judgment based on experience is required to establish whether the time between arrivals will permit an interleaved departure on the same runway without incident. The task is to judge the length of time the first arrival will spend rolling out on the runway; the total length of time the departure will spend taxiing to get into position on the runway, accelerating and then lifting off from the runway; and finally, estimating how long the second arrival will take to reach his decision point to land or execute a missed approach. The pilot has the final responsibility to land and if he feels the controller has brought him in too close to the departing aircraft, he will execute a missed approach to be resequenced to the runway. Missed approaches are avoided whenever possible. The controller workload burden associated with handling mixed traffic operations to dual lane runways was apparent in the real time simulation runs.

This controller workload increase suggests either going to a second local controller using two voice channels or providing some automation aids to the single local controller. If a second controller is employed with a second frequency, the pilots operating on the dual lane system would not be appraised of the traffic to the other parallel runway as they are now through monitoring the common frequency. Experiments performed at M.I.T., [33] using their airborne traffic simulation display (ATSD) cockpit mockup, have indicated that pilots have an acute mental bookkeeping system for traffic awareness in their area. The loss of this awareness will occur when discrete digital data link communications are implemented which will not permit pilots to mentally track traffic in their area. It is concluded, that some aids to the local controller which do not cause loss of pilot awareness, are needed. A visual display depicting the runway/exit/taxiway complex with the moving aircraft identified with alphanumeric tags presents the best candidate. The display should be readily available to both local and ground controllers.

3.2.5 Capacity

The number of operations per hour (capacity) was used in the study as a comparison measure to help establish relative merits for the various dual lane configurations investigated. These capacity figures are either simulation results or values derived using the simulation results. The origin of the values quoted are indicated. Figure 8 is a summary of the single and dual lane runway capacity figures derived from the simulation results. The values on Figure 8 were rounded off for presentation purposes. For example, the simulation found 38 arrival operations per hour to an arrival runway running a 3 nmi interarrival gap. This was rounded to 40 on the summary figure.

3.2.5.1 Single lane VFR capacity

The simulation found a single lane configuration with high speed exits to consistently support 60 VFR mixed operations per hour (Figure 9). A wide range of arrival/departure ratios were found to be supported. At 4 nmi inter-arrival spacings, the arrival/departure ratio was one consisting of 30 arrivals and 30 departures. The wide range of ratios exhibits the possible flexibility available in coping with peak operational loading with little or no loss in capacity handling capability.

-4-15511

		VFR				IFR*			
	TRAFFIC	ARRIVALS		DEPARTURES	TOTAL	ARRIVALS		DEPARTURES	TOTAL
SINGLE LANE	SEGREGATED	40	or	60	-	25-40	or	50-60	-
	MIXED	25-40**	and	35-20**	60	15-25	and	15-25	30-50
DUAL LANE	SEGREGATED	40	and	60	100	25-40	and	40	65-80
	MIXED	55	and	55	110				

* Figure spread is function of weather conditions.

** Figure spread is function of interarrival spacing used.

Figure 8. Simulation Derived Capacity Summary.

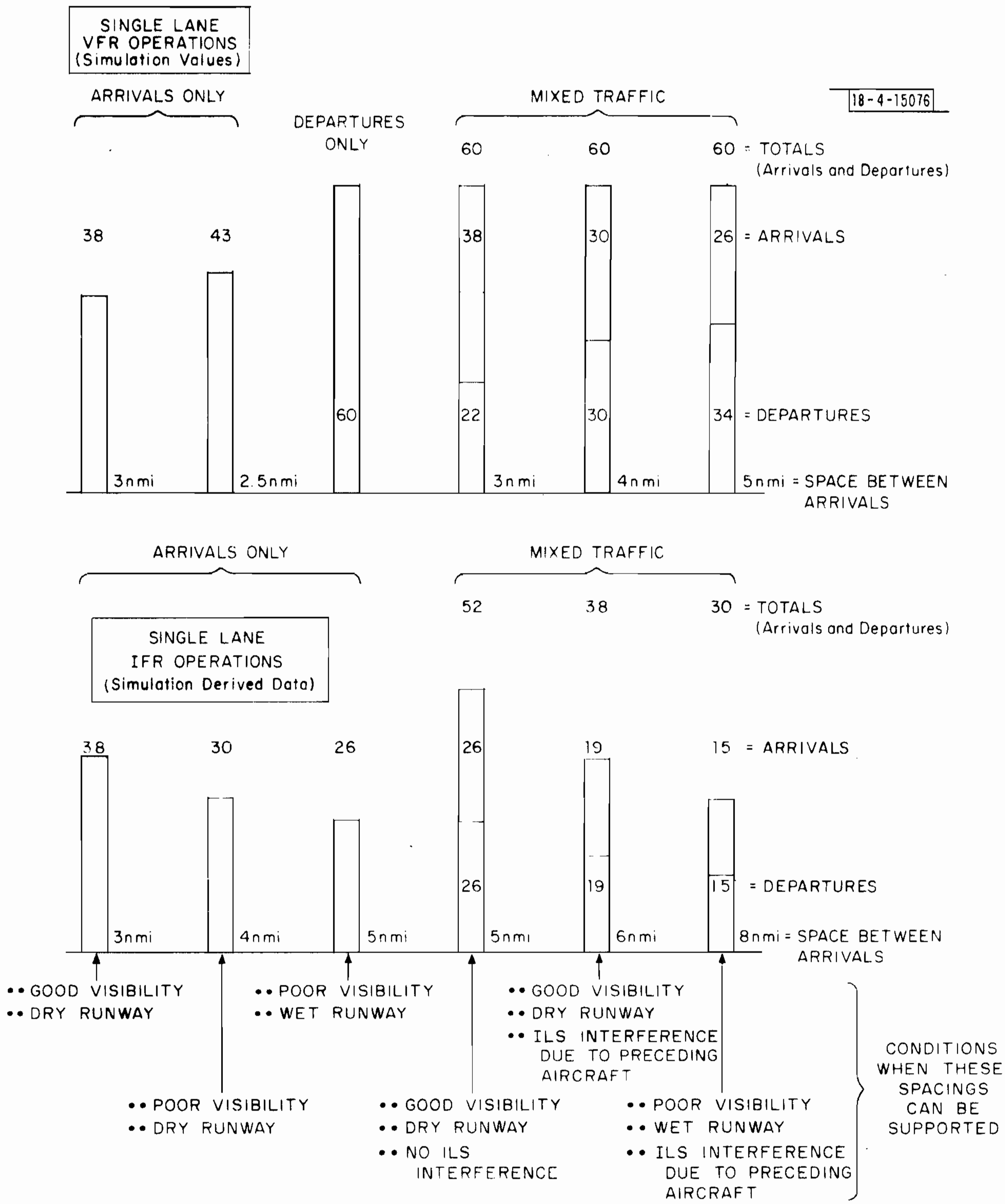


Fig. 9. Single Lane Runway Capacity Summary.

The single lane capacity figures reflect those values which one runway of the dual lane system would be expected to accommodate if there were no dependency considerations between parallel runways. However, due to aircraft runway crossings and wake turbulence restrictions, the single lane figures are seldom achievable for one of the dual lane runways.

The single lane was found to consistently support 60 VFR air carrier departure operations or a one departure per minute average. Higher average rates of up to 80 per hour (one departure every 45 seconds) was found for short periods of time. However, due to the required two minute wait behind heavy departures, the problem of having a departure in position and ready every 45 sec, plus the problem of overloading the departure airspace, the 60 departure per hour figure appears to be the more realistic.

Minimum radar spacing of 3 nmi between arrivals permits 40 arrivals per hour to an arrival runway. If it is found that this spacing could be safely reduced then a single lane with high speed exits could support 45 arrivals at 2.5 nmi spacing and 50 with 2 nmi spacing. Two nautical mile arrival stream was attempted in the simulation but an unacceptable number of missed approaches were created due to the spread of runway occupancy times experienced (43 sec with 7 sec standard derivation).

3.2.5.2 Single Lane IFR capacity

The number of IFR operations was determined to be dependent on the weather conditions. Field observations at airports operating in varying degrees of IFR conditions indicated longer arrival and departure runway occupancy times under poor visibility and wet runway conditions. Weather conditions were not simulated. These conditions were accounted for in the simulation capacity figures by increasing inter-arrival spacings beyond the minimum specified by the FAA under IFR conditions. It is concluded that 30-50 IFR air carrier operations can be consistently supported by a single lane runway with conventional angled exits. Figure 9 shows various arrival/departure combinations possible. These IFR single lane figures were derived from the VFR Simulation values. For example, the 6 nmi spaced arrival traffic of 19 arrivals per hour is half the 3 nmi arrival traffic of 38 per hour from the simulation. The 6 nmi value for inter-arrival spacing to reduce ILS interference created by the previous arrival and the inter-leaved departure is a value derived from talks with operational controllers. The 8 nmi inter-arrival spacing is a similar value used operationally when fog obscures a wet runway. Under these conditions, landing aircraft spend a minute or more on the runway due to the poor visibility and slippery runway conditions.

3.2.5.3 Dual lane VFR capacity

The simulation found an approximate 70 percent increase in dual lane capacity over a single lane from 60 to 100 VFR mixed operations (Figure 8). This increase was achieved by a slight increase in controller workload in going from single lane mixed operations to dual lane segregated operations. The number of arrivals which can be supported in the segregated dual lane mode is restricted by the minimum radar spacing of 3 nmi to 40 arrivals per hour. Mixed VFR operations to both runways has the potential to increase total operations by 20 percent over segregated operations; the increase is from 100 to 120 operations per hour. However, the simulation found only a 10 percent increase to 110 hourly operations mainly due to wake turbulence dependency procedures to runways less than 2500 ft apart. When all heavy aircraft were removed from the mix, thus eliminating wake turbulence restrictions, a full 20 percent increase in operations was found. The

10 percent increase in operations due to handling mixed traffic on both runways is accompanied by a disproportionate increase in controller workload. The arrival/departure ratio of 1:1 was obtained by running 4 nmi inter-arrival gaps and consistently interleaving a departure on both runways. The 4 nmi gap with consistent interleaving of departures was made possible by the reduced arrival runway occupancy times consistent with high speed exit usage.

3.2.5.4 Dual lane IFR capacity

An increase in dual lane IFR hourly operations over a single lane was found to be between 60 to 100 percent accounting for weather conditions. Under the better IFR conditions, (something just less than 3 nmi visibility or just under 1000 feet ceiling) the minimum 3 nmi radar arrival separation to the arrival runway resulting in 40 arrivals was supported. Under these conditions, the dual lane will support 80 operations with a 1:1 arrival/departure ratio for a 60 percent gain over the 50 operations a single lane will support. Under the poorer IFR conditions, an increase from 30 to 65 operations was realized. When the IFR conditions will not permit 3 nmi arrival spacing, usually due to poor visibility, wet runway conditions, or ILS signal interference, then 4-5 nmi arrival spacing is needed to an arrival runway. Inter-arrival spacing of 5 nmi results in 25 arrivals per hour accompanied by 40 dependent departures on the departure runway.

3.3 High Speed Exits

Several airport capacity studies [18-20] discussed the use of high speed exits in order to reduce runway occupancy time and to increase airport capacity.

Factors involved in the utilization of high speed exits are as follows:

(1) Arrival separation

(2) Runway occupancy time

(3) Runway Exit design

  (a) Design speed

  (b) Exit placement from threshold

  (c) Exit geometry

(4) Pilot technique

  (a) Touchdown speed

  (b) Touchdown point

  (c) Deceleration profile followed

  (d) Passenger comfort consideration

  (e) Brake wear consideration

(5) Runway considerations

  (a) Weather effects

  (b) Wind effects

  (c) Day or night operations

  (d) Lighting available

  (e) Visual landing aids available

(6) Exit preference

  (a) Convenience due to gate location

  (b) Assignment of exit

An example of improved capacity is provided by the parallel runway capacity forecasts contained in the Air Traffic Control Advisory Committee report which postulated improved surveillance, guidance, and control functions to decrease the interarrival spacing to 2 nmi. An increased arrival capacity would result from a decrease in the minimum separation standard (presently 3 nmi) to a value consistent with the reduced runway occupancy time. For example, with 2 nmi separation, sixty mi/h exits (considered to be an upper limit to this parameter) are required to free the runway for a subsequent arrival. However, data on such factors as pilot acceptance, and runway and aircraft conditions required for such operations are not readily available. Individual pilot techniques generate widely varying runway occupancy times due to the variation in individual deceleration profiles. Reduced separation cannot be practically utilized until these variations are reduced significantly.

Factors which affect an individual pilot's ability to land consistently are: weather (wind shear, visibility), type of operation (day or night), visual landing cues and aids, and the pilot's skill and concentration. These factors have not been investigated in this analysis.

The effects of minimum runway occupancy time under the constraints imposed by the present minimum separation standards (3 nmi) was an area investigated in the dual lane runway study. Sixty mi/h exits were incorporated into the simulation under the assumption that the pilots would cooperate and accept such an exit speed.

3.3.1 Exit placement

The location of a high speed exit is critically dependent on an aircraft's touchdown speed, point of touchdown, and deceleration profile. To correctly model an arrival, each parameter must be described; however, data in these areas are sparse. A design procedure is to assume a nominal air speed of 1.3 V_s, where V_s is defined as the aircraft's stall speed for its weight, runway altitude, and outside air temperature on landing. The Boeing Jet Performance Manual [21] recommends the nominal approach be followed by a flare procedure to a landing accomplished at a touchdown air speed of 1.2 V_s. Figure 10 illustrates the dependence of the recommended approach speeds as a function of an aircraft's landing weight for a number of jet aircraft currently in the commercial carrier fleet. The problem of correctly handling each aircraft's approach profile is compounded by the fact that operationally, one observes significant variability and deviation from the recommended techniques. [7-16]

Field data [10] supports a mean approach speed of 1.39 V_s, which is somewhat higher than that recommended, with a standard deviation of 0.07 V_s. Likewise, touchdown is accomplished at an increased air speed with a large standard deviation.

The aircraft approach and touchdown parameters, as modeled in this analysis, reflect the observed values. Further, one finds a wide variation in the distance to touchdown exhibited in normal operations. A study [10] on operational landing parameters for a number of first generation jet transports showed a mean touchdown distance from threshold of 1514 ft, with a standard deviation of 593 ft. Other reports [3,8,11] support these findings.

A 1000 ft (1500 $\pm$ 500 ft) touchdown zone was used as the basis for the simulation high speed exit placement. Exits are considered, based on a constant deceleration of 5 ft/sec^2, an average believed to be easily maintained by all arrivals under widely varying conditions [19,29,30,31]. Arrivals are assumed to decelerate to the exit speed and then take the first available high speed exit; no additional exit preference is considered.

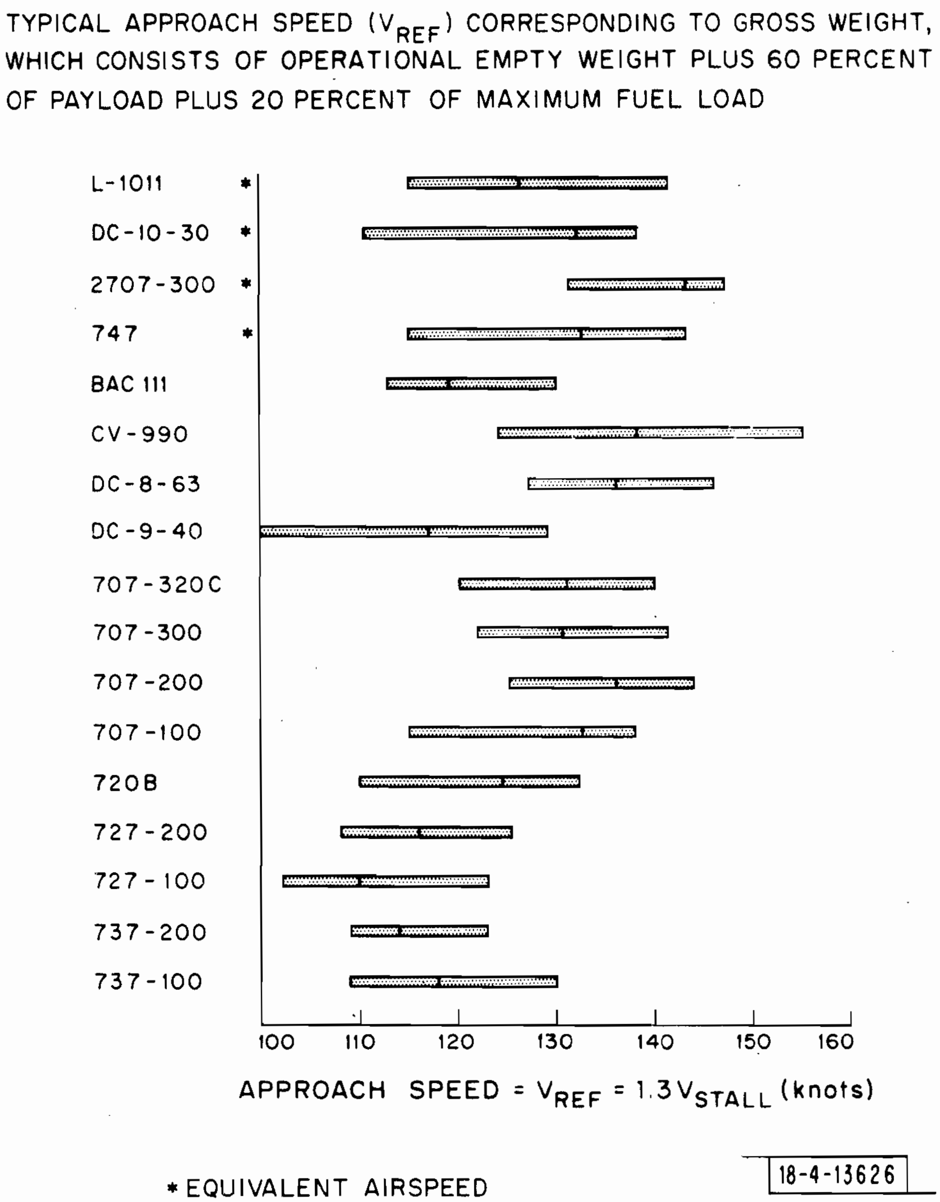


Figure 10. Typical Approach Speeds for a Number of Commercial Carrier Aircraft as a Function of Landing Weight from the Operational Empty Weight Plus Reserves to Maximum Landing Weight (from Ref. 18).

Due to the large variation in operating characteristics between aircraft, separate exits must be established to service a number of classes of aircraft. If maximum throughput is to be achieved, efficient exits must be provided for each class of aircraft which comprise a significant portion of the traffic at that airport. Exits should be located by picking an aircraft class and designing for a touchdown point, a given touchdown speed, and an acceptable deceleration profile. The need for additional exits is established by considering arrivals which touchdown at different speeds and touchdown points. Additionally, one considers whether an adjustment can be made in deceleration by all arrivals in order to exit at the design speed. Each arrival must be handled without excessively long runway occupancy times to minimize the possibility of a missed approach by the next arrival. A second exit may be required for a given class of aircraft if the observed values of parameters such as touchdown speeds and touchdown points are found to vary over a large range.

Figure 11 shows a high speed exit placement tradeoff plot as a function of touchdown velocity, and average runway deceleration to the 60 mi/h point for zero knot wind conditions and a 1500 ft touchdown point. Various additional calculations were performed in order to bound the problem and to develop tradeoffs for the various parameters of concern in the placement of 60 mi/h exits on a runway. A 135-knot aircraft touching down at 1500 ft and braking at an average deceleration rate of 5 ft/sec^2 will arrive at 60 mi/h in 34 sec at a distance of 5800 ft from threshold. If a 60 mi/h exit is located at 6000 ft from threshold, an aircraft could exit at 60 mi/h and clear the runway by 200 ft in another six or seven sec. The simulation assumed the high speed turn-off point to be the point of tangency with runway centerline.

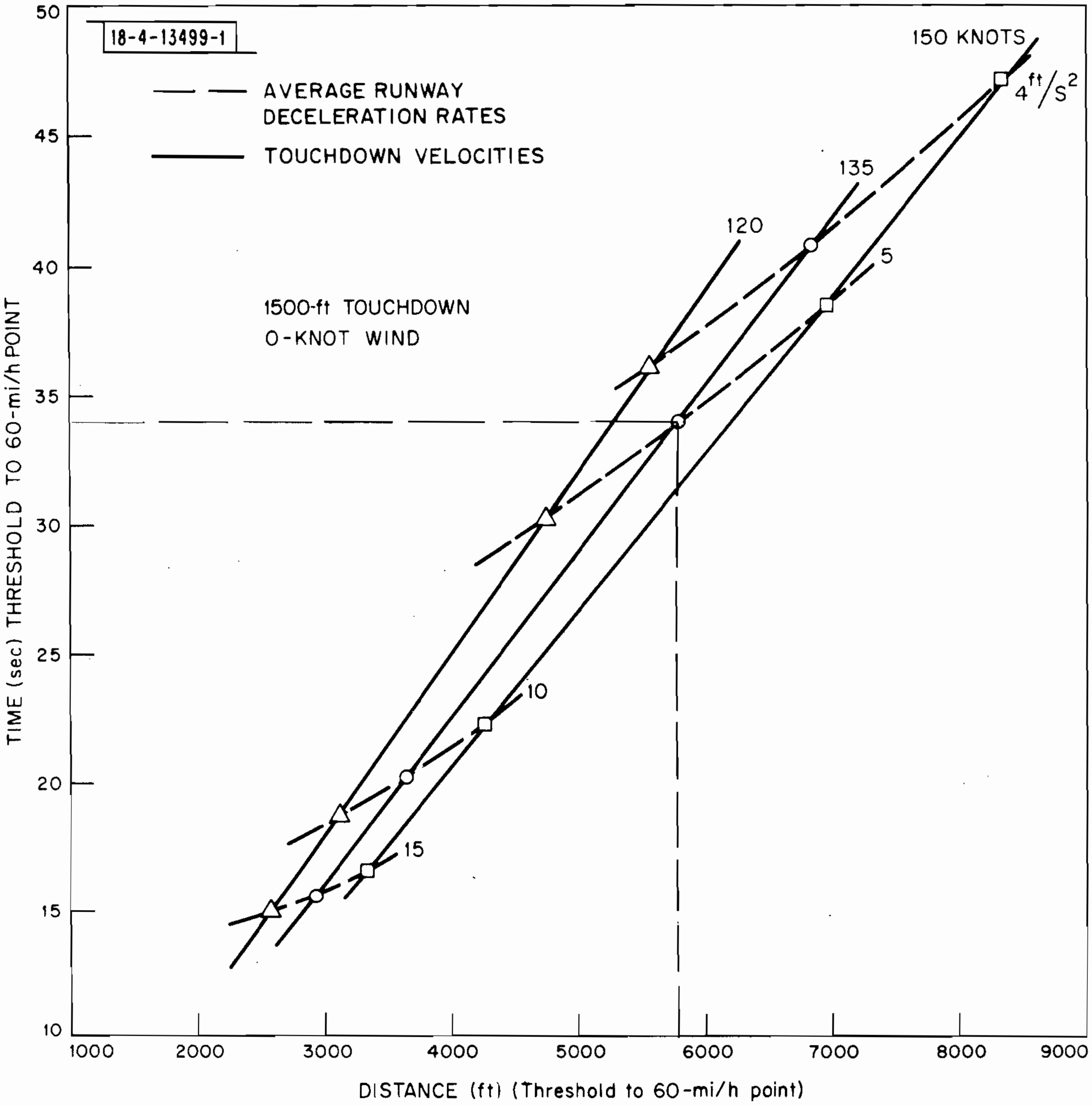


Figure 11. High Speed Exit Tradeoff Diagram for Touchdown at 1500 Feet.

Figure 11 indicates tradeoffs (assuming a 1500 ft touchdown point) for touchdown velocities between 120 knots and 150 knots, and average runway decelerations of 5, 10, and 15 ft/sec^2. High-speed exits at approximately 5,000, 6,000, and 7,000 ft were selected to accommodate commercial carrier jet operations. These placements agree with those recommended by the FAA advisory circular on taxiways [26]. A sensitivity analysis of the impact of eliminating one or more of the high speed exits was performed. It indicated that a single high speed exit was sufficient to handle arrival traffic with 3 nmi separations.

A single-lane runway with high-speed exits was designed, as shown in Figure 7, and traffic was simulated in order to evaluate exit locations and establish baseline data for comparison with the dual lane runway model. As indicated above, 60 mi/h was chosen for the high speed exits. Two 20-mi/h exits were strategically located to service general aviation aircraft. Exits were provided for each class of aircraft considered. Exit placement was determined from an equation of motion for each aircraft class, using an average touchdown speed over a range of touchdown locations and a constant deceleration to the selected exit speed. Each exit turnoff was located to service all aircraft of a given class with touchdown speed less than or equal to the aircraft class's average value; i.e., exit distances from threshold(s) follow from the distance equation

$$S = \frac{v_f^2 - v_i^2}{2a} + \text{t.d.}$$

where exit velocity v_f = 60 mi/h (t2.2 kts), runway deceleration a = -5 ft/sec^2, t.d. = the maximum touchdown distance of 2000 ft (simulation parameter) and touch down velocity (Table 3, p. 118) v_i = 113 kts or 133 kts. The value of v_i is dependent on the class of aircraft the specific exit is designed for. Thus, some fraction of the total number of aircraft with approach speed greater than the average would miss an assigned exit and coast to the next high speed exit. The aircraft that missed the assigned exit tended to be those which landed "long" and/or fast. The wide range in touchdown parameters among aircraft of different classes controlled the placement of two high speed exits. A third 60 mi/h exit was placed beyond the two selected to serve as an exit for those aircraft rolling past the second high speed exit at a speed greater than 60 mi/h. Similarly, the general aviation class exhibits a wide range in touchdown speed. This dictated the use of two G/A exits in order to generate runway occupancy times compatible with the minimum interarrival spacing used in the simulation. The first high speed exits served as an overrun exit for any G/A aircraft rolling too fast to exit from either of the two exits provided. In placing the exits, it was assumed that touchdown zone location is class independent. Data do not exist either to substantiate or to reject this assumption.

The simulation found that 3 high speed exits reduced runway occupany time 20% over conventional angled exits to 43 sec with a 7 sec standard deviation. Current data on high speed exit performance is not available in the literature. The data showed that a majority (~95 percent) of the traffic had runway occupancy times between 29 and 57 sec. Figure 12 shows that for a 57 sec runway occupancy time the next arrival 2 nmi in-trail cannot exceed 126 kts or a missed approach will occur. Figure 10 shows that a significant number of the commercial carrier aircraft normal approach speeds exceed this figure thus, creating a missed approach situation. Some form of speed control on final approach would be necessary to

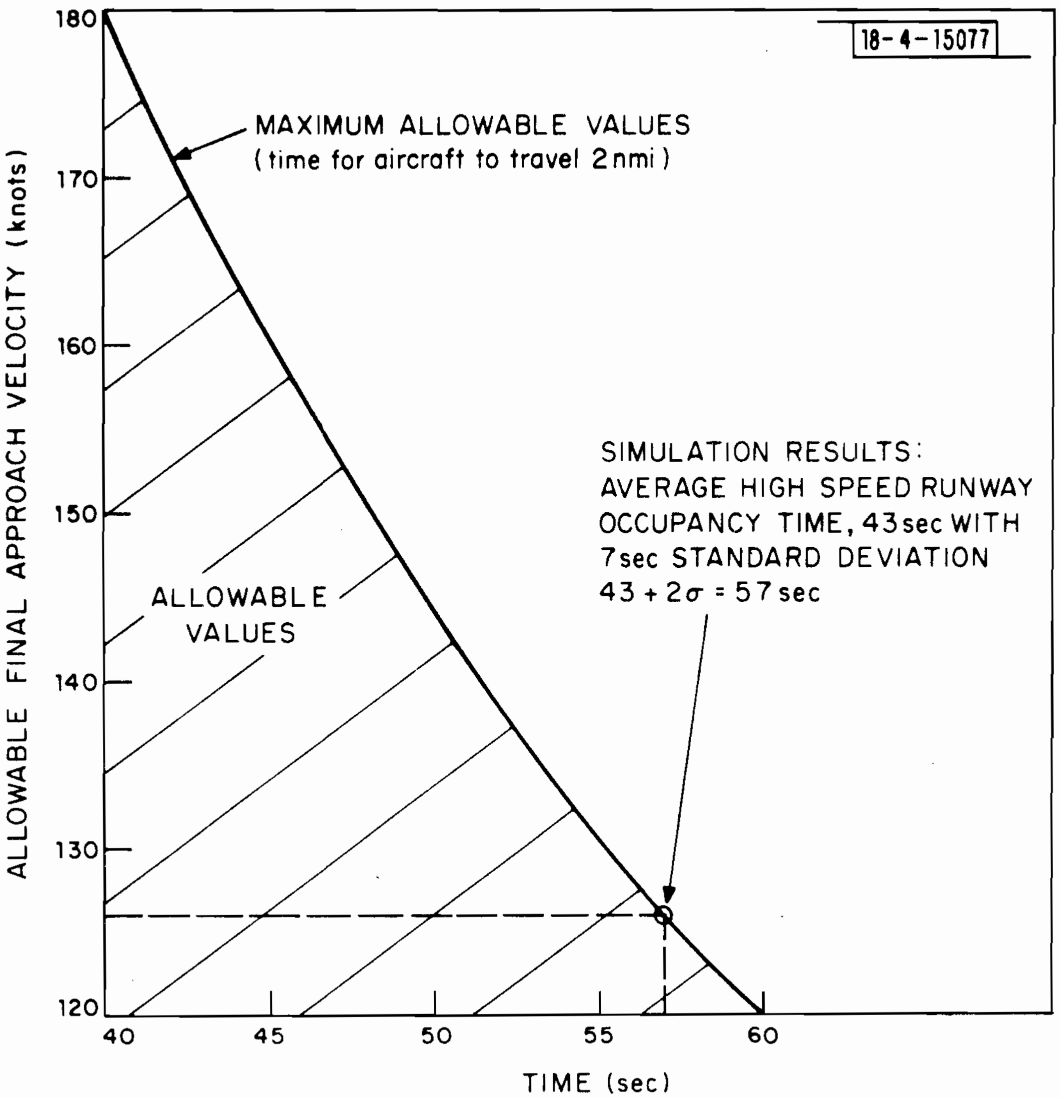


Figure 12. Maximum Allowable Final Approach Speed to Support 2 nmi Arrival Stream.

augment the 20% runway occupancy time reduction to permit consistent runway acceptance of a 2 nmi stream of commercial carrier arrivals. With mixed traffic and 3 nmi separations, departures were accommodated only due to natural gaps, (i.e., after a heavy jet arrival or before a general aviation (G/A) arrival). In order to routinely insert a departure between any two successive arrivals, the interarrival spacing was later increased to 4 nmi.

Figure 13 shows an exit tradeoff analysis for high speed exits (60 mi/h) and conventional angled exits (40 mi/h). The tradeoff was performed using steady streams of arrival traffic to a single runway (Figure 2) over four hour periods. Both 3 nmi and 2.5 nmi arrival streams were analyzed. The 60 mi/h exits were placed as shown on the figure. Simulation runs were also exercised after selected exits were eliminated. The available exits during each run are indicated by the crosses in a vertical column. The 40 mi/h exits were replaced according to the equation for exit placement discussed on page 53. The mean, standard deviations, and number of missed approaches (M.A.) for each of the exit configurations were recorded. Using three 60 mi/h exits an overall traffic mean of 43 sec was found. A single missed approach was recorded for this four hour simulation period.

Eliminating one of the three high speed exits increased the average runway occupancy time by about 5 sec. The elimination of one high speed exit had no effect on the 3 nmi spaced arrivals. However, the 2.5 nmi spaced arrival missed approaches rose to an unacceptable level (10-13 missed approaches). The elimination of the first two high speed exits caused the runway occupancy time to increase to 52 sec causing 5 missed approaches. This increased runway occupancy time caused one more missed approach per hour to occur. A single high speed exit to support 3 nmi arrival traffic was found to be adequate in the simulation.

18-4-45078

40 mph EXIT PLACEMENT (ft)	60 mph EXIT PLACEMENT (ft)		EXIT CLASS (mph)	NUMBER OF EXITS AVAIABLE						
5300	4800		60	×		×				
			40					×		×
6600	6100		60	×	×					
			40					×	×	
7300	7000		60	×	×	×	×			
			40					×	×	×
RUNWAY OCCUPANCY TIME (sec) (mean/standard deviation)				43/7	48/11	47/10	52/15	55/7	62/14	60/14
NUMBER MISSED APPROACHES OVER 4-hr PERIOD										
3-nmi separation				1	1	1	5	4	21	15
2.5 nmi separation				1	13	10	—	25	45	43

Figure 13. Exit Tradeoff Summary.

The three conventional 40 mi/h exits support the 3 nmi arrivals, but cause an unacceptable number of missed approaches to the 2.5 nmi spaced arrival stream.

3.4 Centerline Spacing

The separation (centerline spacing) between closely spaced parallel runways is one of the more critical parameters of a dual lane runway complex. The issues involved in this spacing are:

(1) Safety

(2) Capacity/Delay

(3) Cost

(4) Real estate requirements

(5) Wake turbulence effects

(6) Controller workload

(7) Dependency considerations during IFR operation [24] (arrival/arrival, departure/arrival, departure/departure)

(8) Tradeoff of taxi time/taxi distance/stopping distance/exit velocity/number of aircraft held between runways and inclusive parallel taxiway considerations.

A desire to minimize real estate requirements, cost, and the time an aircraft spends in the system, argue for the closest centerline separation consistent with safety, while the desire to increase operational flexibility, reduce pilot/controller anxiety, reduce hazards due to wake turbulence, and provide stopping and holding space between runways, argue for increased centerline spacing. A balance must be reached, consistent with safe practices, which will permit VFR independent operations to closely spaced parallel runways. Simultaneous commercial carrier arrivals and departures were observed during peak hour operations to 750 ft spaced parallel runways at Los Angeles and San Francisco. Their operations demonstrate that a dual lane runway system does constitute a practical method of increasing an airports capacity while reducing aircraft delays.

Increasing parallel runway centerline spacing permits additional airport operational flexibility. Parallel runways greater than 2500 ft apart are permitted to operate on a wake turbulence independent basis. The procedure of waiting 2 min behind a heavy jet taking off on the adjacent runway is suspended. Likewise, the procedure to clear the adjacent approach path behind a heavy arrival aircraft is also suspended. If the runways are 3500 ft apart, independent IFR departures and independent IFR arrival/departure operations are permitted. At 5000 ft separation, the final dependency regulation between runways is lifted and independent IFR arrivals are permitted.

The centerline spacing considered in this study range from the FAA minimum of 700 ft to support VFR air carrier operations to a maximum of 2499 ft. The basic intent of the dual lane runway concept is to provide an additional parallel runway in close proximity to another runway (due to limited airport space) in order to increase airport capacity handling capability. The 2499 ft spacing was selected as the study upper bound to establish if there were operational benefits other than the lifting of operational restrictions to be gained by increasing centerline spacing above the minimum 700 ft.

Aircraft dynamics, airport conditions, passenger comfort, and exit obstructions (e.g., holding or taxiing aircraft) all enter into the minimum required runway separation when a high speed exit (up to 60 mi/h) is provided which exits into the area between runways. If the outer runway (furthest from terminal) is designated for arrivals, an adequate stopping distance in the taxiway system must be provided for exiting aircraft. The exiting aircraft must be able to stop clear of the other parallel runway or clear of a taxiing or holding aircraft waiting to cross the parallel runway. This stopping distance should be based on minimal braking effort. If this distance is not provided, operations on the inner runway become dependent on the arrival activity on the outer runway, resulting in capacity decreases and controller workload increases.

Preliminary analysis and the runway simulation program directly addressed several of the issues relevant to the topic of centerline separation. These include the issues of aircraft holding requirements, stopping distance based on high speed exit usage, and capacity and delay profiles.

The controller workload problem is treated in a separate section dedicated to a description of the real time experiments under saturation traffic conditions. The remaining issues listed, but not directly modeled here, may temper the separation requirement beyond that established. The centerline separation determined here constitutes a minimum based on pavement requirements to handle saturation traffic under existing ATC standards. Experimental data to quantify the effects of the issues related to safety are sparse and thus can only be subjectively incorporated. A cost/benefit analysis was not pursued.

3.4.1 High speed rollout

The centerline spacing required to allow aircraft exiting at 60 mi/h from an outer runway to stop 200 ft short of an inner runway edge was calculated. The 200 ft clearance between the runway edge and the hold short line is an anticipated requirement when heavy aircraft are holding between dependent parallel runways. The recommended 30° high-speed exit geometry for aircraft to exit at 60 mi/h is diagrammed in Figure 14. As shown, a stop line 200 ft short of the runway edge is assumed in the simulation. Table 1, in part, tabulates the minimum required centerline separation (runways 200 ft wide are assumed) for two braking strategies and several average braking rates. Case 1 strategy provides braking only after the aircraft has cleared the exit turn. Case 2 strategy provides for braking both in the turn and on the straightaway. The braking rates considered ranged from 0.8 to 5.0 ft/sec^2. Deceleration of 0.8 ft/sec^2 corresponds to only rolling friction and no braking while 5.0 ft/sec^2 corresponds to the average runway deceleration value. No operational data were available on braking while in a turn or in a taxiway segment.

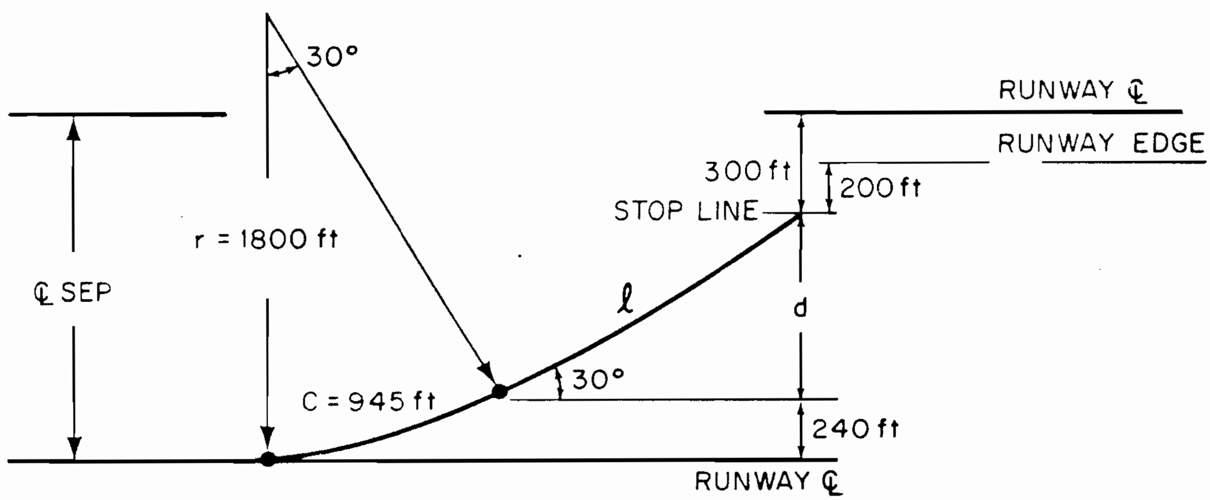


Figure 14. High Speed Exit Geometry as Recommended by FAA Planning Document [26].

Table 1. Tabular values of time to stop vs deceleration rate for two braking strategies. Total centerline separation distances for each deceleration rate are given.

Case	Time to Stop (sec)	Deceleration (ft/sec^2)	ℓ (ft)	C + ℓ (ft)	d (ft)	Total ℄ Separation*
1	110	0.8	3900	4845	1950	2490
1	51	2.0	1560	2505	780	1320
1	42	2.5	1250	2195	625	1165
1	36	3.2	980	1925	490	1030
1	31	4.0	780	1725	390	930
1	27	5.0	625	1670	315	855
2	44	2.0	-	1940	500	1040
2	35	2.5	-	1550	300	870
2	27	3.2	-	1210	135	675
2	22	4.0	-	970	15	555
2	17	5.0	-	775	-	370

Case 1: Coast while in turn with no braking; brake with constant deceleration while on straightaway segment.

Case 2: Constant braking, both in turn and on straightaway segment.

* Assume the requirement to hold 200 ft short of the runway edge.

The calculations showed that if no braking was used (0.8 ft/sec^2) the aircraft would have rolled a total distance of 4845 ft (column labeled c + ℓ in Table 1) and requires a centerline spacing of 2490 ft (last column in Table 1). One tenth "g" (3.2 ft/sec^2) requires a centerline spacing of 1030 ft. Given a centerline spacing of 1000 ft if no braking were applied in the turn, a deceleration of approximately 3-4 ft/sec^2 would be necessary on the straighaway to stop at the stop line. However, under normal conditions air carrier pilots indicate that "light" braking, while in the turn, is acceptable and routinely used.

Roll distance, $C + \ell$, required to come to a stop from a 60 mi/h exit is listed in Table 1 for a number of different deceleration profiles. The elapsed times corresponding to these roll distances (excluding 4845 ft) and the required minimum runway separations (assuming a requirement to hold 200 ft short of the runway edge) are graphically shown in Figure 15 for each braking strategy and each average deceleration rate considered. It graphically illustrates the sensitivity of the centerline separation requirements to the value of the average deceleration. The time axis represents the time an aircraft spends in decelerating from 60 mi/h to a stop with any of the selected deceleration rates plotted. For example, an average deceleration of 3.2 ft/sec^2 would stop an aircraft in 27 sec and require 675 ft of centerline separation when braking throughout the turn and the straightaway (Case 2).

Runway centerline separation of approximately 1000 ft will support 60 mi/h exit turnoff by providing sufficient runout distance between runways for aircraft decelerating under minimal braking. The minimum average deceleration requirement is approximately 2.1 ft/sec^2 (see the recommended centerline separation indicator line in Figure 15, Case 2). This rate corresponds to a value less than half that found for deceleration on runways. The value is believed to be sufficiently conservative and therefore, will not constitute a constraining factor in a pilot's determination to use the high-speed exit provided.

Heavy arrival demand on the outer runway requires the consideration of a second factor. Occasionally, an exit taxiway segment will be required to hold a second exiting aircraft. This becomes the case with increased frequency on runways which have a minimum number of exits and decreased exit speeds. Sufficient rollout space should be provided on the exit taxiway behind the holding aircraft in order that a succeeding arrival will exit its runway at a speed close to the

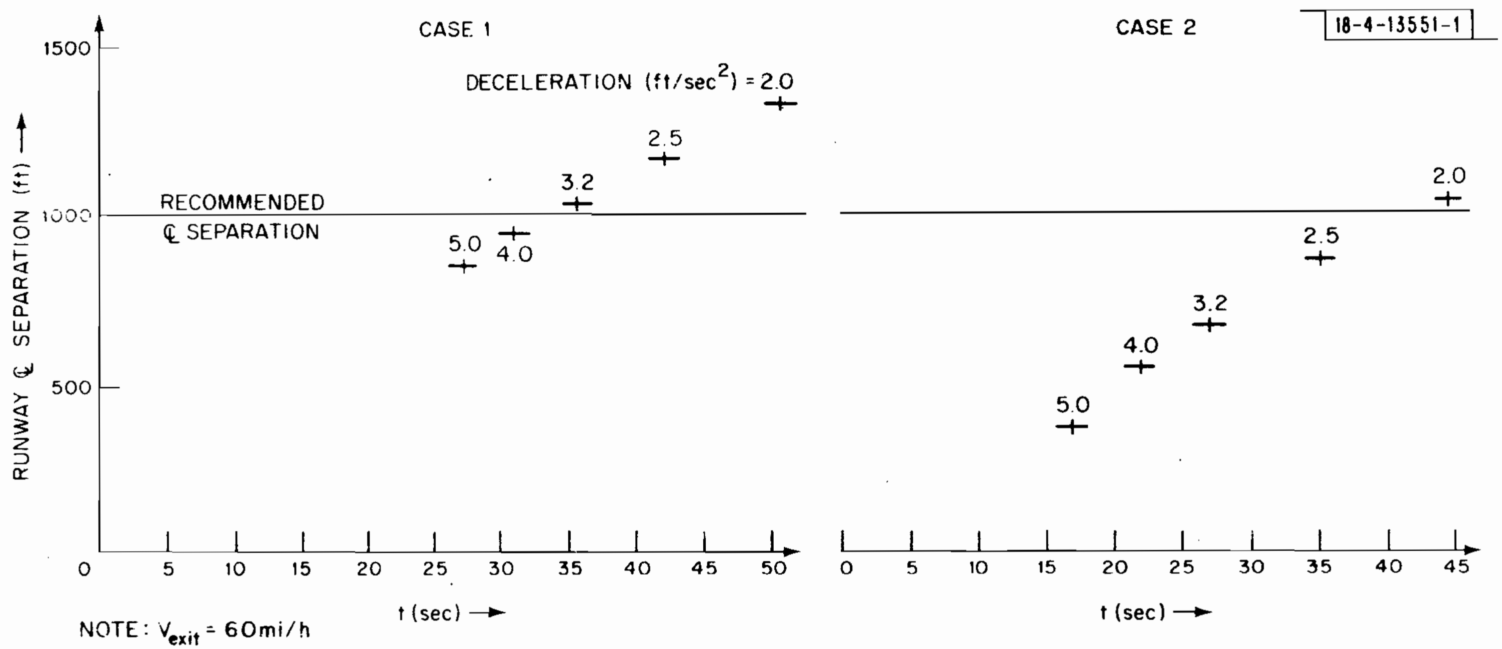


Figure 15. Summary of Centerline Separations.

design speed and will not result in any substantial increase in the runway occupancy time.

Exits designed for reduced speeds require less rollout distance and are generally constructed with an increased exit angle, thereby, reducing actual taxiway distance available for holding aircraft. One finds the requirement of approximately 1000 ft is still desirable in order to support a high arrival rate to the outer runway.

3.4.2 Departures holding between runway thresholds

With departures serviced on the outer runway and arrivals on the inner runway, centerline separation requirements are driven by the need to hold a number of departure aircraft between the runway pairs. The failure to maintain departures at the departure runway threshold generates gaps in the takeoff stream creating a system with reduced capacity. Figure 16 illustrates the hold area available between two runways with centerline separation of 1000 ft under two hold requirements. Figure 16a depicts the available space with hold lines 100 ft short of runway edge corresponding to present minimum requirements. The 600 ft available can comfortably hold two air carrier aircraft in line. One may find in practice that a pilot will not expedite an inner runway crossing to the departure runway while a second aircraft is still holding in the taxiway segment between runways. This becomes increasingly true when braking conditions have been reported less than ideal. Thus, it may be desirable to provide a hold ramp offset from the taxiway centerline to provide the extra margin of safety required.

Figure 16 b shows the reduced holding area assuming the adoption of a proposed FAA criteria to hold aircraft short of a runway at a distance corresponding to the wing span of the largest aircraft serviceable at the airport in

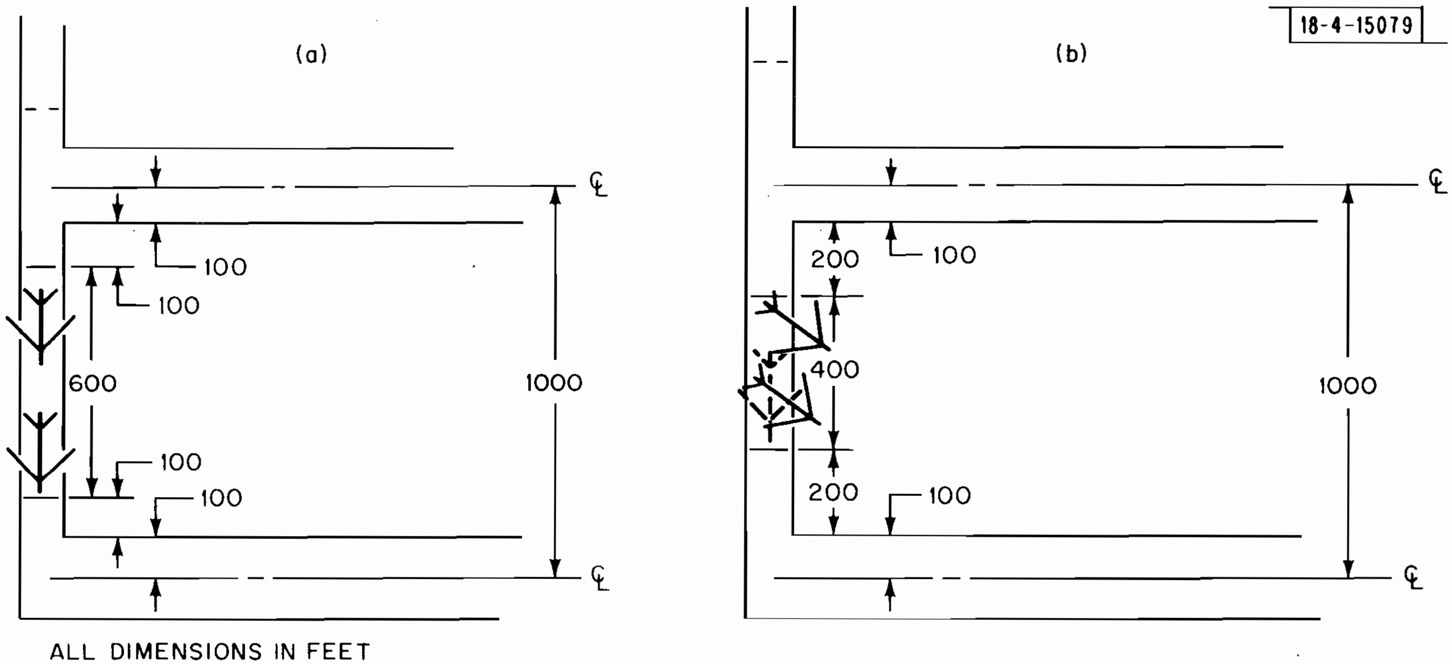


Figure 16. Aircraft Holding Area Between Thresholds.

question (the wing span of the 747 is approximately 200 ft). The separation provided between runways spaced 1000 ft apart as shown can accommodate but one jumbo type aircraft. The adoption of such a criteria would require either an increase of 200 ft in centerline separation to allow for space for two such aircraft or a modified holding ramp to hold aircraft diagonal to the runway pairs as shown. The continuing rise in number of jumbo aircraft makes this situation of holding two such aircraft a likely occurrence. In our experiments, we include the possibilities of holding either one or two aircraft between runways spaced 1000 ft apart.

3.4.3 Experimental investigations

To determine the effect of centerline spacing on dual lane operations, the following three separations were investigated by simulation:

(1) 700 ft minimum authorized separation for independent VFR commercial carrier operations,

(2) 1000 ft distance which is suggested as adequate by our preliminary analysis,

(3) 2499 ft limit beyond which wake turbulent independent operations to the adjacent runway involving heavy jet aircraft are authorized.

Figure 17 is representative of the configurations used. As already indicated, saturation arrival and departure traffic streams were serviced on dedicated runways. High speed exits on both runways stem from the need to determine a preference for the arrival runway. The last three exits on the inner runway are strictly apron access taxiways to connect the outer runway high speed exits to the terminal area and are used only by arrivals serviced on the outer runway. To establish the preferred runway for arrivals, it was first necessary to

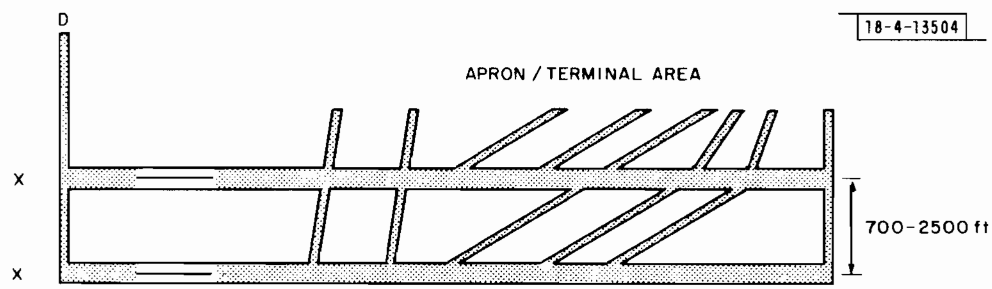


Figure 17. Centerline Separation Experiment.

service arrivals on one runway and later on the other. Both the centerline spacing and arrival runway issues are clearly related. One cannot be settled without investigation of the second.

A representative capacity summary illustrating the total VFR hourly operations handled by each dual lane configuration used to investigate the issue of centerline separation is contained in Figure 18. Presented are the results obtained with arrivals serviced on the inner runway (Grouping I), and arrivals serviced on the outer runway (Grouping II). The schematic diagram of the airport/runway environment in Figure 18 illustrates the two runway strategies involved. Results plotted are those obtained from the programmed controller simulation experiments with arrivals spaced 3 nmi apart operating in VFR conditions. A complete summary of all programmed controller simulation results is contained in Section 5.2.

We direct attention to the changes in capacity as centerline spacing is varied. Consider the case with arrivals landed on the outer runway: capacity is insensitive to runway separation and approaches 100 total hourly operations. Arrivals constitute 38 of these hourly operations.

Controllers directing traffic in the real time interactive graphics simulation experiments (results reported in Section 5.1) were able to duplicate this high level of hourly operations without excessive workload. The strategies followed by the controllers, in general, were to keep arrival delays to a minimum. This was especially true at the lower centerline spacings. Thus, at times, departures were unnecessarily delayed resulting in a reduced departure flow rate. Further real time controller experiments in which departures were provided with an increased priority over arrivals already on the ground, generated a capacity figure similar to that obtained during the programmed controller runs. The control procedure is a variable and easily adjusted to by the controllers in order to handle each particular traffic mix (arrival/departure ratio) efficiently.

Operations Function of

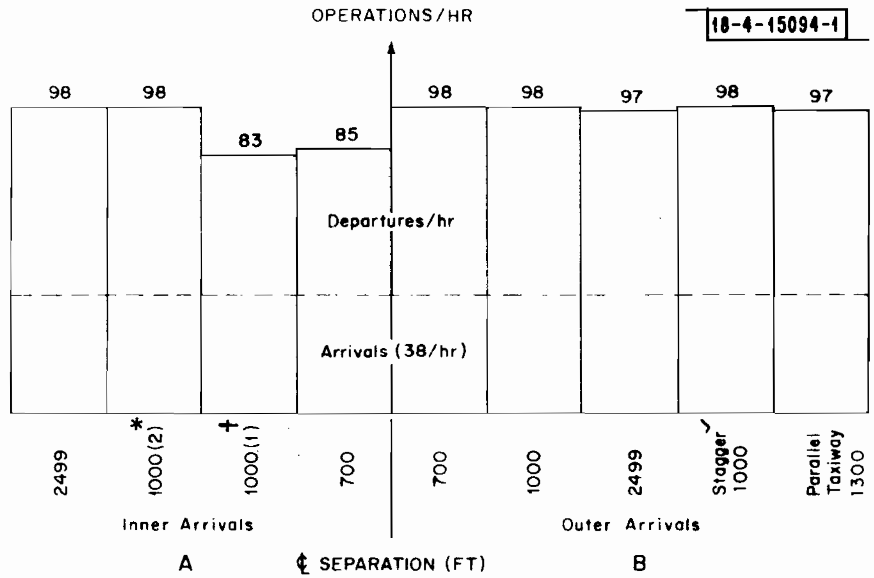
(1) Aircraft Mix

(2) Distribution of Mix

(3) Aircraft Dynamics

(4) ATC Rules

(5) Controller Rules



Simulation Values

(1) VFR Operating Rules

(2) Type 3 Traffic (Fig. 56)

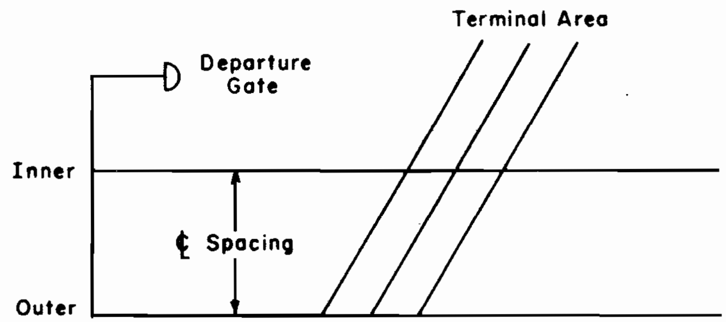
(3) 4-hr Traffic Sample

(4) Departure Gate Schedule (60-sec mean)

(5) 60-mph Exits

(6) 3-nmi Arrival Spacing

A		B
Arrivals	or	Departures
Departures		Arrivals



* Hold 2 aircraft between thresholds

† Hold 1 aircraft between thresholds

✓ 3000-ft stagger

Fig. 18. Fast Time Dual Lane VFR Operations (Centerline Spacing as Arrival/Departure Strategy).

For arrivals serviced on the inner runway (Grouping I) we find that the hourly operations are reduced when only one departure aircraft can be held between the pair of runways. This aircraft holding restriction may be imposed for one of two reasons: space limitations, and safety. The 98 hourly operations obtained on a dual lane with centerline separation of 1000 ft or greater while holding two or more departure aircraft between runways, 1000 (2) and 2499 was reduced to 83 operations per hour when only one departure aircraft was held between runways, 1000 (1).

With departure crossings regulated by the arrival traffic and the maximum allowed queue size restricted to holding one aircraft between thresholds, frequently a constant demand on the departure runway could not be maintained. The total decrease in hourly operations resulted from a restricted departure flow rate. Gaps in the departure stream are created by the combined effect of restricting crossings near threshold when the arrival is within 1.5 nmi and the holding of only one aircraft between runways. Under these limitations, the departure queue is maintained at the inner runway crossing point rather than at the departure runway threshold. The gaps do not materialize when sufficient room exists to maintain two aircraft between thresholds awaiting departure service.

With minor qualifications, the arrival and departure delays were found to be insensitive to centerline separation. In the case where departures were serviced on the outer runway, sufficient centerline separation must be provided to hold at least two departure aircraft between runways. With this minimum condition satisified, the delay to each departure scheduled for takeoff on the outer runway averaged a little less than one minute (3 nmi arrival spacing assumed). Arrivals exit the inner runway and experience no delay taxiing to the terminal/apron area.

With arrivals serviced on the outer runway, the mean arrival and departure delays averaged 39 sec and 144 sec, respectively. Each delay parameter was found to be insensitive to centerline separation.

Simulation found that the departure delay was rather insensitive to changes in demand and in centerline spacing in the case where departures were serviced on the inner runway. However, such was not the case when departures were handled on the outer runway. Although a centerline separation of 1000 ft with space to hold two aircraft efficiently handled departures between 3 nmi arrival traffic, this was no longer found to be the case, when an arrival demand rate increased corresponding to arrivals separated by 2.5 nmi. This departure delay dependence on arrival demand and centerline spacing is illustrated in Figure 48 of Section 5.2.1. The reduced interarrival separation substantially decreased the opportunities available to cross enough aircraft at one time between successive arrivals to fill the departure slots on demand. We found that an improved ATC system in which arrival separation is reduced is best supported by a dual lane complex in which the outer runway is designated to service arrivals predominantly as it is the least sensitive design to changes in heavy traffic demand.

Although additional experiments were performed with arrival traffic spaced 2.5 nmi, 4.0 nmi, and 5.0 nmi apart, each exerting constant demand on the arrival runway, no changes in comparative capacity or delay results were indicated beyond that shown for 3 nmi arrivals. A complete set of the results obtained from these additional VFR experiments is contained in Section 5.2.

The IFR traffic capacities were found to be insensitive to centerline spacing for each arrival demand investigated. Figure 19 illustrates the total hourly operations found for each centerline separation modeled for a number of

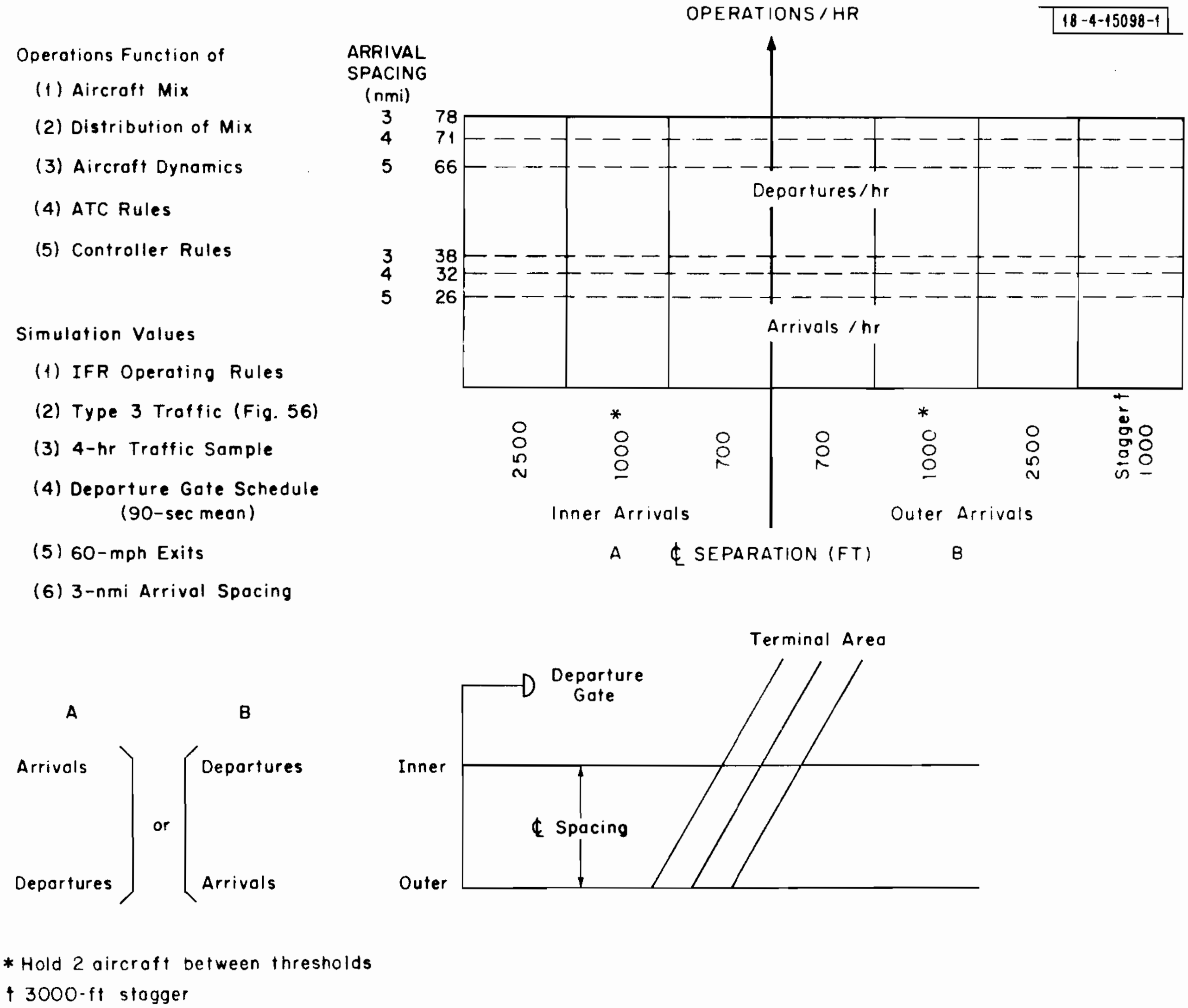


Fig. 19. Fast Time Dual Lane IFR Operations (Centerline Spacing as Arrival/Departure Strategy).

arrival spacings assuming constant demand. Arrival demand rates corresponding to the three separations and assumed mix are also indicated in the figure.

Illustrated, are hourly operations which were found to be totally insensitive to centerline separation for either preference of arrival runway. This behavior was attributed to the strict adherence to a minimum separation between airborne aircraft under radar control. Under such conditions, traffic flow is restricted by the procedures established to provide safety and not by any dual lane pavement requirements.

The low crossing priority given to arrivals from the outer runway did not cause any excessive restrictions on these IFR arrival operations. The mean arrival delays ranged from 17 to 32 sec depending on the dual lane configuration. Pavement utilization is reduced to such an extent under IFR conditions that ground operations proceed unhampered due to runway requirements for arrivals or departures. This does not mean to imply that ground movements on a dual lane runway system are not affected by conditions such as wet and slippery surfaces and reduced ground visibility often accompanying IFR conditions. Capacity and delay could be further affected beyond that found by such conditions.

Further investigation of centerline spacing based on changes in the arrival flow rate, severity of the IFR weather, and increased departure demand did not establish any dual lane requirement beyond that established in the baseline study involving 3 nmi arrivals. The data obtained during these runs are summarized in Section 5.2.

3.4.3.1 Findings Summary

The results of these experiments showed that the dual lane runway capacity is insensitive to centerline separation provided sufficient taxiway pavement exists between runways to handle the traffic serviced on the outer runway. The heavy flow rate possible on a runway dedicated to departures is achieved only when the traffic exerts a constant demand for this service. Limitations, which restrict the maximum size of the departure queue to one aircraft holding short of threshold, defeats this requirement.

To service heavy arrival demand efficiently on the outer runway, required sufficient separation be provided between runways in order to construct rollout taxiways of adequate length. After entering a high speed exit, the arrival must be provided with adequate unobstructed distance to stop short of the inner departure runway.

The analyses performed show that 1000 ft is the minimum separation under which a dual lane runway system can be constructed free of these pavement limiting factors which would work to ultimately reduce capacity in heavy traffic demand situations.

Each of the dual lane configurations, regardless of centerline spacing and arrival runway preference, was able to handle the arrival demand efficiently. However, departures shows a sensitivity to arrival demand when departures were serviced on the outer runway. In that case, departure delays exhibited a large dependence on the arrival rate. This change was least for the largest separation (2499 ft) studied.

3.5 Arrival/Departure Runway Preference

As traffic increases, it is desirable from a controller workload standpoint to shift operations from a single to a two runway operations. It may be desirable from a controller workload viewpoint to designate one runway exclusively for arrivals and one exclusively for departures. The question of which runway should be used for arrivals is considered here. The following are the critical issues involved in determining arrival/departure runway preference:

(1) Runway crossing strategy dependent on arrival runway assignment.

(2) Runoff area opposite high speed exits.

(3) Aircraft holding between runways.

(4) Jet blast effects of taxiing/holding aircraft.

(5) ILS interference.

The issues of runway crossing strategy and aircraft holding between runways, were explicitly treated in the arrival/departure runway preference experiment. The remaining were considered implicitly in the design of the experiments.

The runway crossing strategy issue is dependent upon the designation of arrival and departure runways. If the runway furthest from the terminal is designated for arrivals, the question arises as to how to best effect the crossing of the inner runway by arrival aircraft. Arrival aircraft land on the outer runway exit and hold short of the inner departure runway. A strategy is required to expeditiously cross the inner departure runway. However, if the arrivals are assigned to the inner runway and departures to the outer, the need arises for departures to cross the arrival runway to the outer runway. Arrivals land and exit into the apron area from the inner arrival runway.

The assignment of arrivals and departure traffic to separate runways generates a requirement to investigate which assignment strategy results in the greater capacity and efficiency of operation. The ATCAC study suggested that the runway closest to the terminal area should be supplied with high speed exits to service arriving aircraft while departing aircraft should use the outer runway. The apparent advantage in this strategy is that all arrivals taxi directly to the terminal area without encountering any delays.

In the field, it was found that the alternate runway assignment strategy is preferred. Discussions with controllers confirm that arguments for landing arrivals on the outer runway are reasonable.

Controller workload is reduced with arrivals on the outer runway and departures on the inner runway. It is an easier control procedure under heavy service demands to coordinate an arrival already on the ground with a departure ready to move in the system, than to cross a departure across the active arrival runway.

Additionally, all high speed exit decelerations are accomplished in areas clear of obstacles and surprises, and require coordination only with aircraft either in take off or landing phase, assuming 1000 ft centerline separations. In the preliminary analysis of the centerline separation issue, it was found that two aircraft could be held short of inner runway holding 200 ft from the runway edge with this separation. No additional offset of the dual lane complex away from the terminal area is required. If arrivals were serviced by the inner runway, it would still be necessary to provide additional real estate and clear areas in order to space the runways away from the apron area to provide for safe rollout of aircraft on high or intermediate speed exits.

The disadvantage in the outer arrival-inner departure runway allocation scheme is that some minor delay (measured in seconds) is experienced by arrivals which are required to hold short before crossing the departure runway.

With arrivals assigned to the outer runway, a departure may be momentarily delayed from take off in order to cross an arrival which landed on the outer runway and is waiting to cross the inner. However, since a departure may hold after taxiing into position on the runway for any number of reasons, this short wait does not actually become a delay caused by the crossing aircraft. A minimum requirement for separation (departure to departure) between aircraft with different performance characteristics, departure control restrictions, and heavy aircraft separation rules are examples of momentary delays ordinarily experienced by departures holding in place for take off clearance.

Jet blast effects are minimized with arrivals on the outer runway and departures on the inner runway. Interpretation of jet blast contours [22,23] Figure 20) indicate the possibility of generating a hazardous situation when an arrival is letting down over threshold behind a crossing heavy jet taxiing to the outer runway for departure clearance. Figure 20 shows a blast contour behind a DC-10 trijet for breakaway power. The contour shows a 35 mi/h blast to a height of 60 ft over a distance of more than 450 ft from the tail of the aircraft. An inner arrival letting down 50 ft or less over the threshold could be seriously affected by an outer runway departure heavy jet taxiing well clear of the present 100 ft hold short mark.

The FAA Instrument Landing System (ILS), which is the primary navigational aide used to conduct an instrument approach, is highly succeptable to interference caused by multipath signals. Any large vertical reflective surface, such as the vertical stabilizer of a taxiing aircraft within the radiation pattern of the system's antennae, is a potential source of this problem. The result of multipath interference

18-4-15080

NOTES:

(1) ALL VELOCITY VALUES ARE STATUTE MILES/HOUR

(2) CROSSWINDS WILL HAVE CONSIDERABLE EFFECT ON CONTOURS

(3) RAMP GRADIENT WILL AFFECT REQUIRED TAXI AND BREAKAWAY THRUST

(4) SEA LEVEL STATIC-STANDARD DAY

(5) ALL ENGINES AT SAME THRUST

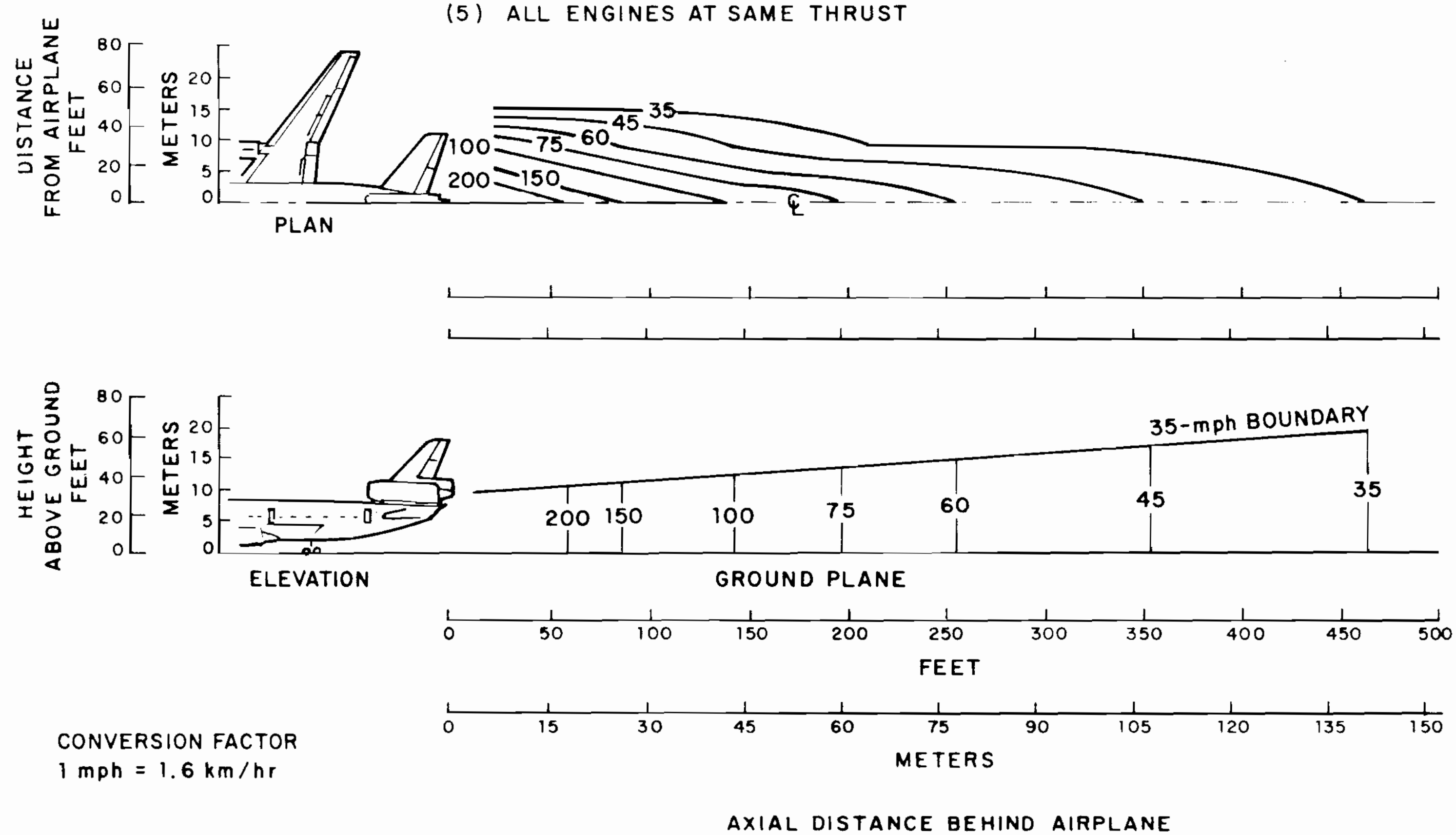


Figure 20. Jet Engine Velocity Contours Breakaway Power.

is an erratic glide slope and localizer receiver indication rendering the cockpit instrument useless for the precision approach. Operationally, at sites where this is a problem, the zone near the approach end of the runway must be kept clear of taxiing aircraft while one on final is conducting the ILS approach under conditions of poor visibility. This requirement reduces the airport's flexibility. The airport then operates at reduced capacity and generates increased aircraft delays under heavy service demand. Thus, it becomes an attractive proposition to designate the outer runway as the ILS equipped approach runway. It is sufficiently offset from terminal taxiways and the inner departure runway to operate free of the interference problem.

3.5.1 Experimental procedure

To investigate arrival and departure runway preference, two configurations were selected with runway centerline separations of 1000 ft. This distance provided the required separation between runways for arrivals landing on the outer runway and exiting at 60 mi/h to come to a safe stop short of the dependent departure runway before crossing it. In configuration A (Figure 21), arrivals are cleared to land on the outer runway and instructed to hold short of the departure runway for runway crossing clearance. In configuration B (Figure 21), departures were scheduled for takeoff on the outer runway with arrivals landing on the inner runway. Departures are required to obtain a controller clearance before crossing the endpoint of the arrival runway. With departures on the outer runway and space to hold two aircraft short of the departure threshold, the 1000 ft centerline separation did not act to constrain traffic movement in any manner. It was, therefore, unnecessary to extend the study of runway preference for arrivals and departures for increased centerline separations.

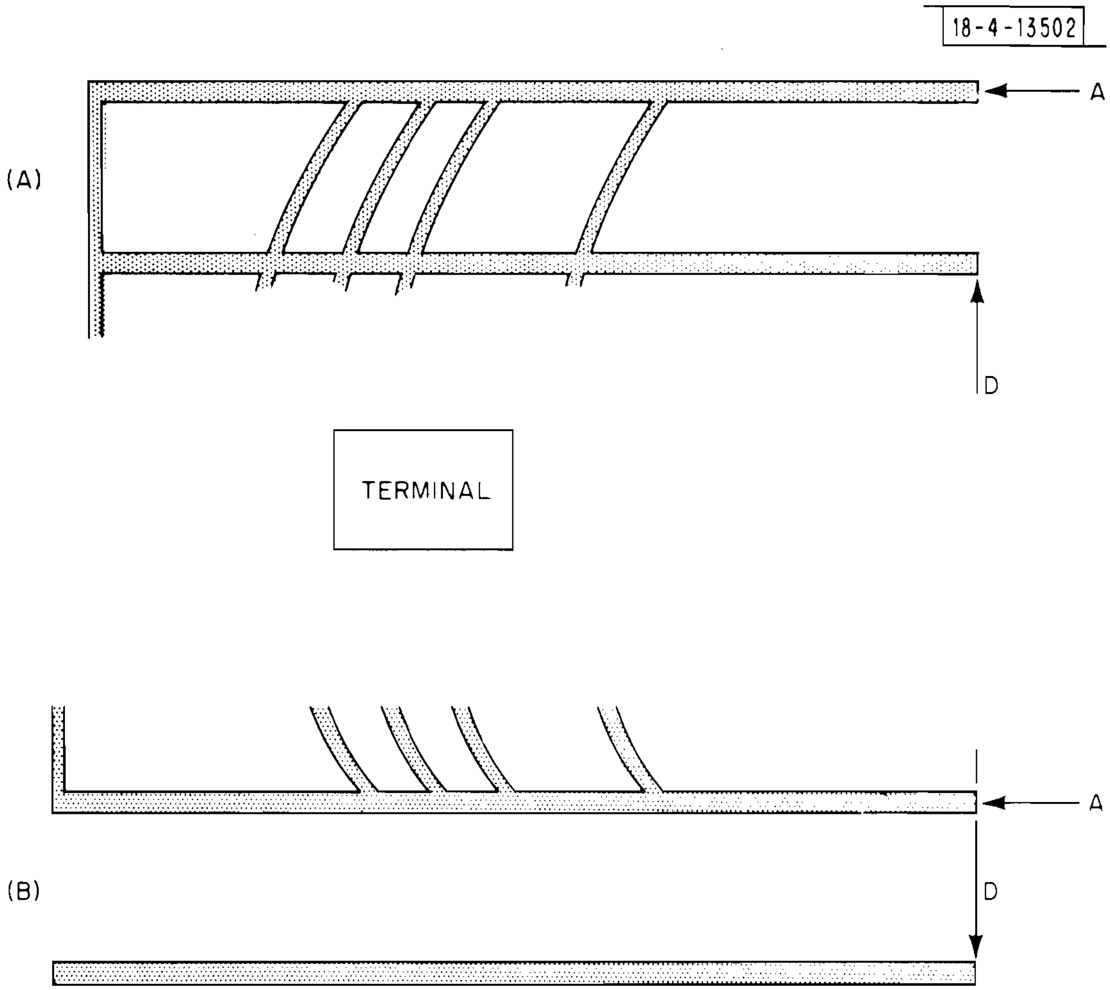


Figure 21. Runway Configurations with 1000-ft Centerline Separations - used to Investigate Arrival and Departure Runway Preference.

(a) Arrivals land on the outer runway and cross the inner departure runway to get to the terminal area.

(b) Arrivals land on the inner runway and taxi directly to the terminal area. Departures taxi across the arrival runway.

3.5.2 Capacity/delay findings

The centerline spacing experiments discussed previously (Section 3.4) were conducted with arrivals first serviced on the outer runway and finally on the inner in order to establish which procedure would provide maximum flexibility from a pavement standpoint. These simulation results (operations under VFR and IFR) established that when two or more aircraft can hold between runway thresholds (i.e., centerline spacing at least 1000 ft) the number of hourly operations achievable with either strategy does not change. This essentially remains true for all the traffic demand rates investigated. However, as the arrival demand increases, an increase in the number of departures per hour is observed on configurations which hold only one aircraft between runways, 700 ft and 1000 (1) ft, and depart on the outer runway. This counter intuitive result is due to the increased number of arrival gaps per hour during which one aircraft can cross to fill in an existing departure gap. Since the departure runway can service a departure in ~45 sec and only 1 aircraft can be held between runways the departures released are a function of the arrival spacing. When the arrival spacing is reduced creating more gaps (more arrival aircraft per hour with less time per gap) the departures released can be increased as the departure runway can be more evenly fed. Correspondingly, the mean delay experienced by departures decreases due to better departure service in each of these two cases. When two or more departure aircraft can be held between thresholds, it was found that for inner arrivals and outer departures, that departure delays over the simulated four hour traffic sample are on the order of one minute. These average one minute departure delays are partially due to the departure queue waiting to cross under incoming inner arrivals to reach the outer departure runway. An inherent departure stream delay is present due to the traffic mix and distribution. For example, a heavy departure requires a 2 min wait before a following non-heavy departure on the same runway or on the adjacent runway can depart. Departure delay, however, did exhibit a sensitivity to arrival demand. A threefold increase in mean departure delay was observed in going from an arrival spacing of 3 nmi to 2.5 nmi. Inner arrivals create no arrival delay while outer arrivals were found to be delayed an average of 40 sec while waiting to cross the departure runway.

Comparable departure delays incurred for the reverse strategy of outer arrivals (inner departures) are on the order of 2.5 to 3.0 min. These departure delays to the departure stream queue are partially caused by the inner departures waiting for the outer arrivals to cross the departure runway going to the terminal area. Departure delays were, however, insensitive to the arrival demand.

During the real time simulation experiments, controllers found each strategy equally workable under the highest traffic demand conditions when each of the two different operations (arrivals and departures) were segregated to separate runways. They expressed a preference for the operation with outer runway departures. However, in this case, the total communication workload was not simulated accurately as routine cautionary advisories (jet blast and wake turbulence advisories) were omitted. This tended to simulate a control operation as an easier matter than it actually is. Conversely, when arrivals were serviced on the outer runway, the controllers expressed a bias by providing higher priorities to a rolling arrival regardless of the departure queue status. This practice also reduced the communication requirements, except that capacity also suffered. The controllers voiced a natural preference by chosing the strategy which gave them a maximum hourly traffic count.

After considerations of the need to provide advisories to pilots (based on jet blast and wake turbulence considerations), the need to alter priorities under certain traffic demand conditions, and the need to maintain a sterile approach area in the case of ILS approaches during IFR conditions, we conclude that the most easily workable and flexible configuration is provided by designing the outer runway for arrivals.

3.5.3 Centerline separation and runway allocation summary

Based on the results found from investigation of the arrival runway preference issue and those already established earlier on the centerline spacing issue, it was concluded that the dual lane configuration most suited to support close spaced runway operations (simultaneous VFR operations and dependent IFR operations) is one in which the outer runway is designated as the arrival runway separated by a minimum distance of 1000 ft from the inner runway designated as the departure runway. In this mode, controller workload is minimized as the adverse effect of jet blast is minimized (i.e., traffic can be moved without constantly issuing cautionary advisories). Workload is further reduced since the conflict situations peculiar to dual lane operations are less critical with arrivals on the outer. It remains to determine whether or not some modification to this established dual lane configuration provides additional improvement. Modifications such as stagger, parallel taxiway, and runway crossing strategies will be discussed and simulation results presented.

3.6 Runway Threshold Stagger

It was suggested that providing threshold stagger could increase capacity and reduce delays. We have not attempted a study of the safety aspects of operating staggered thresholds; however, brief accounts of the safety related effects are included. The issues explored through analysis and simulation were the following:

(1) Suspension of wake turbulence rules for staggered runways with less than 2500 ft centerline spacing. [25]

(2) Effecting runway crossings so as to minimize interruption to arrival or departure traffic flows.

(3) Staggering so that no runway crossings are necessary.

3.6.1 Suspension of wake turbulence procedures

Present wake turbulence procedures [25] essentially state that non-heavy aircraft stay at least 5 nmi behind a heavy jet on final approach to the same runway as well as to an adjacent parallel runway less than 2500 ft apart. From what is observed in practice and from what is known about wake turbulence, [28] one arrives at the subjective conclusion that wake turbulence generated by a heavy aircraft can be avoided by a knowledgeable pilot landing on the adjacent displaced runway (upper runway, Figure 22). Landing all heavy aircraft on the runway displaced into the approach zone (lower runway, Figure 22) will ensure that all arrivals to the adjacent runway can execute a safe VFR approach by remaining on a nominal glide path passing over the turbulance created by the heavy jet aircraft. The minimum separation restriction due to wake turbulence on an aircraft making the approach to the adjacent runway might not be necessary. Examples of simultaneous VFR appraoches of heavy and non-heavy jets have been observed to 750 ft spaced flush threshold parallel runways. Commuter Twin Otter aircraft legally execute a simulataneous VFR parallel approach by staying higher than the heavy jet, well clear of its wake vortices, and landing long and beyond the touchdown point of the heavy jet.

Some altitude separation on the final approach paths between side-by-side arrivals is provided by staggered thresholds (Figure 22). Stagger provides a

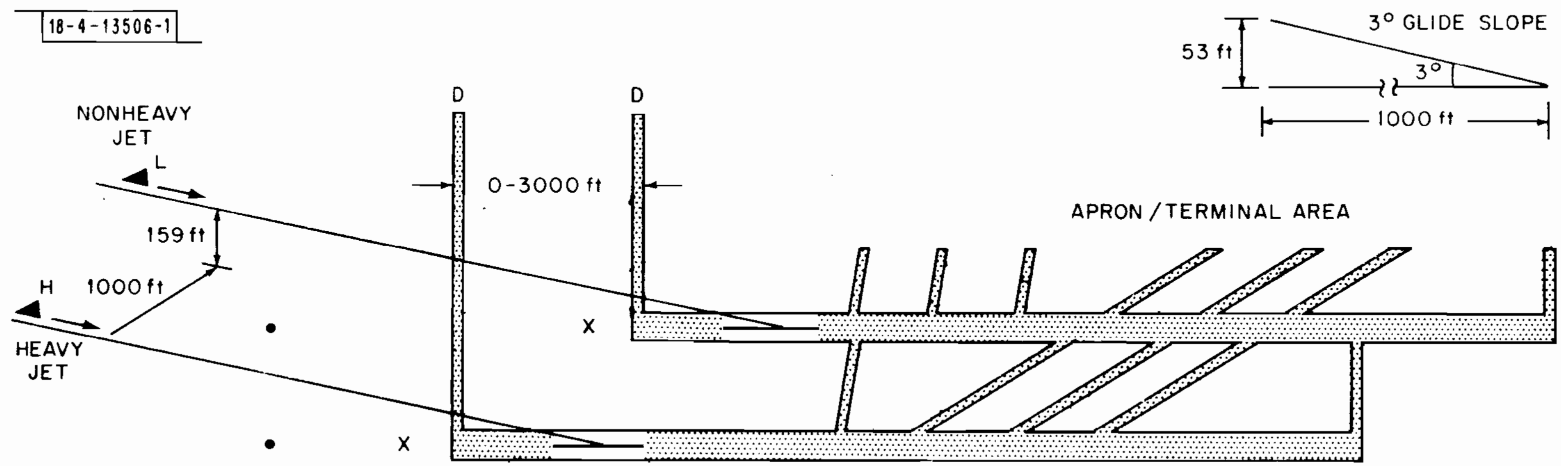


Figure 22. Staggered Thresholds.

theoretical 53 ft of altitude separation per 1000 ft of threshold displacement for two aircraft on parallel approaches on similar 3° glide paths to adjacent parallel runways. Figure 22 shows the theoretical 159 ft vertical separation due to the 3000 ft stagger depicted. The vertical separation can be increased by increasing the stagger displacement and/or by adjusting one or more of the glide path angles. Not enough is known about the concept to determine whether a few hundred feet vertical separation is enough to provide the safety factor needed to adopt this procedure. To implement this concept suggests the installation and use of two glide slopes to maintain the desired vertical separation.

A similar argument to allow simultaneous independent departures one of which is a heavy aircraft on staggered parallel runways less than 2500 ft apart, also exists. Present policy [25] states that a non-heavy aircraft departing on either runway less than 2500 ft apart must wait at least 2 min behind a heavy departure. If heavy aircraft were segregated to the inner runway (upper runway, Figure 22) then simultaneous non-heavy departures on the outer runway could be effected by lifting off before the heavy liftoff point and overflying the wake vortices due to the heavy jet.

For either the simultaneous arrival or simultaneous departure case, the potential capacity increase is a function of the percentage and distribution of heavy aircraft utilizing the dual lane complex. For example, if all the heavy aircraft arrived in groups for service then little increase in capacity would be realized as there is no adjacent runway wake turbulence restriction between heavy aircraft only between heavy and non-heavy aircraft.

3.6.2 Runway crossing strategy

The stagger was used to effect runway crossings which minimized interruption to arrival and departure traffic flows. Wake dependence rules were in effect. High density traffic simulations were performed on both the staggered and flush dual lane runway systems. Figure 22 is representative of the staggered runway configurations tested under high density traffic operations. Simulation results indicated no increase in VFR operations or IFR operations but a decrease in VFR departure delays for a stagger of 3000 ft. Three thousand feet is an arbitrary number which was selected for this simulation as a real estate compromise. Both flush thresholds and 3000 ft stagger fast time simulations achieved the same number of VFR operations. The number of IFR operations were found to be less than the VFR operations due to IFR operating restrictions. However, the same number of IFR operations were achieved for both flush threshold and 3000 ft stagger configurations. The 3000 ft stagger configuration reduced VFR departure delays by allowing the outer arrivals to cross the inner departure runway behind departure aircraft 3000 ft closer to the departure threshold. This allowed the crossing to be effected while the departure was still accelerating to lift-off velocity thereby, not using vital departure runway time causing increased departure delays. IFR departure delays were unaffected as runway crossing time was not a factor due to the lower number of IFR operations achieved.

The controller workload was found to be the same for flush threshold operation as for 3000 ft stagger operation. An equal number of control commands ("hold short of departure runway, continue taxi, or cross without delay") were issued by the local controller in his task of coordinating a runway crossing with staggered thresholds.

3.6.3 Non-interference operations

Staggering runway thresholds so that departure and arrival traffic may proceed on a non-interference basis (crossings made beyond runways) showed the most promise. Arrival and departure traffic operating on a non-interference basis reduces controller workload and minimizes VFR arrival and departure delays. Average arrival delays were reduced by about a half minute while departure delays were reduced by about two minutes. The number of operations did not increase over those obtained with flush thresholds. Figure 23 illustrates a staggered runway complex taken from the masterplan for the new Copenhagen International Airport [27]. Arrivals and departures are allocated separate runways with the assignment dependent on direction of operation. When arrivals land following an approach originating from the west, the innermost runway is used for landing with departures serviced on the outer runway. With wind conditions that dictate a landing from the opposite direction, the runway assignment is switched to service arrivals on the outer and departures on the inner. The general layout is such that high speed ground movements (touchdown, roll-out or lift-off zones) are never in close proximity to slow moving traffic passing through the taxiway system. Land availability is a critical factor as this design probably requires a stagger of more than 6000 ft.

3.6.3.1 Threshold stagger findings

Staggering runway thresholds were found to reduce delays and to have little effect on dual lane capacity. VFR arrival and departure delays were minimized when runways were staggered such that access to the outer runway was gained on a non-interference basis with inner runway traffic. The delay reductions due to stagger were only achieved during VFR operations.

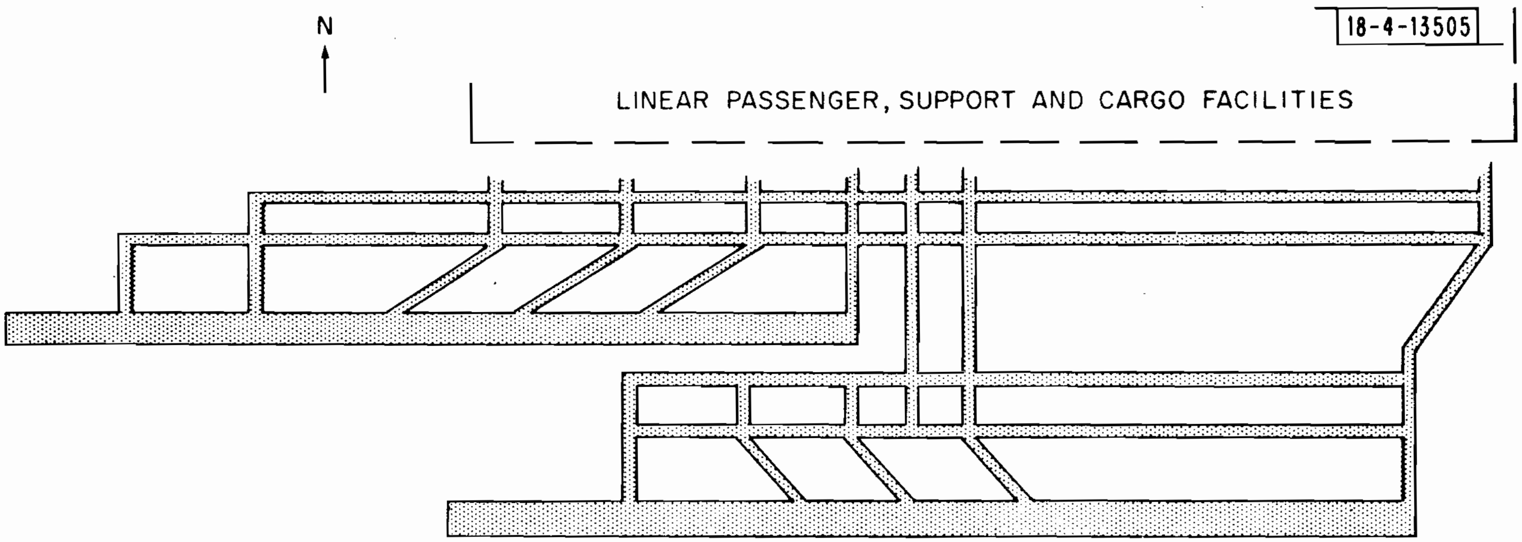


Figure 23. Arrival and Departure Traffic Routed on a Non-Interference Basis on Runways Separated by Large Stagger.

3.7 Inclusive Parallel Taxiway

It has been suggested, that placement of a parallel taxiway between two closely spaced parallel runways would facilitate operations in a heavy traffic environment. The critical issues to be explored concerning an inclusive parallel taxiway are the following:

(1) Increase in centerline spacing required

(2) Traffic routing strategy

(3) Traffic conflict resolution

(4) Operational procedures

(5) Controller workload

(6) Runway exit velocity/clearance/rollout

(7) Crossing behind departure aircraft, thereby increasing capacity and reducing departure delays.

The following discussion pertains to a generic dual lane complex with an inclusive parallel taxiway (see Figure 24). In order to provide adequate room for a large aircraft (235 ft long) to hold 200 ft short of the edge of the departure runway which joins the apron area on one of the perpendicular taxi segments to the parallel taxiway and to also provide for unrestricted movement on the parallel taxiway by a second arrival to taxi past the occupied taxiway segment, separation of approximately 650 ft would be required between a parallel taxiway and departure runway. To maintain operational flexibility 1250 ft centerline spacing would be needed. A 600 ft separation between arrival runway and parallel taxiway is assumed. This required separation reflects dimensional considerations alone. In addition, jet blast effects and a provision for minimum aircraft separation for safety would require even greater spacing to permit an aircraft to pass behind one holding on a perpendicular taxiway. Unrestricted operation on the parallel taxiway appears to be impractical between the parallel taxiway and the departure runway.

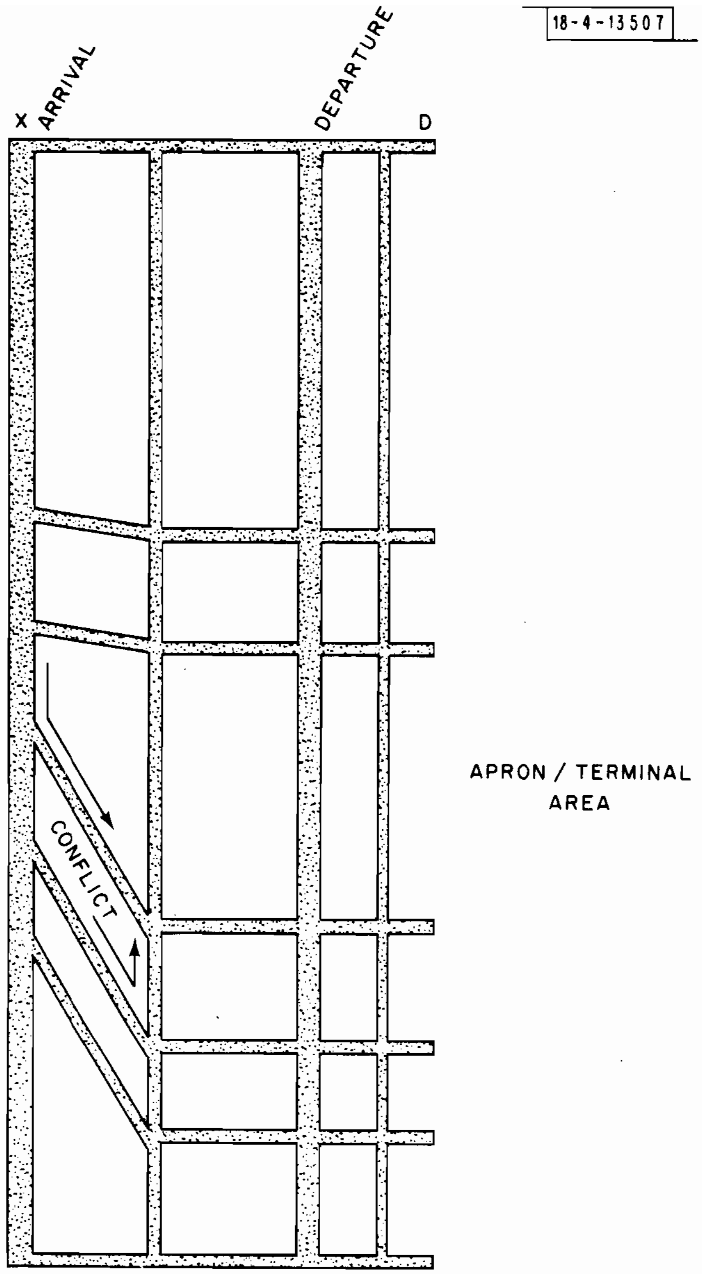


Figure 24. An Inclusive Parallel Taxiway between the Runways of a Dual Lane Runway System.

Having to come to a complete stop at the intersection of the exit taxiway and the parallel taxi strip in order to enter the parallel taxiway, potentially could generate longer runway occupancy times. The runway may be utilized to decelerate in order to come to a safe speed before rolling onto a closely-spaced parallel taxiway if the exit taxiway segment proves to be too short to provide for comfortable deceleration after runway exit.

A parallel taxiway may generate ground traffic flow conflicts and thus, a larger controller workload. Aircraft on the parallel taxiway can be turned over to a ground controller or remain under local controller jurisdiction. In either case, an increase in additional responsibility, coordination, and workload is indicated. Consider a heavy aircraft taxiing to center crossover strip and doubling back after having used its high-speed exit. This will block a second arrival's use of the first high-speed exit until the preceding heavy aircraft has taxied past the exit taxiway strip and parallel taxiway intersection (see arrows denoting the conflict in Figure 24).

Runway separation, as shown in Figure 24, was selected as 1250 ft in order to simulate maximum flexibility of a parallel taxiway. Exit location, number, and speed remain unchanged from the previous simulation experiments.

The parallel taxiway provides a route from the outer arrival runway to the inner runway; and by doubling back, the crossing can be accomplished near the touchdown zone of the inner runway. This, of course, is at the expense of greater taxiing distances for outer runway arrivals. The local controller is required to exercise control over taxiing aircraft which increases his workload. Alternatively, the parallel taxiway could provide a rollout path to complete a high speed exit before approaching the inner runway.

3.7.1 Summary of findings

A parallel taxiway configuration similar to Figure 24 was used to simulate arrival traffic to the outer runway while handling departure traffic on an inner runway. This traffic arrangement was selected to investigate the use of the taxiway to cross the outer arrivals closer to the departure runway threshold in order to minimize departure delays. The number of VFR or IFR operations did not change from that experienced without the taxiway. This usage of the taxiway was not considered a viable IFR technique under conditions of poor visibility. Under IFR conditions, the controller would have problems seeing the taxiway and the pilots would be restricted in their visibility of other aircraft in the taxiway system.

The VFR average departure delay was not found to decrease from the similarly operated flush threshold configuration as was expected. The parallel taxiway delay found from the fast time simulation was not as low as the 3000 ft stagger delay using the same strategy of crossing close to the departure runway threshold behind departures. The parallel taxi departure delay appears to be greater because of the single file nature of the parallel taxiway traffic crossing closer to the threshold. The flush threshold and stagger crossings of two or more arrival aircraft were effected in parallel reducing the departure delay figures. This parallel taxiway operation was at the expense of additional taxi distance and time (~30 sec for every 1000 ft taxi increase).

The simulation findings indicated, that in practice, with high traffic densities, the parallel taxiway between the runways may create many conflicts and cause a large increase in controller workload. As traffic flows increase, the simulation found that potential conflicts on the parallel taxiway greatly increased demanding more of the controllers time. No increase in the number of operations was obtained due to the addition of the inclusive taxiway. The lack of operational data for a taxiway placed between two parallel runways did not permit a verification of the simulation results.

3.8 Midpoint vs Endpoint Crossing

At the Seattle-Tacoma Airport, it was proposed to taxi departure aircraft across the two runways near their midpoints in order to use the outer runway for take offs. This was proposed as a temporary configuration dictated by the closing of the parallel taxiway while new parallel taxiways were under construction. The question arose as to the advantage of endpoint crossing versus midpoint crossing of a runway.

Batch crossing of the arrival runway during a natural gap in the arrival flow appears to be the one characteristic of midpoint crossing which might be of advantage. This strategy provides a source of departures when gaps are filled in the arrival traffic flow. The hypothetical departure routing at Seattle-Tacoma Airport is depicted in Figure 25.

Several FAA personnel (Air Traffic Control Specialists) were interviewed in order to establish a safe separation distance between a crossing aircraft and an aircraft on final approach. A separation of 1.5 nmi was established to be the minimum aircraft separation if midpoint crossing traffic was already rolling. This distance must be increased to 2 nmi or more if the taxiing aircraft is required to cross, starting from a stopped position.

A taxiway/runway intersection crossing becomes increasingly more difficult as the intersection separation from threshold increases. At distances approaching 5000 ft, it would be of no use with arrivals spaced 3 nmi apart. The further an

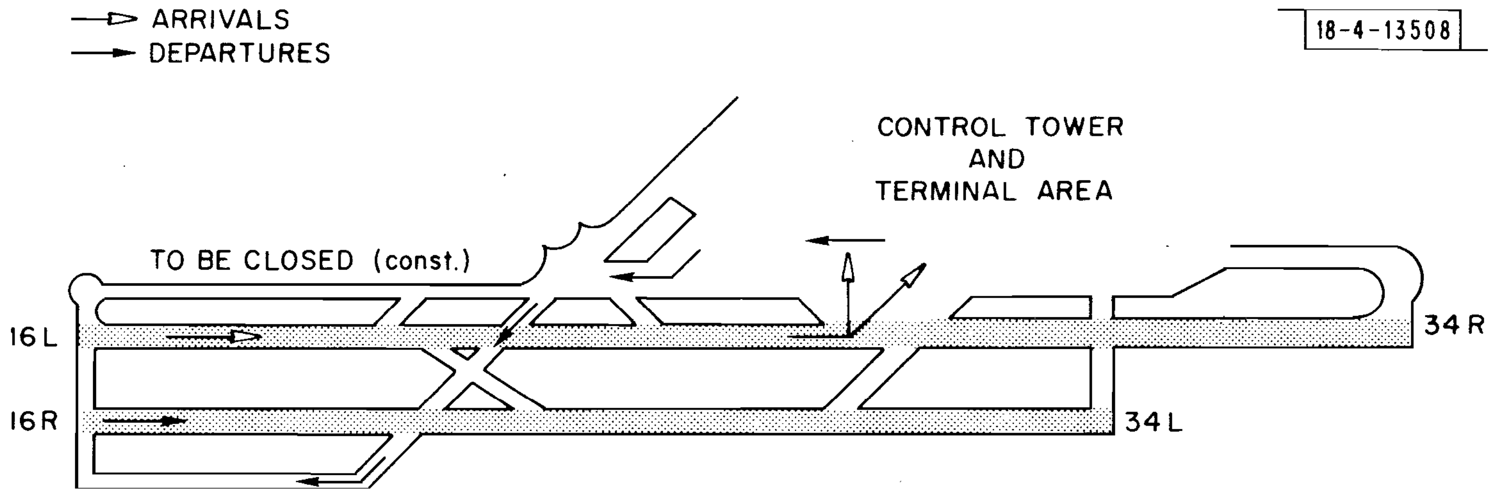


Figure 25. A Schematic Diagram of Seattle-Tacoma Airport Illustrating a Midpoint Crossing Technique for Departure Aircraft.

intersection is from touchdown, the longer a waiting aircraft, holding to cross an intersection, must wait and give way to the decelerating arrival not yet clear of the intersection. During this waiting period, the next arrival (nominally spaced 3 nmi) is rapidly closing the separation distance which existed between the successive arrivals on final approach. Crossing would require a forced creation of gaps in the arrival flow of saturation traffic or increased spacing between successive arrivals. This procedure would decrease total airport capacity.

On the other hand, the minimum separation which exists between successive arrivals provides a sufficient interarrival distance to cross aircraft if a threshold crossing is commenced at the time the threshold is crossed by an arrival. This remains true for interarrival distances down to 2 nmi.

3.9 Specific Dual Lane Configuration

With the foregoing analysis and simulation findings in mind, the dual lane runway system may be envisioned as depicted by Figure 26.

The investigation of the parameters characterizing the dual lane system established a minimum separation of 1000 ft be provided between the pair of runways. Additional separation does not degrade operations in any way. No stagger is necessary as the data available through studies on wake turbulence does not support the idea that the runway pairs can be made to operate independent of wake tubbulence effects through some amount of stagger. Study of the taxiway between the parallel runways showed no operational advantages. Possibly, at airports with specific terminal designs, it may be used to relieve apron and terminal taxiway congestion where this is a major problem. The study did not investigate the parallel taxiway in the context of the total airport

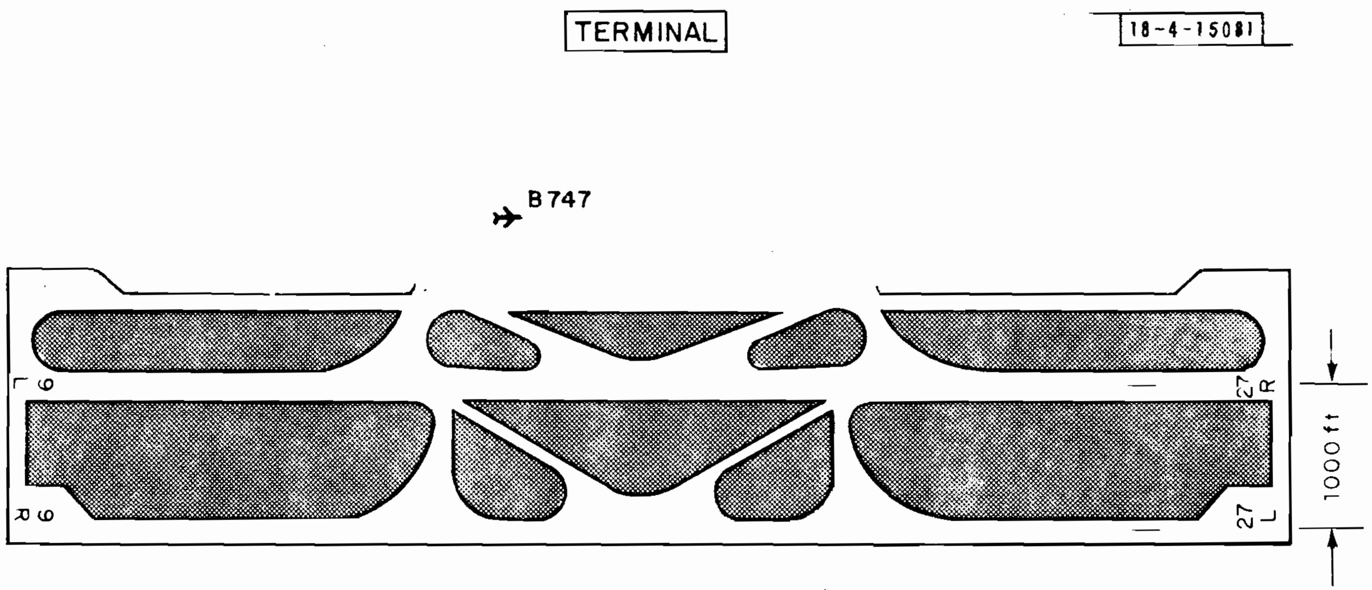


Figure 26. Typical Dual Lane Runway System.

requirements. It was established that at least one high speed exit plus a general aviation exit is desireable on each of the two runways. Segregated operations (arrivals on one runway, departures on the other) is the preferred mode of operation.

The outer runway should be designated as the predominant arrival runway as this allocation provides maximum flexibility for IFR and modified VFR traffic requirements. The inner runway is designed to also service arrivals when the demand requires it.

4.0 RUNWAY SIMULATION PROGRAM

4.1 Program Description

The performance of a proposed runway system prior to actual operation is difficult to predict. A live trial could be costly and time-consuming to implement, difficult to modify (once deficiencies are detected), and the number of variables that could be accommodated would be limited; therefore, computer simulation is an attractive technique for use in the initial evaluation of a design. Simulation can aid in the evaluation of alternative designs and although it never indicates the choice directly, the user is provided with data that he may use as a guide in the design process.

The airport simulator used to evaluate dual lane configurations was programmed on the TX-2 computer at Lincoln Laboratory, utilizing the interactive graphics capability. The capability available in the TX-2 system [4] allowed the simulation to be created in a few months and provided a great deal of flexibility; for example, all features of a runway and taxiway layout could be changed easily and rapidly.

In the simulation, the pilot response to controller commands was modeled. The pilot was modeled to respond cooperatively and promptly to reasonable instructions. This type of cooperation between pilot and controller is necessary if high traffic rates are to be achieved.

The Runway Simulation program consists of three primary parts.

(1) The edit design mode which allows the user to design, interactively, a configuration of runways and taxiways which represents a specific airport.

(2) The real time simulator mode which allows the user to generate traffic (both arrivals and departures), causes the traffic to move under a set of motion rules, and permits the user to issue commands to the planes similar to those given by local and ground controllers at an airport. While the simulator proceeds, statistical information is accumulated for each plane including its total time in the system, its time on the runway, and its time on the taxiways. In addition, enough information is stored away to allow playback of a session in order to analyze a particular situation as it develops.

(3) The programmed controller mode permits the simulation to proceed in fast time to generate the required data for quantitative comparison of the dual lane runway configurations studied.

4.1.1 Edit/design mode

During edit/design mode, the user starts with a blank airport map on the cathode ray tube. By use of the drawn characters, he indicates (in any order desired) the location of runways, taxiways (which are thought of as sequences of taxiway segments, each of which is straight), and arrival and departure fixes (points at which arriving and departing aircraft appear in the simulation). A data tablet [5] is used for drawing. In addition to the original positioning commands, there are commands which place on the screen a ruler or a compass rose for use in accurate positioning. A list of the airport design instructions is contained in Table 2. A complete list of all commands available and their symbols is shown in Appendix B.

Table 2. Runway Design Program.

I.	Commands available to invoke subroutines used to generate any runway/taxiway configurations: 1. Runway 2. Taxiway 3. Touchdown Zone 4. Departure Fix 5. Arrival Fix
II.	Commands available as aids in developing the required airport map: 1. Delete item 2. Move end point of item (approach or departure fix, taxiway, runway) 3. Ruler 4. Protractor
III.	Additional commands provided to assist construction and provide convenient editing (also available in Simulate): 1. Scale up by a factor of two 2. Scale down by a factor of two 3. Recenter map about indicated point 4. Reset scale to original scale 5. Scale up encircled area 6. Provide a scaled x-y grid

NOTES

1. A runway is specified by providing its end points.
2. A touchdown zone is also specified by its end points.
3. Taxiways are straight line segments connecting two end points specifying a given segment. Straight line segments can be connected without limit.
4. A departure fix can be added to any taxiway segment.
5. An arrival fix can be added anywhere along any runway centerline extended. Missed approach points are automatically specified at this time. Currently, the decision point to miss appears 500 feet from threshold.
6. Runways and taxiways can be drawn to intersect.

4.1.2 Real time simulator mode

When the airport design is satisfactorily entered, the user may enter simulate mode. A simple computer check is performed on the airport configuration to insure that departure fixes are attached to taxiways. Simulation then begins. A clock appears on the screen and advances every second.

4.1.2.1 Arrivals

The user indicates that traffic is to begin from some specific arrival fix. The stream of traffic may either be generated from a script or from a uniform probability distribution. A plane will be entered into the system at the arrival fix headed toward the runway associated with the arrival fix at a time based on the selected arrival spacing. The plane type and approach speed will be generated either statistically or obtained from the script. Each second, the new position of the plane is calculated and the plane is displayed as a triangle at the new position. A missed approach test is perfomed when the plane reaches 500 ft (parameter to the simulation) from the threshold of the runway. A missed approach is a procedure which a pilot will execute when in his or the controller's judgment, it would be better to go around again and make another approach. For simulation purposes only, a decision point 500 ft from the runway threshold was chosen. This is the point at which the calculation is performed in the simulation; not the point at which the pilot would make a decision. This distance was selected so that there would never be two aircraft occupying the runway simultaneously. The 500 ft is not to be construed as the IFR missed approach point recommended by the FAA. If a departure or previous arrival is on the runway, a missed approach is declared; the plane symbol changes to a plus sign and the plane is tracked to the opposite end of the runway and removed from the simulation. If a missed approach does not occur, the plane advances toward threshold and flares with an instantaneous speed drop of 10 knots (parameter).

A touchdown point is randomly selected from within the touchdown region (specified during edit mode). When the plane reaches the touchdown point, the symbol changes to one resembling the silouette of an airplane and it begins to decelerate at a rate which is plane-type dependent. It continues to decelerate until it reaches a target speed which is determined by the speed at which the plane can safely negotiate the next runway-taxiway intersection. Upon achieving that target speed the aircraft cruises at this speed until the exit is reached. The exit speed is determined from the angle between the runway and taxiway (parameter).

When the plane reaches a taxiway, it checks to see if it has reached the turnoff speed and whether there is room to enter the taxiway and stop before reaching any plane currently in the taxiway. If the plane satisfies these criteria, it enters the taxiway; otherwise, the target speed is set for the next runway-taxiway intersection and the plane continues on the runway. After the plane has entered the taxiway and traveled a short distance (parameter) along the taxiway, the plane is declared clear of the runway. Thereafter, the plane is under the direction of the controller. If no commands are issued, the plane continues to the end of the segment. If there is no taxiway adjacent to the end of the current one, the plane is declared to have reached the apron and is removed from the simulation. The controller may issue commands such as turn (right or left), stop, or proceed to next intersection and stop.

When two planes are following each other on a taxiway and the first one stops, the program insures that the trailing plane will also stop. The rule is as follows: If a plane is within interaction distance of the aircraft ahead, currently, 800 ft), and is moving faster than 5/4 of the speed of the forward aircraft, then the trailing aircraft will adjust its speed to reach 4/5 of the forward aircraft's speed. These values were arbitrarily selected to provide a reasonable stopping strategy for the simulation.

When not under the restrictions imposed by the headway rule, the aircraft will always endeavor to maintain its preset taxiway speed.

Summaries of the arrival and taxiway oriented events are shown in Figures 27 and 28, respectively.

When a plane leaves the system, a line is entered into the data file including information about when the plane entered the system, whether it is an arrival, departure or missed approach, its runway occupance time, taxiway time, total time in the system, and delay time. This information is then available for later analysis.

4.1.2.2 Departures

The sequence for departures is similar to that for arrivals. The plane is generated at a departure point and then travels through the taxiway system under direction of the controller. When it is on a taxiway segment adjacent to a runway, the plane may be given clearance onto the runway. This permission may include clearance to depart, in which case the plane will immediately begin accelerating to liftoff speed after turning onto the runway. If the aircraft is given permission to taxi into position and hold, the aircraft will taxi to runway threshold, align itself with the runway, and come to a stop on the runway. The program selects a liftoff speed from a uniform distribution based upon its plane type and accelerates the plane until it lifts off. After liftoff, the plane will be traced for a short time (plane type dependent) and then removed from the system. A departure event summary is included in Figure 29.

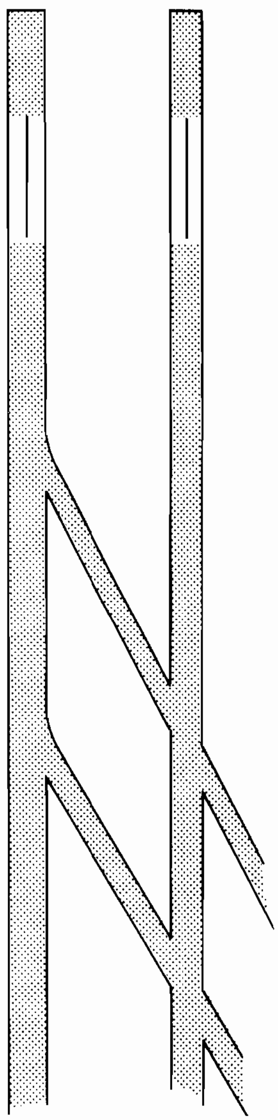
▽

Aircraft (▽) appears over outer marker with a randomly-selected speed appropriate for the type of aircraft and having a nominal spacing behind the preceeding arrival.

Arrival continues approach, during which time controller can transition arrival to the parallel approach, miss the approach and over fly the runway, or continue the approach without change.

X

At a programmed decision point (X), the aircraft elects to land or to miss the approach. The decision to miss the approach is made if the preceding arrival or a departure is still rolling on the runway.



The arrival aircraft's approach speed drops 10 knots when passing threshold, simulating the speed lost during the flare maneuver.

The aircraft touches down at a point randomly selected in the touchdown zone and begins a constant deceleration from the touchdown speed.

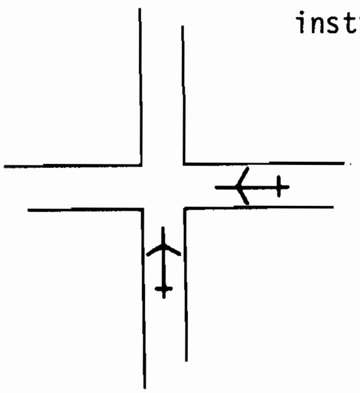
Aircraft deceleration continues until an upcoming exit is reached. If the exit speed is reached prior to arrival at the exit, the aircraft will coast at this speed until it exits.

Aircraft exits at a programmed exit speed and begins taxiway deceleration toward a speed of 20 knots.

While the aircraft is in the taxiway system, the controller can command the aircraft to stop short of the departure runway or to continue and taxi across.

If asked to hold short, the aircraft decelerates to a stop 200 ft short of the runway centerline and holds to await instructions to resume taxiing. If instructed to cross with no delay, the aircraft continues at taxi speed.

Figure 27. Arrival oriented events.



In order to provide required directions or to resolve conflicts which may occur in the taxiway system, any aircraft can be instructed by the controller to:

(1) Hold short of next intersection.

(2) Turn left at the next intersection.

(3) Turn right at the next intersection.

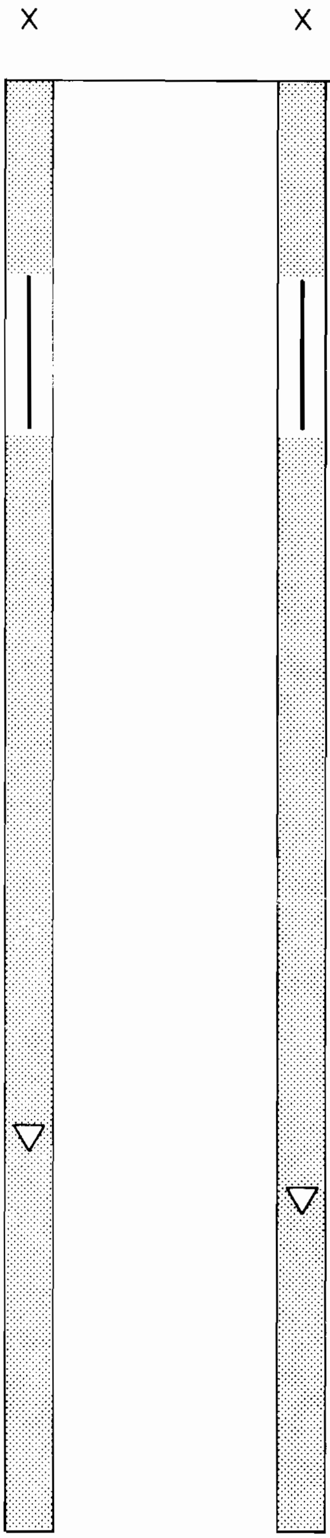
(4) Resume taxiing if decelerating or if holding.

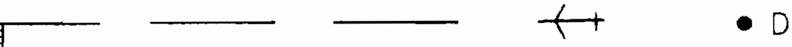
Additionally, aircraft can be instructed to cross one intersection and to hold short of the next intersection with another taxiway or runway.

If required for whatever reason, any aircraft can be instructed by the controller to come to an immediate stop.

While in the taxiway system, aircraft will slow to a stop behind an aircraft holding on the taxiway.

Figure 28. Taxiway oriented events.





Departure aircraft ( ) appears at a departure fix (D) and accelerates from a stop to 20 knots taxiing velocity.

While taxiing, the aircraft can be instructed by the controller to:

(1) Continue taxiing.

(2) Hold short of first runway.

(3) Cross first runway to hold short of second runway.

(4) Taxi into position and hold.

(5) Be cleared for takeoff.

Where appropriate, commands are given to holding aircraft or to aircraft in position awaiting further clearance.

Takeoff speed is randomly selected from a uniform distribution based on aircraft type. Aircraft lifts off (▽) following rollout at constant acceleration.

Figure 29. Departure oriented events.

4.1.3 Programmed controller mode

The interactive graphics real time simulator program was amplified to provide for a programmed controller capability.

The interactive features included:

(1) The ability to turn the display on for purposes of viewing

(2) The ability to turn the display off to make full use of the machine's computation speed

(3) To change the simulation rate while the program was in the display mode.

Other selected features were incorporated to aid in the editing function.

The programmed controller simulations use the same dual lane runway system employed during real time control analysis. The inputs to the various simulation exercises were standardized wherever possible in order to facilitate comparison of the individual configurations. Arrival and departure scripts were generated to provide similar airport traffic samples to each dual lane system in a given group of experiments.

In all cases, the aircraft proceed to the runways and exit taxiways as described in the figures depicting arrival, departure, and taxiway events discussed earlier in relation to real time interactive graphics mode. The real time simulation program provided headway control. Only the source of controller decisions has changed. Specific instructions to resolve conflict problems which might occur at runway or taxiway intersections are now programmed instead of controller issued. Figures 30 through 34 depict the critical decision area during VFR, IFR, and VFR mixed operation mode.

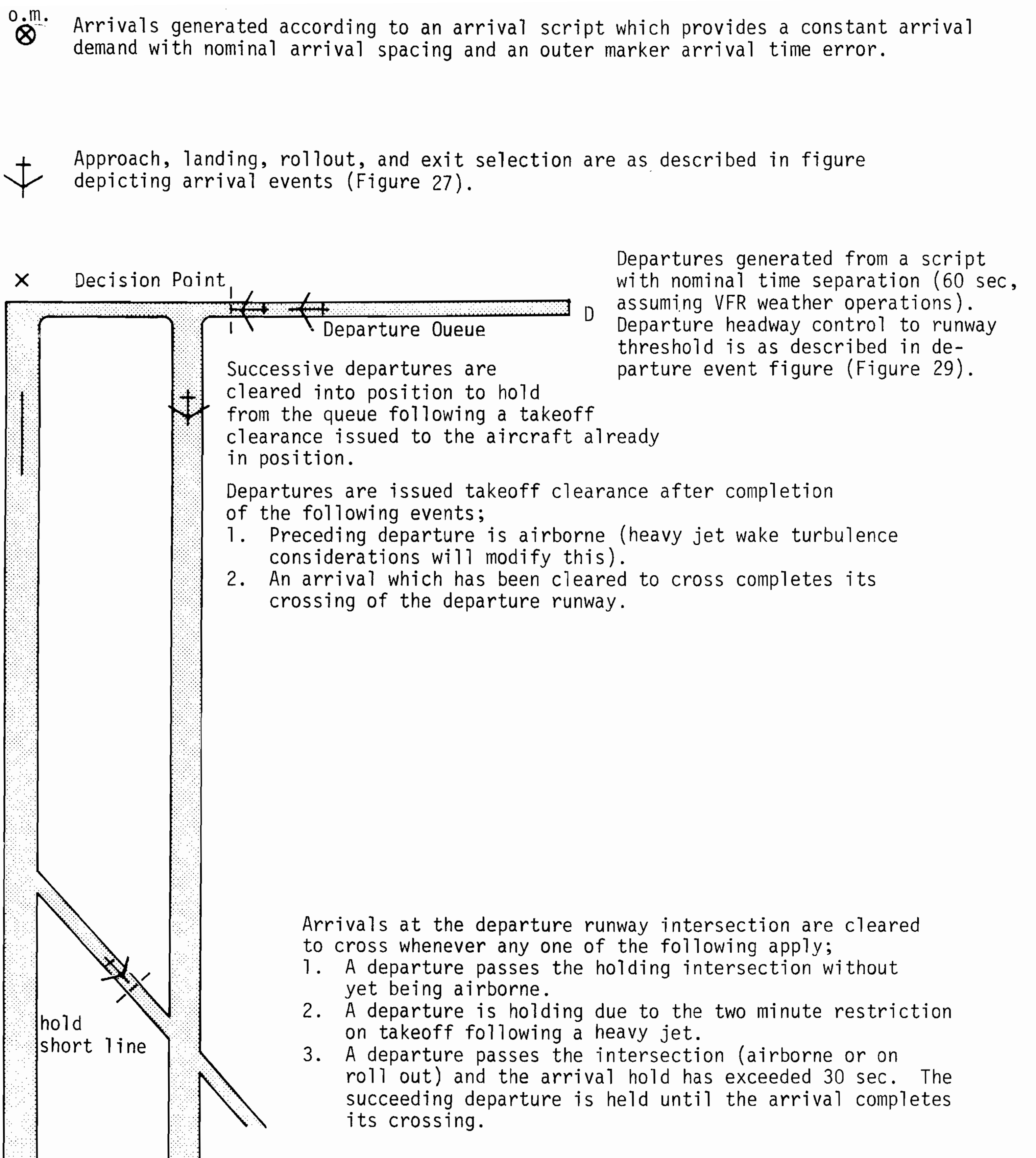


Figure 30. VFR Outer Runway Arrival Control Policy.

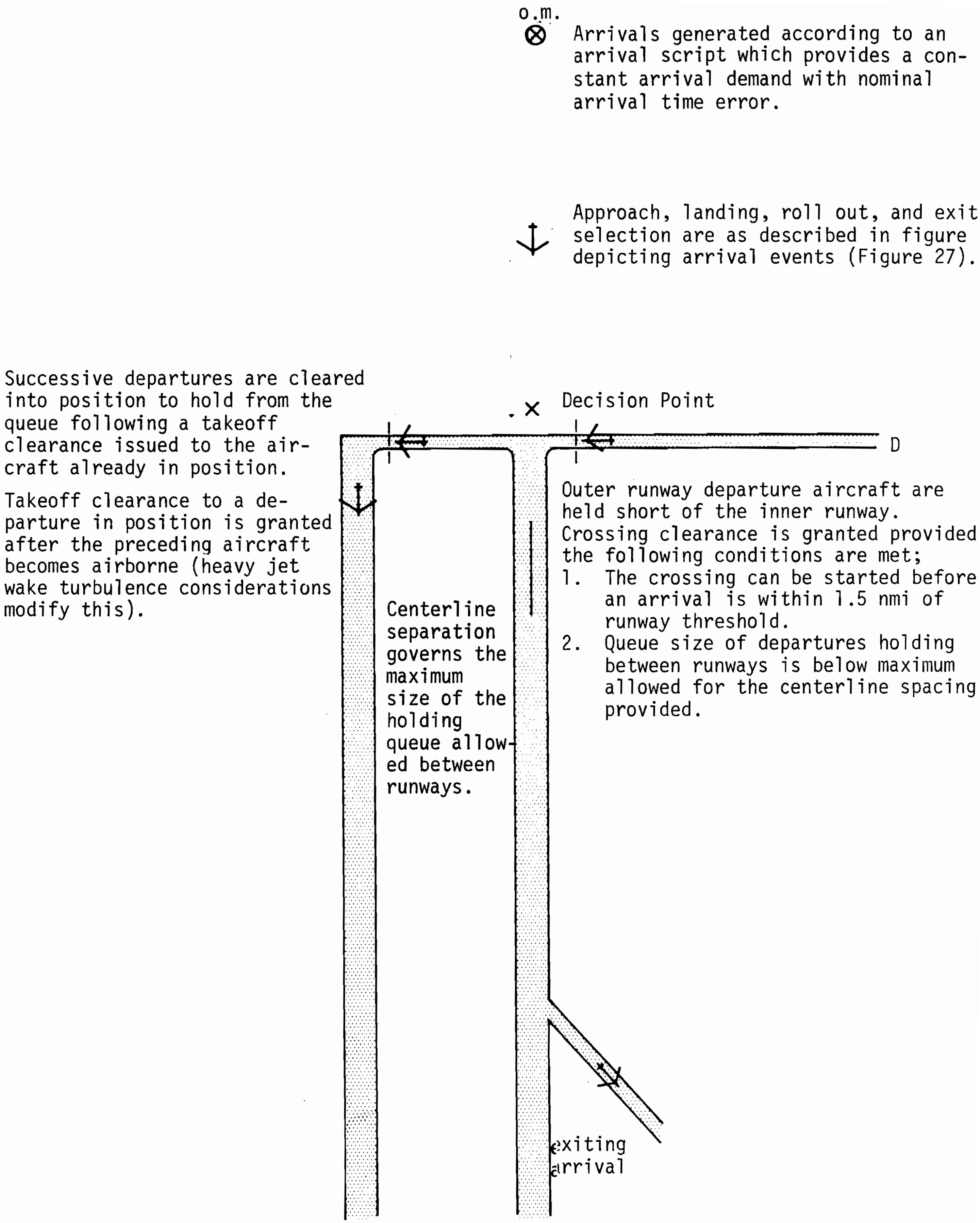


Figure 31. VFR Inner Runway Arrival Control Policy.

o.m.

⊗ Arrivals generated according to an arrival script which provides a constant arrival demand with nominal arrival spacing and an outer marker arrival time error.

Approach, landing, roll out, and exit selection are as described in figure depicting the arrival events (Figure 27).

2 nmi

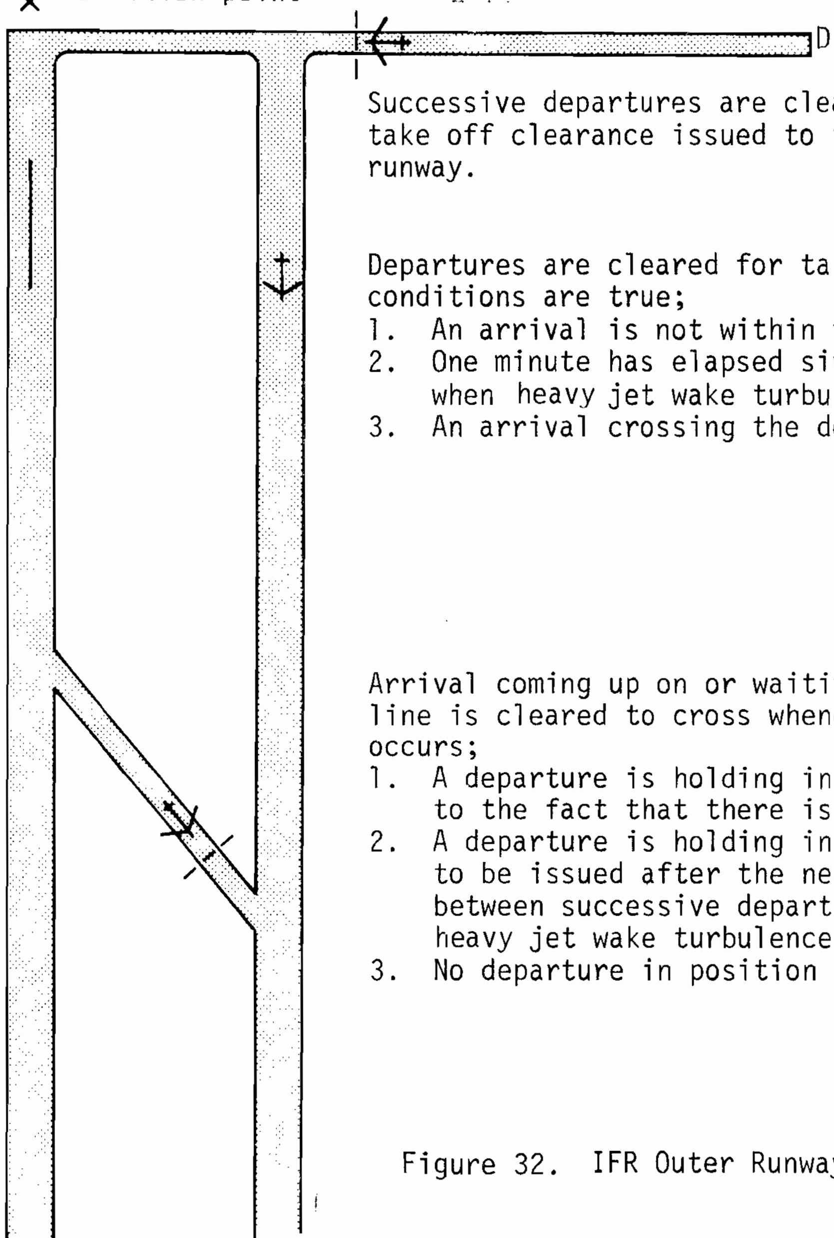
- outer limit of zone

IFR approach zone

- inner limit of zone

× Decision point

Departures generated from a script with nominal time separation (90 sec assuming IFR weather conditions). Departure headway control to runway threshold is as described in departure event figure (Figure 29).



Successive departures are cleared into position to hold following a take off clearance issued to the aircraft already in position on the runway.

Departures are cleared for take off provided the following conditions are true;

1. An arrival is not within the IFR approach zone.
2. One minute has elapsed since the previous departure (modified when heavy jet wake turbulence considerations are involved).
3. An arrival crossing the departure runway has cleared it.

Arrival coming up on or waiting at the departure runway hold short line is cleared to cross whenever any one of the following situations occurs;

1. A departure is holding in position restricted from takeoff due to the fact that there is an arrival within the IFR approach zone.
2. A departure is holding in position awaiting takeoff clearance to be issued after the necessary one minute delay had elapsed between successive departures (modified to two minute delay if heavy jet wake turbulence considerations must be involved).
3. No departure in position requesting takeoff clearance.

Figure 32. IFR Outer Runway Arrival Control Policy.

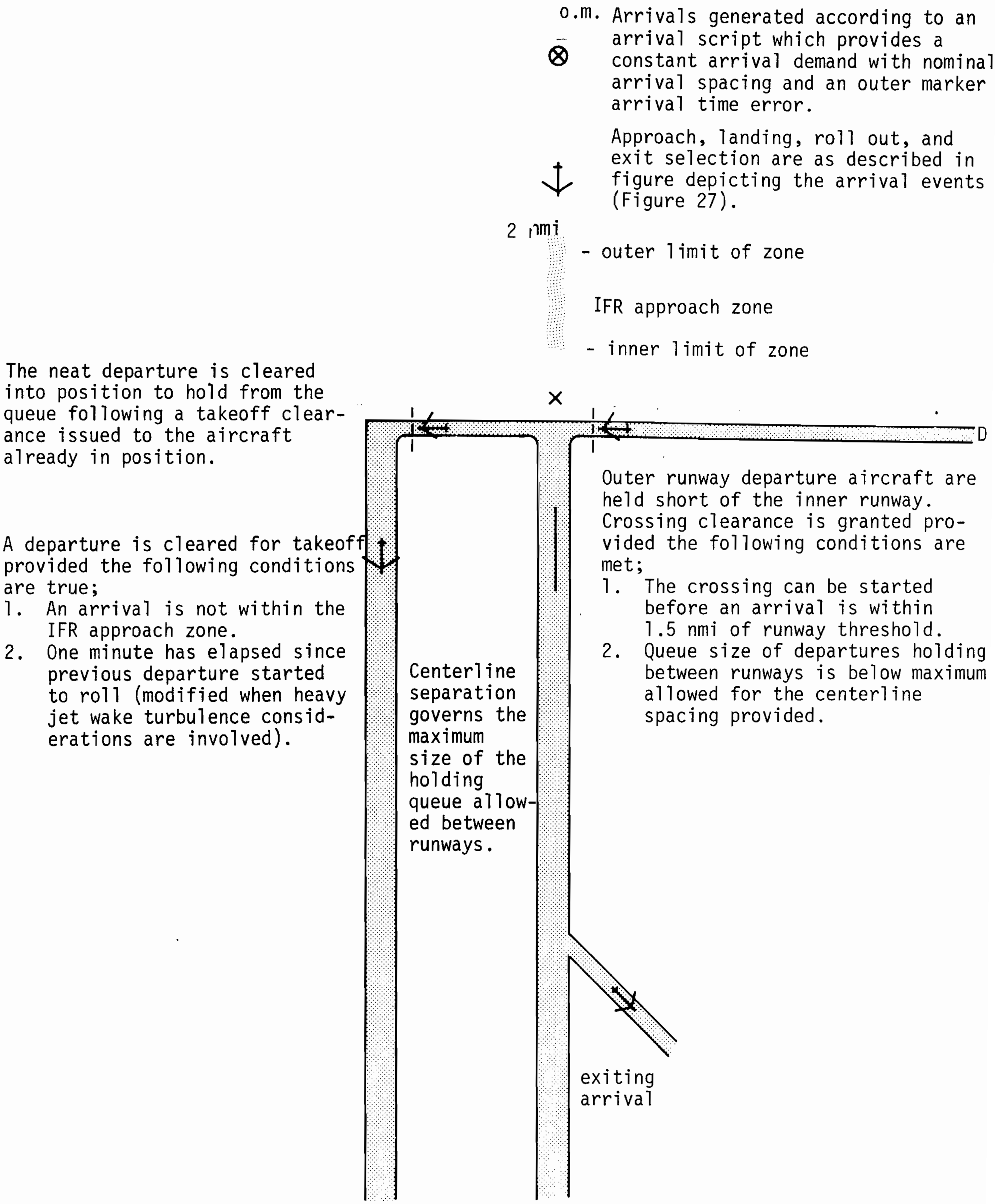


Figure 33. IFR Inner Runway Arrival Control Policy.

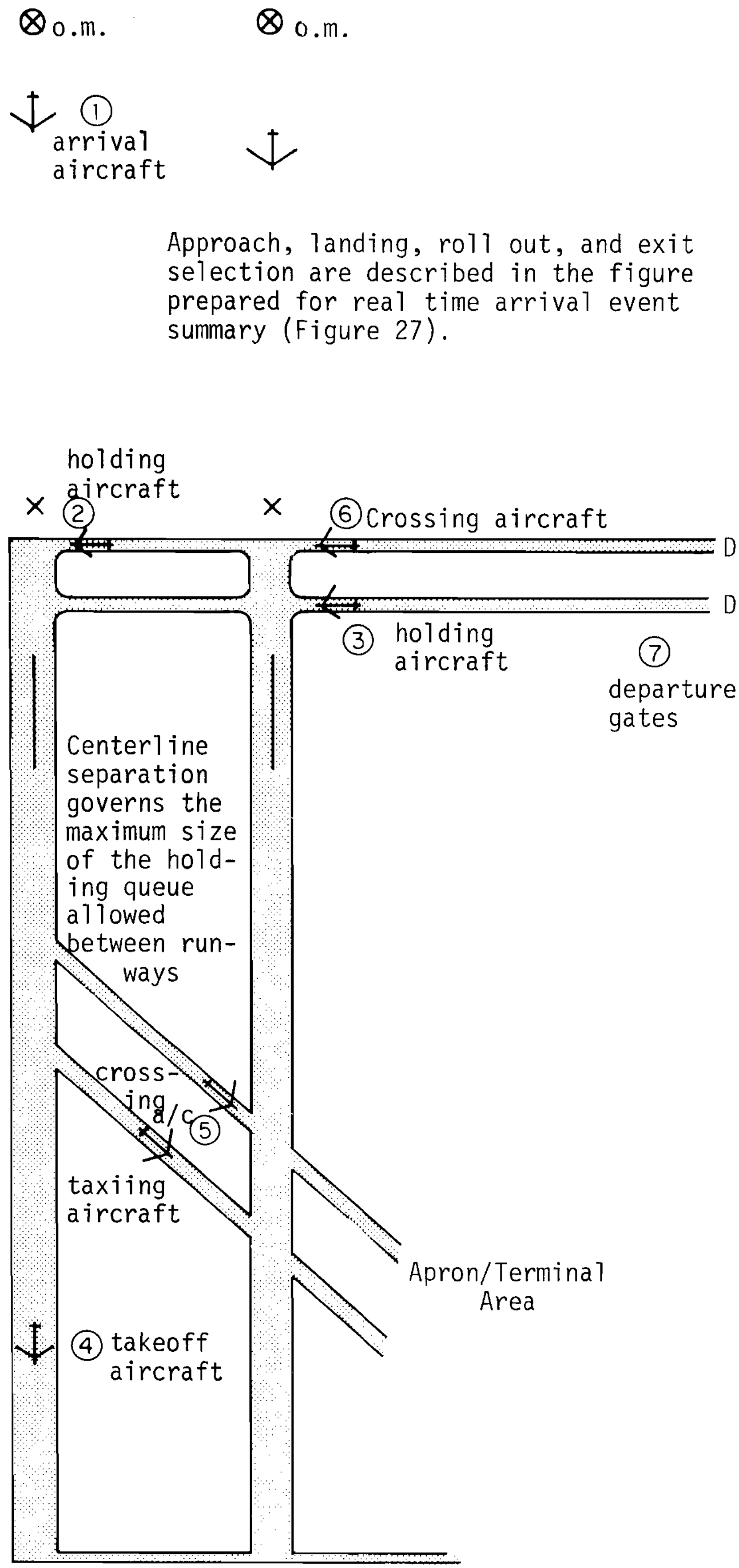


Figure 34. VFR Mixed Operation Control Policy.

1. Aircraft are generated at each outer marker from prepared traffic scripts with nominal interarrival separation provided between aircraft to each runway (typically 4 nmi in trail). If runway centerline separation is less than 2500 ft, the script to one runway is dependent on that prepared for the adjacent runway. This dependence is due to heavy jet wake turbulence considerations.

2. For a departure which is holding short of the runway to be cleared into position behind a landing aircraft, an estimate is made as to whether sufficient time exists for the landed arrival to exit the runway and the departure to become airborne before the next arrival crosses the decision point selected. If the preceding departure (on either runway if considered dependent) was a heavy jet, then this must also be factored into the estimated time requirement.

3. In addition to 2 above, one must consider arrival aircraft crossing the departure runway. Any arrival aircraft which has waited longer than 90 sec to cross the inner runway will be given priority over a holding aircraft and receive a crossing clearance. This additional crossing time must be factored into the time estimate made above before a departure is cleared into position subsequent to takeoff.

4. Departures which were holding in position behind a landed arrival aircraft are cleared for takeoff after the arrival has exited into the taxiway system. Departures which were holding in position behind a preceding departure are cleared for takeoff following liftoff (modified when heavy jet wake turbulence considerations must be invoked).

5. If an arrival aircraft has been holding longer than 90 sec to cross the inner runway, a departure will not be put into position on the runway until the waiting aircraft has crossed. The aircraft will cross if:

   1. An arrival aircraft is more than 1.5 nmi from threshold and an arrival is not on the runw ay rolling to its exit short of the holding intersection.
   2. There is no departure in position awaiting takeoff clearance or on the runway.

   After the crossing has been effected the test for departure to be placed into position on the runway (#2 above) is rerun.

6. Outer runway departure aircraft are held short of the inner runway. Crossing clearance is granted provided the following conditions are met:

   1. The crossing can be started before an arrival is within 1.5 nmi of runway threshold.
   2. Queue size of departures holding between runways is below maximum allowed for the given centerline spacing provided (i.e., 700 ft - one, 1,000 ft one or two, 2499 ft-four).

7. Departures with nominal interdeparture separations are generated at each departure gate from scripts (120 sec in trail separation assuming mix operations in VFR weather conditions). Departure headway control to runway threshold is as described in figure depicting departure events (Figure 29).

4.1.4 Traffic generation rules

Arrivals

(1) Scenario - Arrivals are specified to enter the simulation from an approach point. Entrance time, aircraft type and approach speed are specified in the script.

(2) Distribution - When an arrival is generated from an approach fix, the next aircraft to be generated is queried. At this pregeneration time, the aircraft type is selected by a random draw from a distribution of aircraft types. Once the type is known, the approach speed is selected randomly from a uniform distribution over the approach speed interval for this aircraft type. The separation distance between the next arrival and the one just generated is calculated based on the aircraft types. Each arrival type has a designated spacing which must be maintained behind it. The spacing behind a heavy aircraft depends on whether the aircraft is followed by a heavy aircraft or some other aircraft type. The time until generation is calculated as follows:

$$\Delta t = \frac{d_{RW}}{S_1} - \frac{(d_{RW} - d_S)}{S_2} + t_e$$

where d_{RW} = distance from approach fix to threshold ($\leq$ 5nm)

d_S = required spacing between aircraft

S_1 = speed of aircraft just generated (75-156 knots)

S_2 = speed of aircraft being pregenerated (75-156 knots)

Δt = interval between successive generations.

t_e = positive delivery error selected from a uniform distribution.

Generation of arrivals in accordance with this equation insures that as the first arrival reaches threshold, the next arrival will be at least d_S from threshold.

Departures

(1) Scenario - Departures are specified to enter the simulation from a departure point. Entrance time and aircraft type are specified in the script. The initial speed is 0 knots.

(2) Distributions - The interval between successive departures is selected from a uniform distribution. The aircraft type is chosen by a random draw from a preselected aircraft type mix.

4.1.5 Aircraft parameters and ATC rules summary

The values for various aircraft parameters used to model aircraft characteristics [2,7-16] are included in Table 3. A parameter with a range of possible values obtains a random value selected from a uniform distribution. The ATC rules and procedures used by the controller during real time simulation are summarized in Table 4. The rules used during programmed controller simulations were summarized by the figures contained in the previous section.

4.1.6 Simulation features

A facility is provided for the user to request a snapshot of the current situation and store it away. At a later time, he may request that snapshot to be brought back and may continue simulation from that instant.

Every command issued via the data tablet is saved. If the user desires, this information may be recovered and used to rerun the simulator through the exact same sequence. This may be done at different rates than the original run and permits the analyst to analyze, in detail, interesting segments of the action.

Table 3. Values of Various Parameters Used to Model Aircraft.

Parameter	Category: Heavy	Large	Medium	General Aviation
Final Approach Speed (Knots)[10,18]	143 $\pm$ 13	143 $\pm$ 13	123 $\pm$ 15	90 $\pm$ 15
Touchdown Speed[10]	(Approach Speed Less 10 Knots)			
Runway Deceleration (ft/sec^2)[8,9,19]	5	5	5	4
Lift-off Speed (Knots)[20]	170 $\pm$ 20	160 $\pm$ 15	115 $\pm$ 15	80 $\pm$ 20
Runway Acceleration (ft/sec^2)[8,9,20]	7.0	7.0	7.5	5.0
Taxiway Speed (Knots)[3,16]	20	20	20	20
Taxiway Decleration (ft/sec^2)	3	3	4	2
Taxiway Acceleration (ft/sec^2)	3	3	4	2
Distance Aircraft Travels into Taxiway to Provide Runway Clearance (ft)*	400	400	400	125
Percentage of Type in Mix	20	40	30	10
Minimum Spacing Behind a Heavy (nm)	3	5	5	5
Minimum Spacing Behind anything but a Heavy (nm)	3	3	3	3

Pilot Response Time to Selected Control Commands (sec) 5 $\pm$ 3

Active Runway Crossing Time by a Taxiing Aircraft (sec) from a stop[3] 30 $\pm$ 5

* This is a simulation parameter and does not reflect current ATC action.

Table 4. ATC Procedures and Separation Criteria.

When the first arrival aircraft is over runway threshold, the next arrival aircraft is at least a distance d_S, the required spacing from the threshold. Some positive delivery error is assumed.
Current wake turbulence procedures require five nautical miles (nmi) between a heavy aircraft and following aircraft, except another heavy aircraft.* The rules are enforced for both arrivals and departures.
An arrival must execute a missed approach, if the preceding arrival or departure aircraft is still rolling out on the runway when the arrival aircraft crosses the missed approach test point.
Transitions to the adjacent runway will not be made if the arrival aircraft specified in the following list are closer to the threshold than the distance shown: Heavy 4 nmi Large 3 nmi Medium 3 nmi General Aviation 1.0 - 1.5 nmi
A taxiing aircraft will not cross in front of a rolling departure.
A departure will not be cleared for takeoff until the crossing aircraft has cleared the width of the runway.
A crossing of the arrival runway will not be attempted when an arrival is less than 1.5 nmi from threshold.
Departures are placed into position by controller judgment.
Two minute separation is provided behind a departing heavy aircraft and any other type aircraft on either of the parallel runways.
Departures are released following departures in compliance with the following rules: (1) Minimum requirements for separation between aircraft with different performance characteristics. (2) Departure control restrictions. (3) Application of heavy aircraft separation rules.

* This does not correspond to the latest version of the rules governing heavy jet operations.

5.0 SIMULATION DATA

5.1 Real Time Controller Simulation Data

Three basic runway--traffic configurations were investigated:

(1) Single lane - arrivals/departures

(2) Dual lanes - arrivals on one/departures on other (segregated traffic)

(3) Dual lanes - arrivals/departures on both (mixed traffic).

Appendix D, Real Time Data Summary, contains a table entitled: Dual Lane Runway Real Time Experiments. The table is a matrix of data gathered using four ATC controllers (I, II, III and IV) directing simulated traffic using the TX-2 computer. Controllers I and II were readily available for TX-2 experiments whereas controllers III and IV had only limited availability. All four controllers were familiar with the simulation before data on this matrix was recorded. Experiments for controllers III and IV were selected to gain further insight into areas which had not been thoroughly explored by controllers I and II.

One of the primary purposes of the real time simulation was to eatablish a set of rules which could be programmed into the computer to simulate an actual ATC controller. These rules were modified as necessary by knowledge gained observing controllers in tower cabs at high density airports operating dual parallel runways.

The real time experiments were terminated when it was determined that little more could be gained through exercising live controller experiments. Consequently, some of the experiments by certain controllers were not conducted. It is difficult to draw conclusions from any limited sample of real time computer runs. Controller variability is a factor in the data results. Controllers are trained to react to specific situations and each develops his own techniques within the framework of the stated FAA ATC regulations. Variability also occurrred from day to day for the same controller. However, these real time runs do indicate trends which were later substantiated in the fast time results. It is these trends which are discussed here.

5.1.1 VFR controller data

5.1.1.1 Single lane

It was observed that a single lane could accommodate approximately 60 operations per hour (Figure 35, Plot A) consisting of arrivals and departures. However, the actual makeup of the 60 operations depended on the nominal arrival spacing which dictated the arrival demand for the single runway. The arrival demand rates as a function of the simulation dynamics for the arrival spacings employed were:

Nominal Arrival Spacing (nmi)	Demand Rate Number of Arrivals Per Hour
5	26
4	30
3	38

The demand rate achieved by individual controllers (Figure 36) was limited by missed approaches. Missed approaches were caused by a controller misjudging the timing such that he would try to get a departure between two arrivals causing the second arrival to go around due to the departure still occupying the runway.

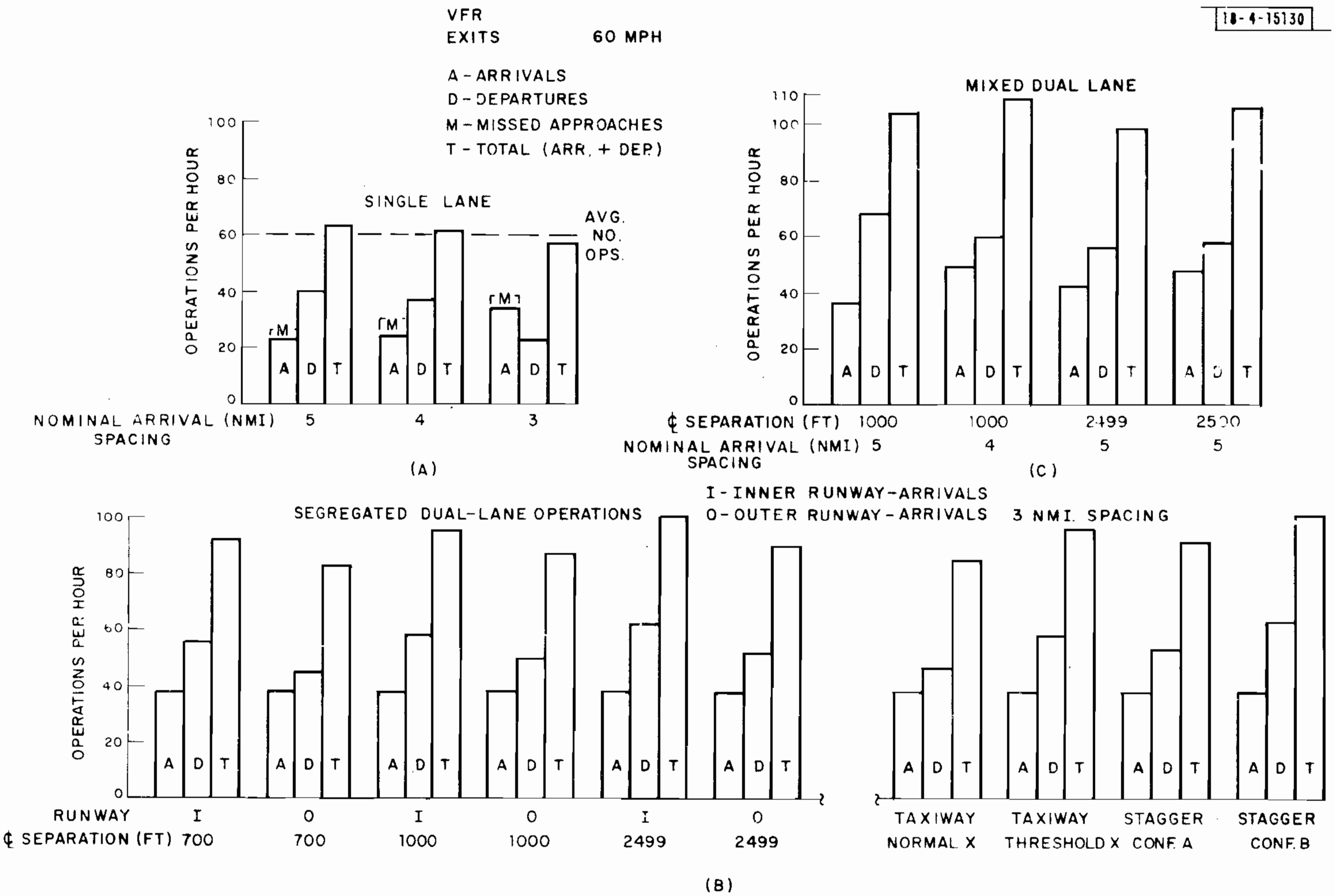


Figure 35. Real Time VFR Summary of Hourly Operations Single Lane.

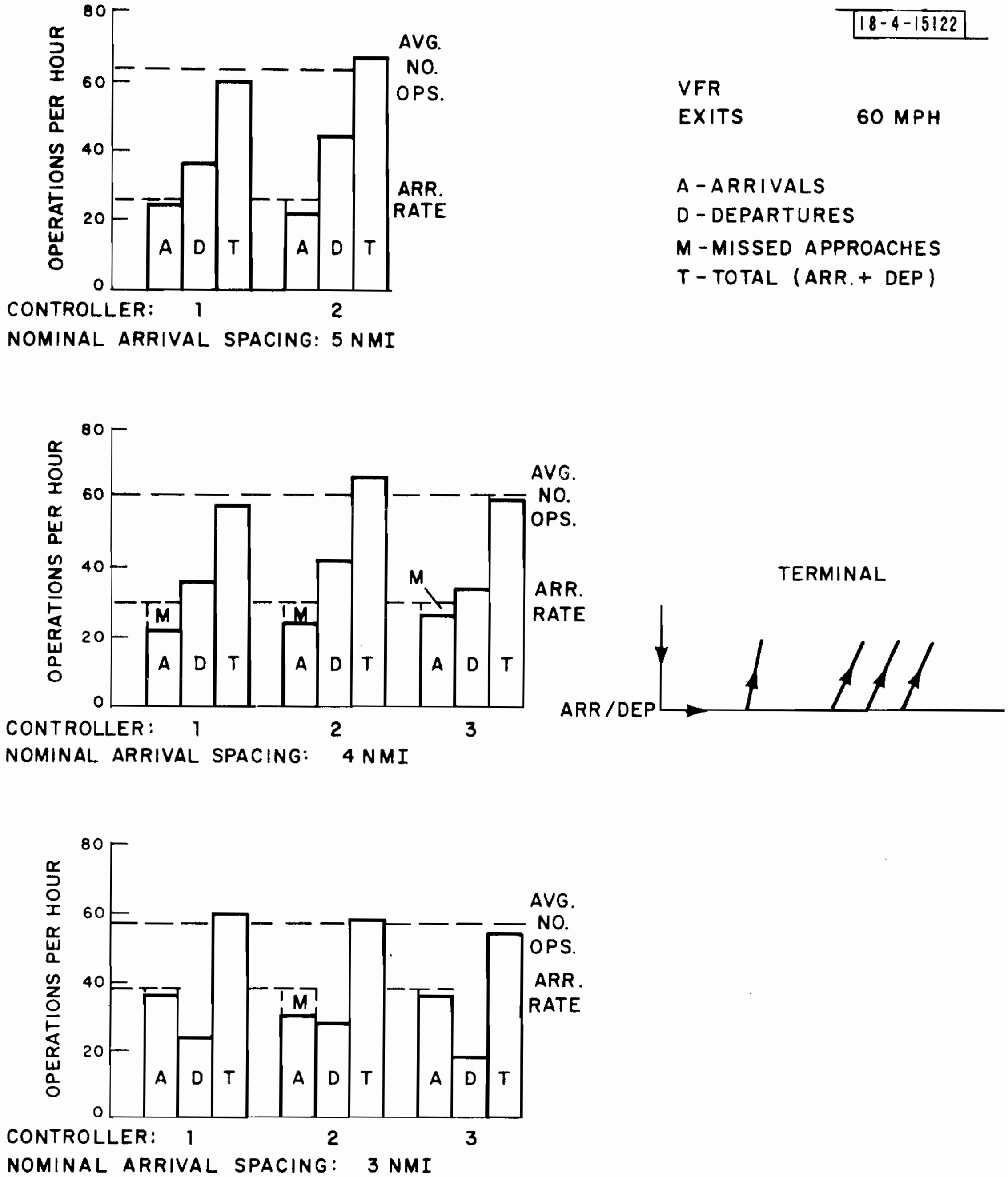


Figure 36. Real Time VFR Single Lane Operations vs Arrival Spacing.

The controllers initial reaction was that the simulation should allow the controller to recall a departure aircraft which had been cleared into position to hold on the runway when it became clear that a go around was imminent. Controllers do employ this tactic occasionally to get out of a tight situation. However, continual operational use of this procedure by a controller would lose the confidence of the succeeding departure and arrival pilots, thereby, negating any beneficial effects this flexibility might provide. The simulation did not allow a plane in position on the runway to be recalled.

The single lane observations suggest that 60 commercial-type operations (VFR conditions with IFR spacing) is a good average value achieved on a single independent runway. However, controller workload at this level starts to become excessive due to the number of priming commands necessary to brief the pilots on the controllers intentions. To continually achieve this average value of 60 mixed operations per hour, suggests some automation aids to assist the local controller.

5.1.1.2 Segregated dual lane

Segregated dual lane experiments with arrivals on one runway and departures on the other were performed. The issues investigated were centerline spacing, arrival/departure preference, center parallel taxiway, and staggered thresholds.

Centerline Spacing and Arrival/Departure Preference

Centerline spacings of 700, 1000 and 2499 ft were explored with arrivals being brought in first on the inner runway while departures used the outer and later reversing to arrivals on the outer while departures used the inner. The experiments were conducted with the nominal arrival spacing of 3 nmi creating a demand of 38 arrivals per hour. Figure 35, Plot B, shows that these arrivals were accommodated on both the inner and outer runways. This plot also shows that the average number of operations with arrivals on the inner was consistently higher than with arrivals on the outer for all three centerline spacings explored. The plot further shows that the average number of operations increased as the centerline spacing was increased from 700 ft to 1000 ft to 2499 ft. Analyzing these observations shows the increases in total operations always was achieved due to a corresponding increase in departures since arrivals were fixed at 38 per hour by the arrival spacing.

The rationale for these occurrences is the controller preference for giving the rolling arrival aircraft priority over holding departures. With arrivals on the outer exiting into the area between the runways the tendency was for the controller to permit the arrival to keep rolling and cross the inner departure runway. This often occurred with a departure in position on the runway waiting for takeoff clearance. This created a dependency relationship of the inner departure runway on the outer arrival runway. The number of departures on the inner runway was, therefore, reduced from an ideal one per minute or 60 per hour figure. With the situation reversed, arrivals on the inner and departures on the outer, the rolling arrivals exited into the apron area not effecting the outer departure runway. The outer departure runway was fed aircraft between the arrivals in the 3 nmi gaps making the two runways semi-independent. A dependency relation still existed due to the combined effects of a limited departure holding area between runways and the arrival gap timing. The outer departure runway when fed properly could approach 60 departures per hour. The result was that arrivals on inner and departures on outer handled approximately 100 operations per hours (38 arrivals, 60 departures) while the reverse resulted in less operations due to the decrease in the number of departures released.

This controller preference also accounts for an increase in total operations for outer arrivals as the centerline spacing is increased. With the 700 ft centerline spacing, as soon as an outer arrival exiting between runways entered the area, the controller would concentrate on keeping the aircraft rolling to cross the inner departure runway at the expense of departure operations. As the centerline spacing was increased to 2499 ft, the rollout distance between the runways was such that the outer arrival aircraft was at taxi speed (20 mi/h) for an appreciable period and was not as critical a factor in the controllers mind when crossing the inner departure runway. The controllers were more willing to stop the aircraft short of the inner and let the departure roll before crossing the aircraft resulting in a greater number of departure operations as the centerline spacing was increased.

The reason that the total operations were higher as the centerline spacing was increased for inner arrivals with outer departures, was a function of the departure holding space between runway thresholds. As the holding space for departures between runways was increased in going from 700 ft to 2499 ft, the number of commercial departures which could be crossed and held increased. At 700 ft, one departure could be crossed and held, at 1000 ft, two departures and at 2499 ft, four departures could be held. This holding zone between runways acted as a buffer with the greater spacing allowing a larger buffer. The larger buffer provided the controllers with steadier loading of departures at the greatest centerline spacing. The average number of operations for this type of operation increased from 92 at 700 ft, 95 at 1000 ft, to 100 at 2499 ft. However, Figure 37, Plots A, C, and E, suggests that the departure operations are a function of controller technique. One controller had 98 operations at 700 ft while another had 100 operations at 1000 ft; both at or near the average value of 100 at 2499 ft.

Taxi time (Figure 38, Plot A), which includes delay time, was essentially a constant for arrivals on the inner runway. Delay time is defined as the time the aircraft is stopped in the taxiway system either waiting for takeoff or to cross a runway. The arrivals on the inner had zero delay time as they were never stopped before reaching the apron area. The taxi time recorded for inner arrivals were the times recorded from the start of taxiing after exiting the runway until the aircraft reached the apron area. Taxi times for arrivals on the outer runway had greater times because of the delay incurred crossing the inner runway and because of the greater taxi distance from the outer runway to the apron area. Taxi time also increased as centerline spacing increased for outer arrivals. This is expected due to the greater taxi distance involved with 2499 ft centerline spacing as opposed to 700 ft spacing. However, it may also be observed (Figure 39, Plot A) that average arrival delay time increased at the 2499 ft spacing over the delay times recorded at 700 and 1000 ft. This was due to controller technique in preferring to hold more often outer arrival aircraft attempting to cross an inner runway at the 2499 ft spacing than at the 700 and 1000 ft centerline spacings as discussed previously. This preference allowed more departures on the inner runway at 2499 ft spacing which reduced the average departure delay time (Figure 39, Plot B).

Figure 38, Plot B shows a bar graph of average departure taxi time versus centerline spacing. It is defined as the time from the entrance of the departure

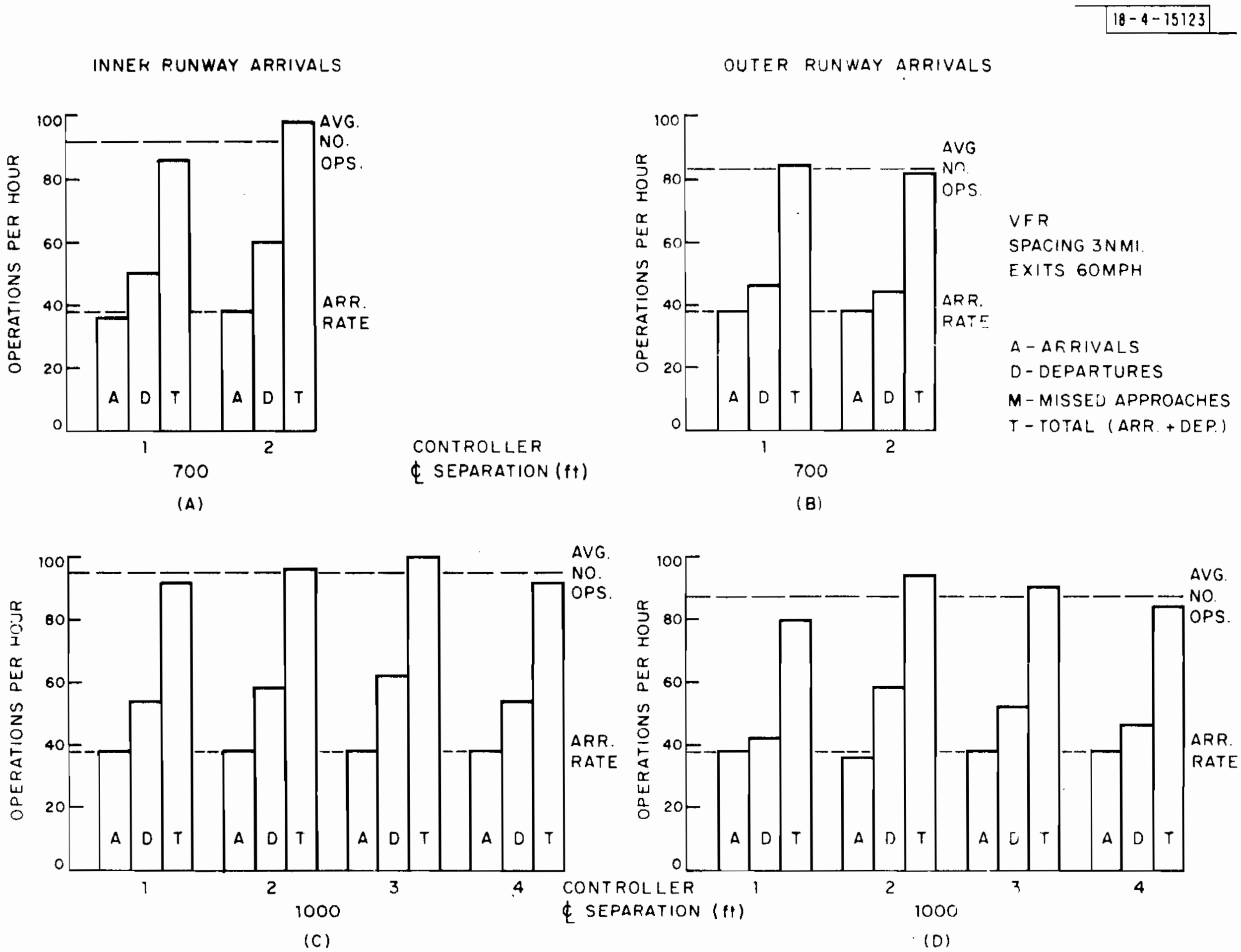


Figure 37. Real Time VFR Centerline Separation and Arrival/Departure Preference Operations.

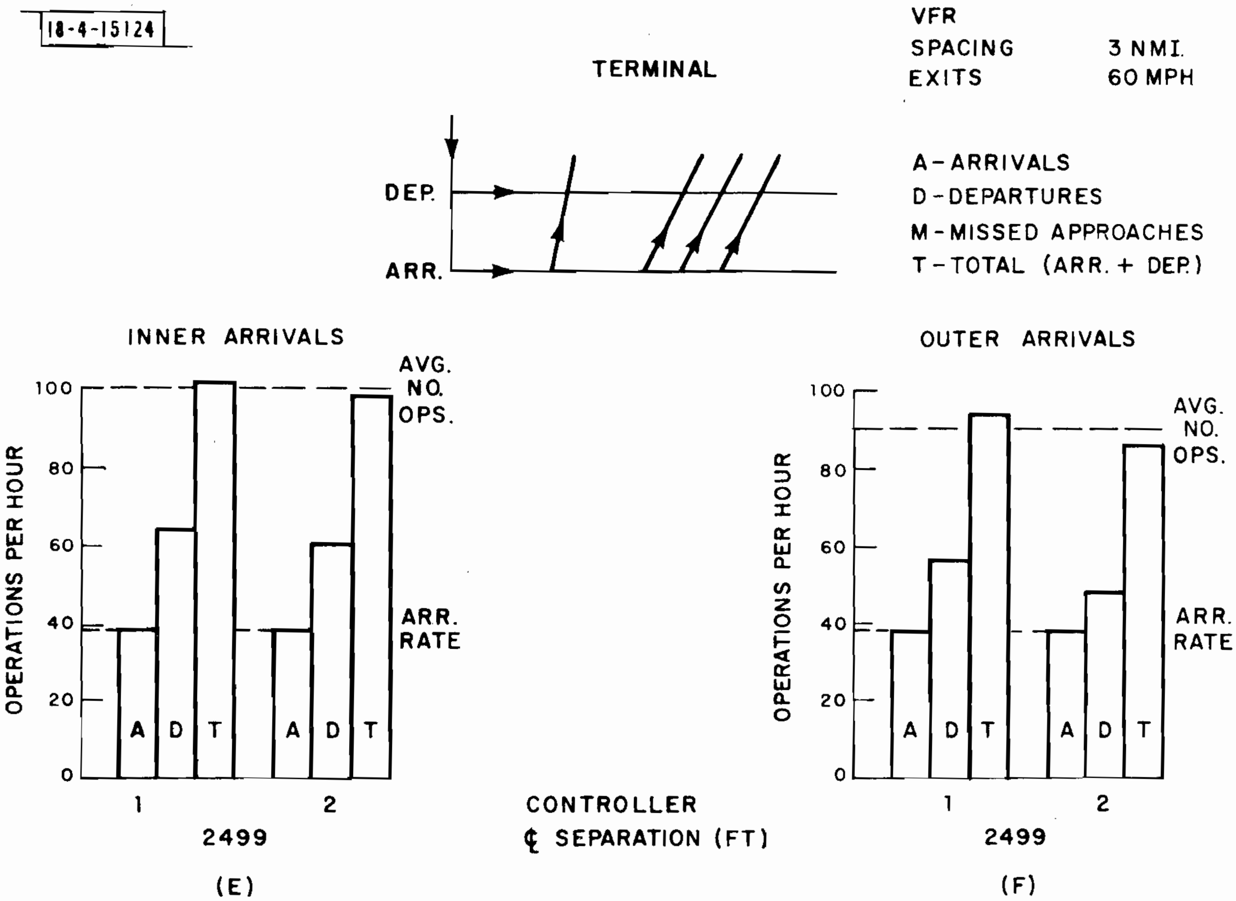


Figure 37. (Continued)

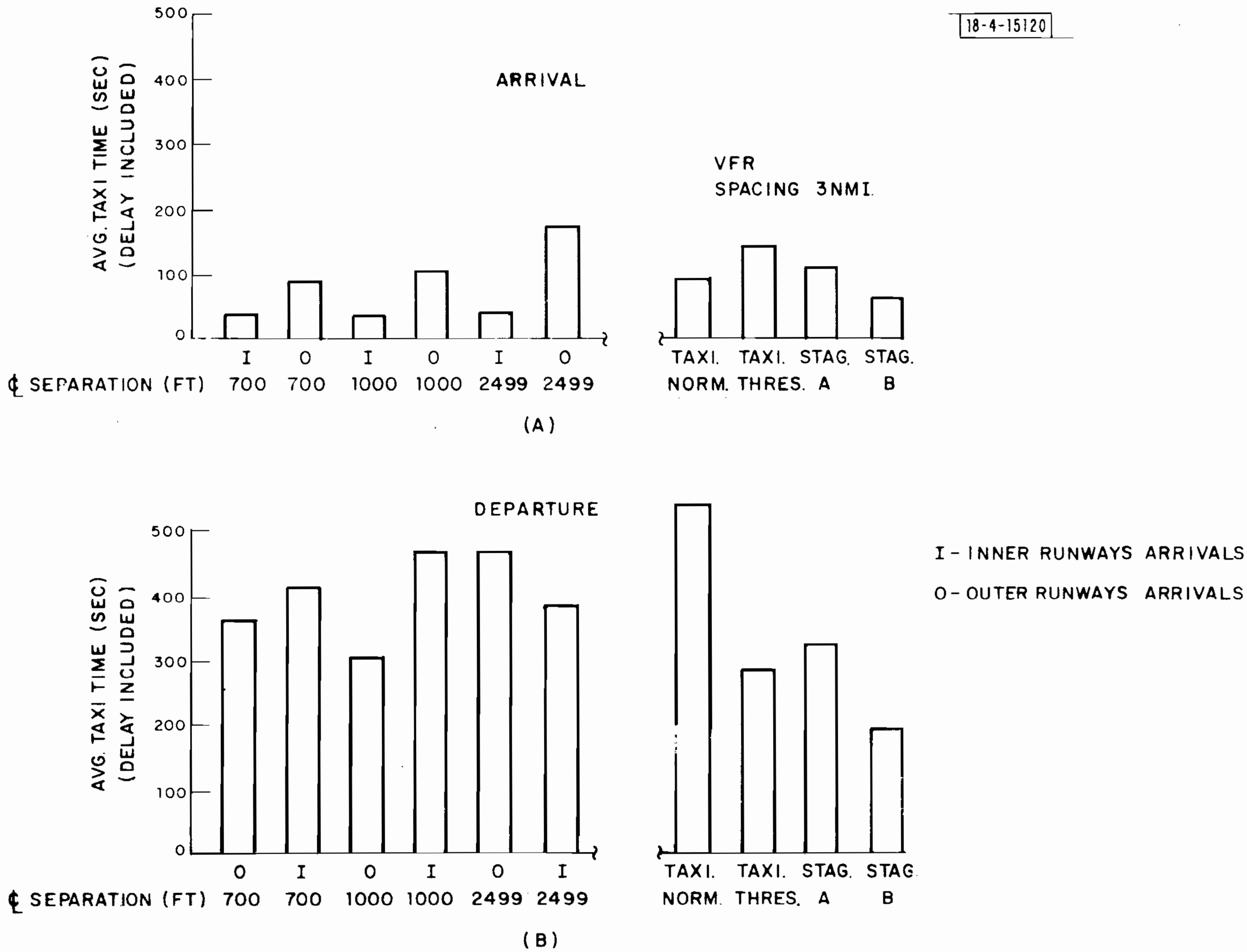


Figure 38. Real Time VFR Segregated Dual Lane Taxi Time Summary.

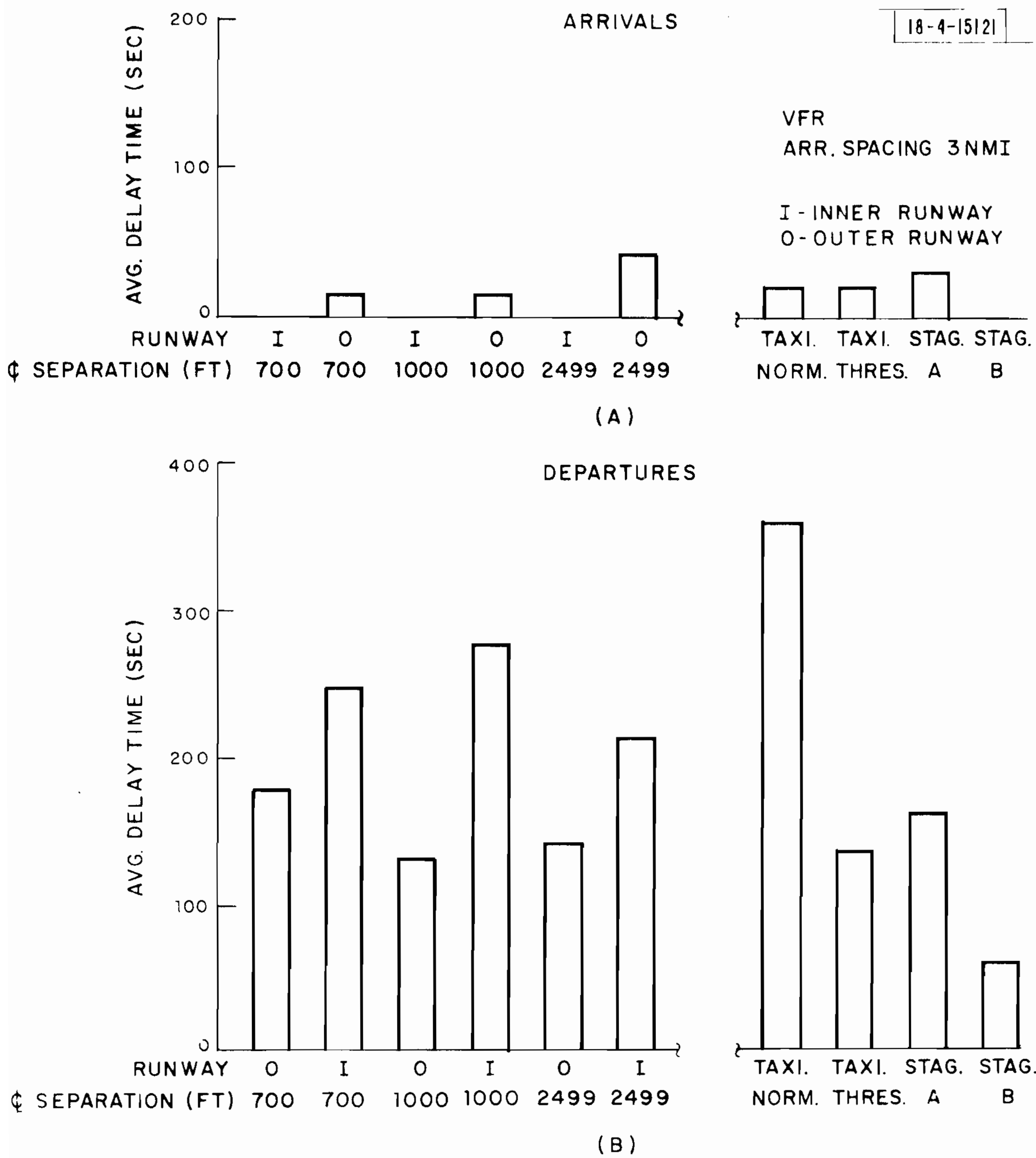


Figure 39. Real Time VFR Segregated Dual Lane Delay Time Summary.

into the taxiway system until the departure enters the runway system. It includes taxiway delay time.

The greatest number of operations was achieved at 2499 ft centerline spacing for both arrival/departure configurations. Arrivals on the inner and departures on the outer resulted in the greatest number of operations independent of the centerline spacing used. Arrival delay times were greatest for outer arrivals at the 2499 ft spacing.

These observations were determined by the authors to be functions of controller technique and not a consequence of the centerline spacing or arrival/departure preference per se. By running the real time simulation we found that the same maximum number of operations could be achieved at any of the three centerline spacings and at either of the arrival/departure configurations. This was done by altering the control preference of keeping an outer arrival rolling to cross the inner runway. The inner departure was permitted to takeoff while the arrival was made to wait until the departure had passed the taxiway segment the arrival was holding on, at which time, the arrival was cleared across the inner runway. The average holding (delay) time for outer arrivals that were made to wait using this strategy was 45 sec.

Inclusive Parallel Taxiway

A parallel taxiway was added between the two dual lane runways to establish if the provision of this operational flexibility could result in increased number of operations. The controllers were initially asked to use their own judgment in the use of this taxiway as a rollout area for exiting arrivals. It was established that at the 1300 ft centerline spacing determined necessary between runways employing the center taxiway high speed rollout onto the taxiway was not a factor. The number of operations decreased over those achieved at 1000 ft spacing (Figure 40, Plot A). This decrease was most likely due to the added controller work load of deciding how to best utilize the taxiway.

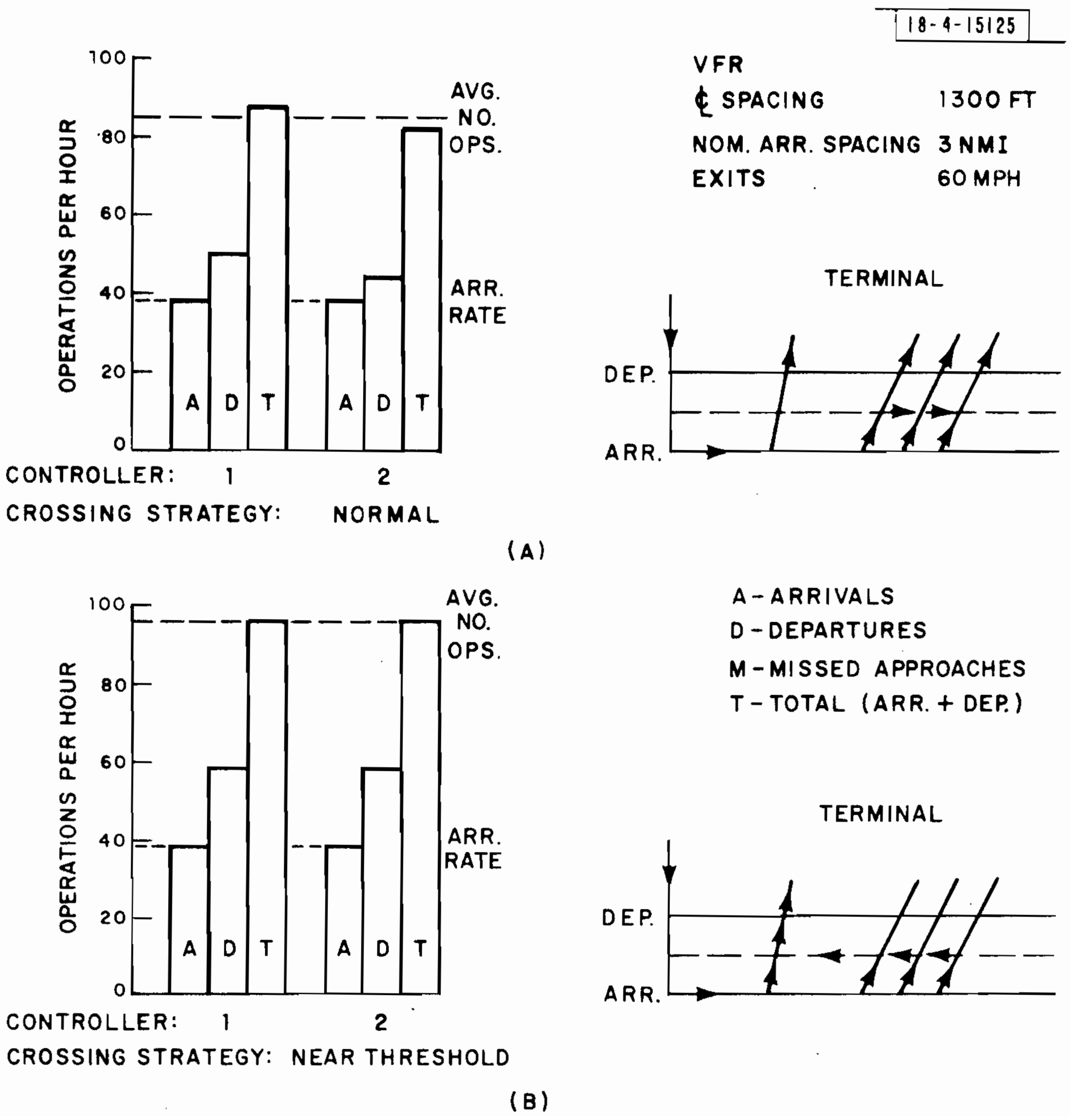


Figure 40. Real Time - VFR Parallel Taxiway Operations Inclusive.

The controllers were then asked to use the taxiway to bring arrivals back near the threshold (Figure 40, Plot B) of the inner runway where they would be crossed. This strategy resulted in the number of operations approaching the previously acheived 100 operations (38 arrivals, 60 departures). The arrival taxi time increased (Figure 38, Plot A) over the normal crossing while the departure taxi time decrease (Figure 38, Plot B) due to the added number of departures released (58 versus an average of 47 for normal crossing).

Staggered Thresholds

Two threshold stagger configurations were explored (Figure 41). Stagger configuration A was found to be inferior to configurations B. Arrival aircraft to configuration A had to cross the inner departure runway while in configuration B the crossings (except for general aviation) were made beyond the end of the inner runway. The latter provided independent ground operations (except for G/A crossings) on the dual lane runways. The 100 operations were achieved with no average arrival delays and the smallest departure delays of all other configurations investigated. Departure taxi time for this configuration was also the minimum achieved (Figure 38B).

5.1.1.3 Mixed dual lane

Mixed dual lane experiments (Figure 42) were performed to establish the number of operations a set of dual lane runways could sustain. Mixed dual lane operations were conducted by scheduling two semi-dependent arrival streams (wake turbulence dependent) to the pair of parallel runways. Two departure streams were also scheduled to the two runway thresholds. The two arrival streams are called semi-dependent because with a heavy aircraft on final approach to either one of the runways, a dependency relationship existed. A following non-heavy aircraft on approaches to either runway must maintain at least 5 nmi distance behind the heavy aircraft. The preferred operation of dual lane runways

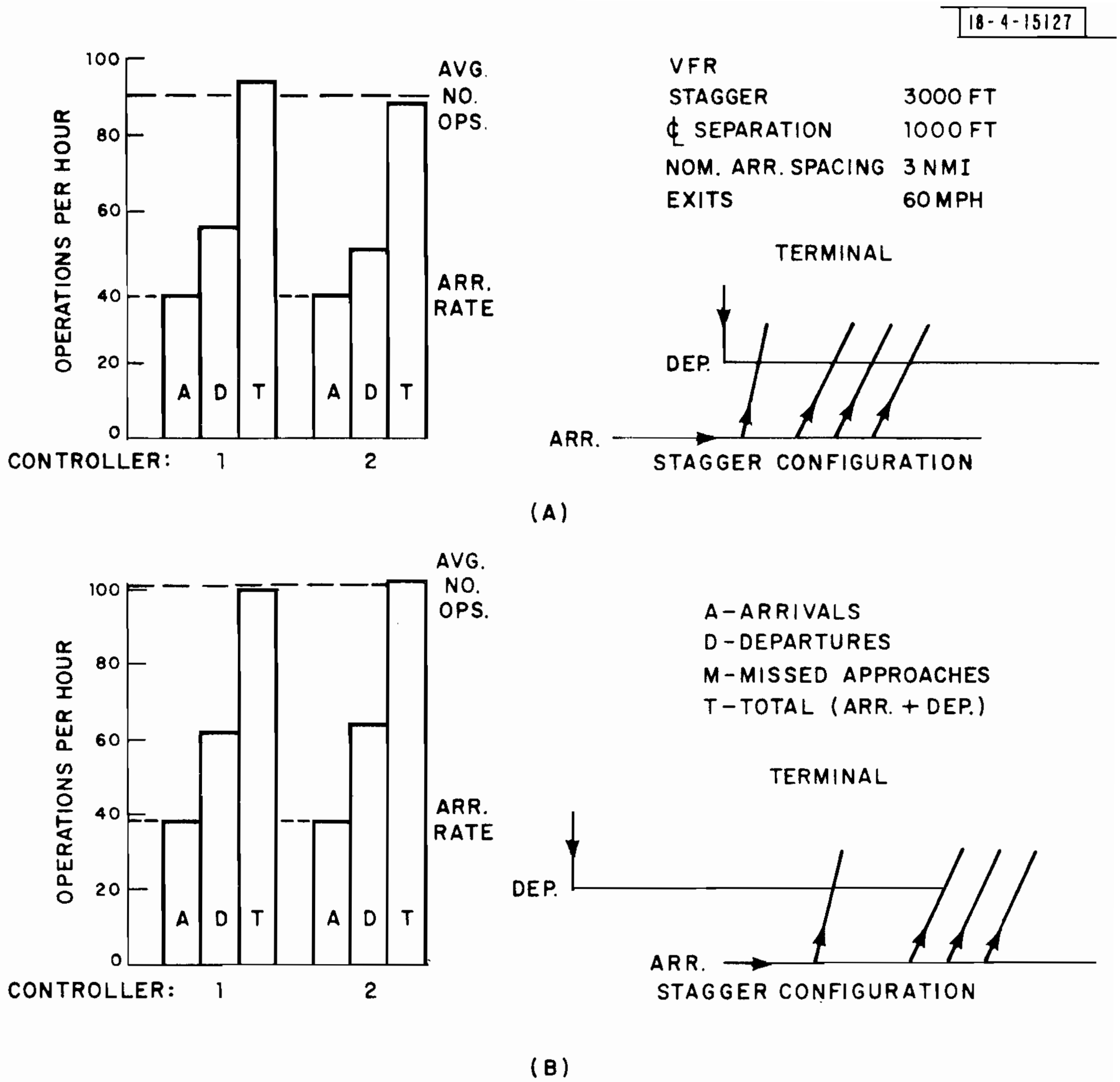


Figure 41. Real Time - VFR Staggered Threshold Operations.

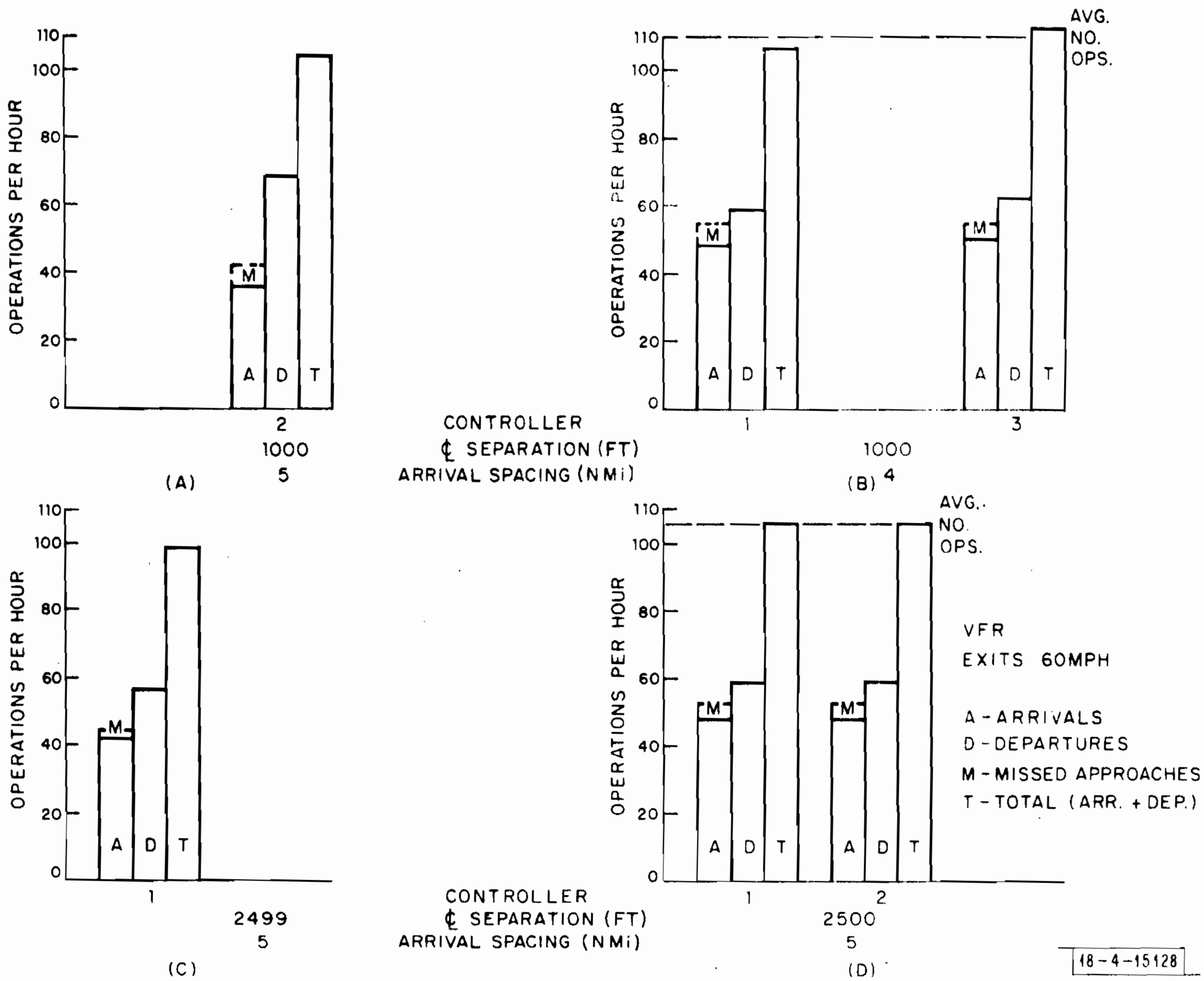


Figure 42. Real Time VFR Mixed Dual Lane Operations.

is with segregated operations as discussed previously. Segregated operations means arrivals are scheduled to one runway and departures to the other. Mixed operations create situations which do not normally appear during segregated operations. The controller attempts to interleave a departure between successive arrivals on both runways.

When a runway is being used for both arrivals and departures in a heavy traffic situation, a critical controller decision is whether to clear a departure into position to hold on the runway after an arrival passes over the runway threshold. This calls for a judgment on the part of the controller. The controller must have some assurance that the landing aircraft will exit the runway expeditiously and that the departure aircraft will execute an immediate takeoff when cleared. This assurance is necessary as the next arrival aircraft with 4 nmi arrival spacing will be 90 to 100 sec behind the first. If the first arrival lingers on the runway or the departure hesitates on takeoff, a missed approach will be caused.

The average number of mixed dual lane operations (Figure 35, Plot C) varied from 98 to 109 for the configuration explored. The arrival demand varied with the arrival spacing and when the centerline spacing increased to 2500 ft. The dependency relation of staying 5 nmi behind a heavy aircraft on an approach to the adjacent runway is lifted at 2500 ft centerline spacing. This had the effect of increasing the total arrival demand at the same 5 nmi arrival spacing from 44 to 52 (Figure 42, Plot C,D) when going to 2500 ft runway centerline spacing.

Mixed dual lane operation had the effect of appreciably increasing controller work load but only increasing total operations by approximately 10 percent over segregated operations.

5.1.2 IFR controller data

IFR experiments (Figures 43 and 44), simulating 0.5 nmi visibility and 200 ft ceiling as discussed in real time IFR experiment procedure section, were conducted. The IFR experiments had three objectives:

(1) Determine whether IFR conditions had any impact on VFR established dual lane criteria.

(2) Establish a set of IFR rules which could be used in fast time analysis.

(3) Estimate the extent of the reduction in the number of operations to dual lanes due to IFR conditions.

It was observed that running traffic under IFR rules did not alter the findings pertaining to the dual lane criteria under investigation from that found running under VFR Rules. Under IFR conditions, arrivals were restricted to one runway with departures to the other. In general, when attempting to establish the number of IFR operations a dual lane system will support, it was found that a "one for one" situation occurs under heavy traffic demands. For every arrival, a single departure can be released. With 3 nmi arrival spacing, the potential number of operations becomes 76 (38 arrivals, 38 departures). At 4 nmi arrival, spacing the figure becomes 60 operations (30 arrivals, 30 departures) and at 5 nmi, the number of potential operations is 52 (26 arrivals, 26 departures). The "one for one" situation occurs because of the departure dependency on the adjacent arrival aircraft. When the arrival is within 2 nmi of the threshold, the departure aircraft is restricted from takeoff. This is true in order to eliminate any airborne conflicts if the arrival elects to make a missed approach and go around again. As the arrival spacing is increased beyond 5 nmi, it is possible

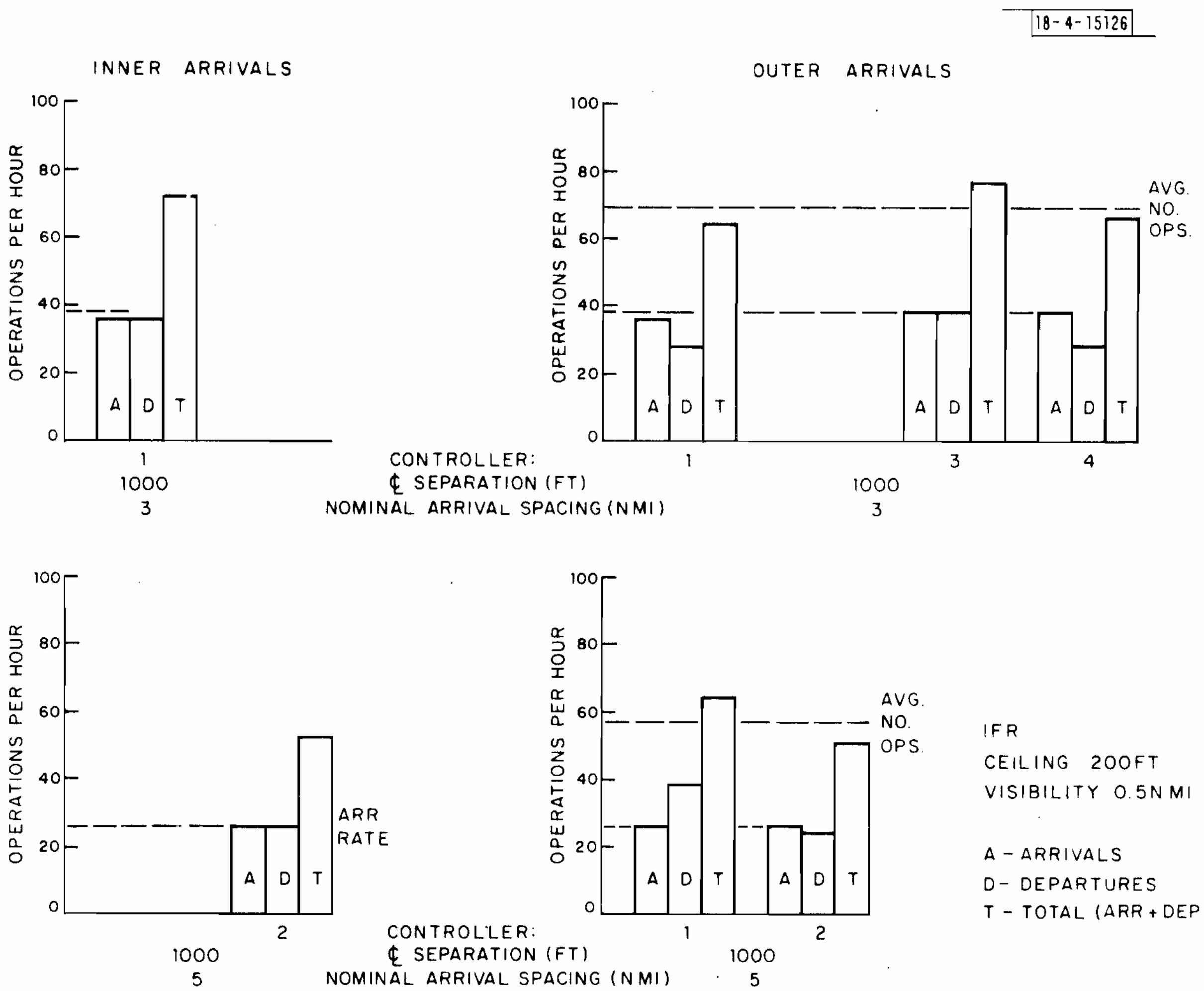


Figure 43. Real Time IFR Centerline Separation and Arrival/Departure Preference Operations.

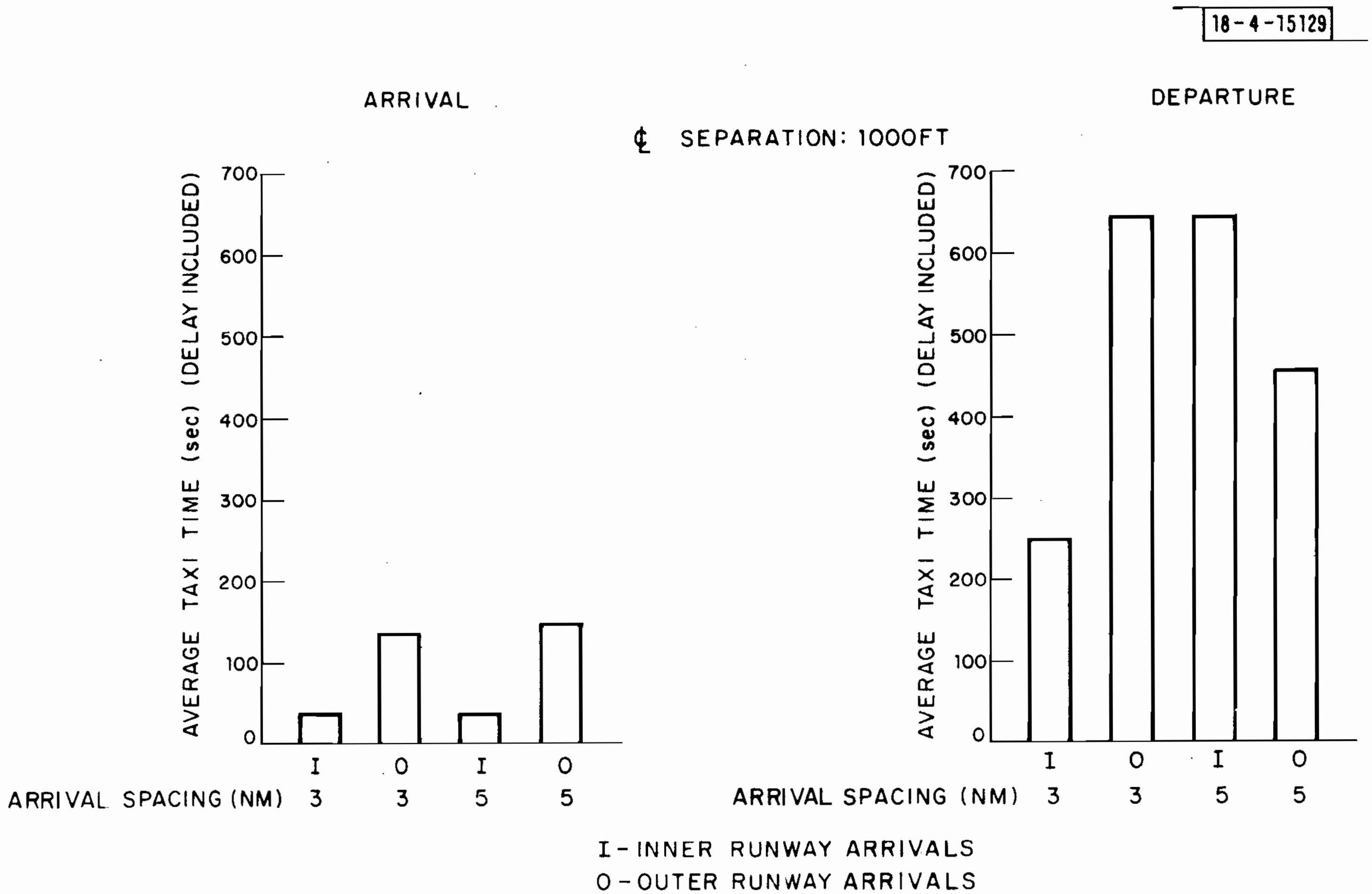


Figure 44. Real Time IFR Segregated Dual Lane Taxi Time Summary.

to consistently get two departures released for every adjacent arrival or a "two for one" situation. Under 5 nmi, arrival spacing "two for one" is possible but the timing becomes critical.

The controller workload was observed to become excessive when 3 nmi arrival spacing was employed. The number and length of voice transmissions required of IFR traffic distracted the controller from maintaining the overall status of operations. The simulation of IFR traffic was not authentic from the standpoint of arrival runway occupancy times. Observations at actual airports under IFR conditions reveal arrival aircraft occupy the runway longer than under VFR conditions. Arrival aircraft have been observed to go past their normal exits tending to brake minimally due to wet runway and poor visibility conditions. It is believed that 4 or 5 nmi arrival spacing will remain the preferred spacing at actual airports using dual lane runways under the IFR conditions simulated even with the acceptance of high speed exits. The number of operations a set of dual lane runways is likely to support consistently is between 50 and 60 per hour. These experiments suggest that two local controllers be used to direct IFR traffic to dual lane runways. One controller for arrivals and one for departures. Close coordination and cooperation will be required of the two to resolve the many potential conflicts which arise under saturation traffic conditions. Also suggested by these experiments are some automation tehcniques to aid the local controller is keeping track of each aircraft status, position, and identification in the air and on the ground, within the dual lane runway system.

5.2 Programmed Controller (fast time) Simulation Data

5.2.1 VFR programmed controller data

In general, arrivals and departures were assigned to separate runways dedicated to each operation. This facilitated a clearer understanding of both the effects of each parameter and the effects of parameter variation.

The regulations and restrictions imposed on VFR aircraft movements are minimal. A brief account follows which provides a description of the arrivals, the departures, and the movements involved in the crossing situations. Aircraft on final approach have priority and are given the right of way. No ground traffic is cleared to cross the arrival runway (at threshold or anywhere along the length of the runway) after the arrival is within a selected distance (1.5 nmi) of threshold. If a second aircraft, already on the runway surface (arrival or departure), continues to occupy the active arrival runway for any reason at the time the arrival reaches the programmed decision point, it will execute a go around. It is tabulated as a missed approach and dropped from the system. Runway exit selection by an arrival is as described in Section 4.1.2 on the general descriptions of the simulation and the interactive mode features.

The dependent inner runway crossing strategy followed by arrivals which were serviced on the outer runway is as follows. A crossing is accomplished by a holding aircraft after a departure has passed the intersection providing the departure is still in its rollout and has not lifted off, or while a departure holds in place delayed by the two minute rule applied after a heavy departure, or if the arrival has already been holding 30 sec or longer at the intersection it crosses before a departure which is in position and ready to roll.

In the cases where departures were serviced on the outer runway, the number of aircraft which could hold between thresholds of the parallel runways was restricted. Centerline separation fixed this number to: one aircraft for 700 ft separation, either one or two aircraft when the separation was increased to 1000 ft, and four aircraft with near 2500 ft centerline separation.

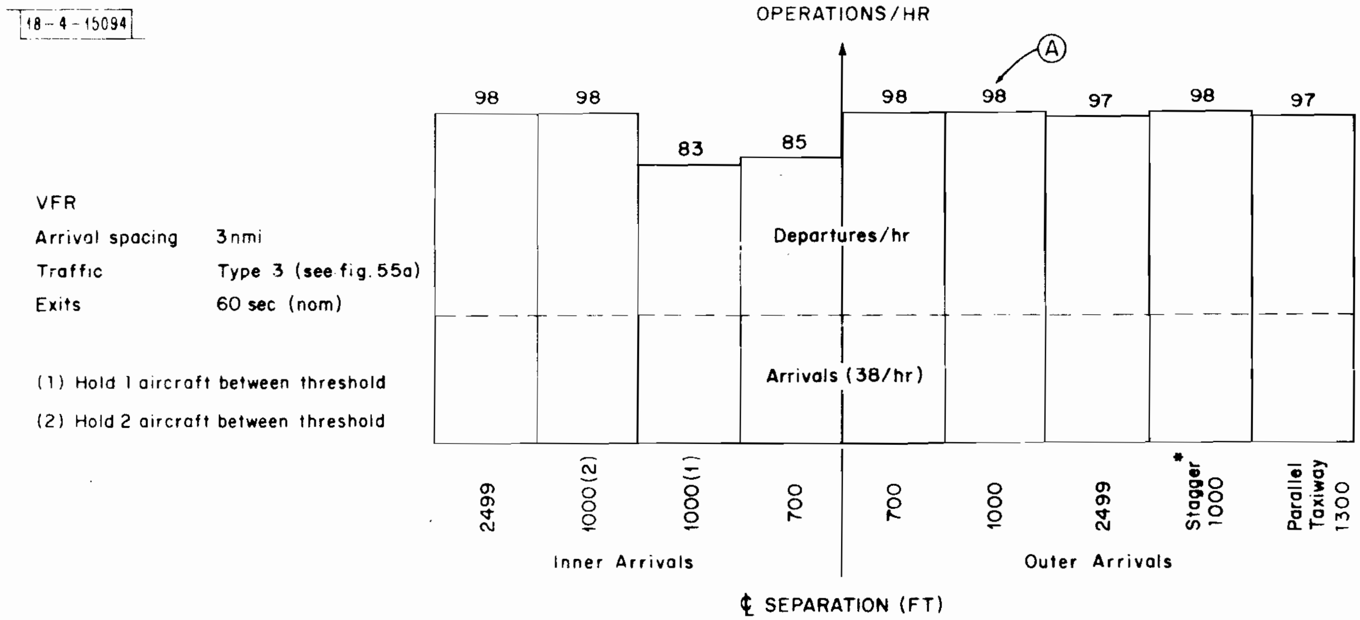
Departures to either runway dedicated for takeoffs were put into position to hold following a previous departure. Takeoff clearance was initiated following liftoff of the preceding departure aircraft subject to restrictions imposed by the application of rules governing heavy jet operations. In the cases where departures were serviced on the inner runway, an additional consideration was applied before takeoff clearance was issued to a holding departure. If an arrival has been holding at an intersection awaiting crossing clearance longer than 30 sec, the arrival is crossed with the departure subsequently cleared for takeoff immediately behind the crossing arrival.

The applicable separation requirements dictated by the presence of heavy jet type traffic are applied to both arrivals and departures.

5.2.1.2 VFR simulation results summary

Each dual lane configuration was first run with traffic at an inter-arrival spacing of 3 nmi. This separation, together with the selected mix which represents the traffic sample to a large metropolitan airport, translated to an arrival flow rate of 38 aircraft per hour to the arrival runway.

Figure 45 summarizes the configurations studied. The bar graph presentation illustrates the maximum capacities as obtained during the programmed controller simulation runs when dedicated runway usage is maintained. The configurations included were selected so as to adequately investigate and quantify the dual lane runway system as a function of its characterizing parameters.



		2499	1000 (2)	1000 (1)	700	700	1000	2499	Stagger* 1000	Parallel Taxiway 1300
Arrivals	Delay (m/sd)†	—	—	—	—	37/33	39/33	36/40	22/26	48/59
	Total time	199/25	199/27	200/26	202/25	292/44	308/42	350/48	281/33	332/92
Departures	Delay	56/38	57/37	1441/751	1167/526	123/71	151/99	183/107	49/46	183/76
	Total time	411/47	367/53	2295/956	2152/854	436/104	492/157	541/183	319/62	496/97
	Taxi time	295/36	254/43	2184/953	1997/900	311/93	365/152	411/178	202/48	368/96
	Runway occupancy time	64/31	61/32	59/24	53/23	74/35	75/34	78/34	66/30	75/27
	Queue length	6	5	61	57	6	8	13	4	10
(Time in sec)										
Departure delay trend		S	S	I	I	O	O	O	O	O
Arrival delay trend		N	N	N	N	S_1	S_1	S_1	S_1	S_1

B C D

* 3000-ft stagger

† Mean/standard deviation

Figure 45. VFR Traffic Operations and Delay Profiles (3 nmi arrivals).

Further comparative evaluation of the dual lane configurations was performed by comparing various delay indicators. The arrival and departure delays are listed below each configuration's capacity representation in Figure 45; each is designated by its mean value and standard deviation (mean/standard deviation) in seconds. The deviation values provide some indication as to whether or not the mean is a typical value for the output parameter in question. A large standard deviation relative to the mean would tend to indicate that it is not and that additional information would be useful. For delay times, we have included the trend profile as a way to provide this additional information. Trend designators are developed in Appendix E. Delay is defined as the time spent on a taxiway segment waiting to move in the system. For arrivals to the outer runway, this represents the time spent holding on the exit taxiway at the intersection with the departure runway for the purpose of receiving a crossing clearance. Priority is not given to the arrival aircraft at the intersection. Instead, advantage is taken of one of a number of situations to cross an arrival aircraft; cross behind a departure assuming a large portion of the runway is used on rollout, cross during the period the two minute rule is in effect applicable after heavy jet departures, or cross on a controller's decision not to hold one arrival between runways much longer than 30 seconds.

Departure delay represents the time spent holding in the departure queue short of the departure runway. When departures are serviced on the outer runway, this delay includes the effect of departure aircraft held short of the arrival runway due to inner runway crossing restrictions which apply when an arrival is within 1.5 nmi of threshold.

To illustrate the data in Figure 45, consider the performance of the configuration with 1000 ft centerline spacing with arrivals on the outer runway. Its maximum capacity under saturation demand conditions showed 98 operations per hour (point A). Of these, 38 were arrivals experiencing a mean delay of 39 sec in crossing the departure runway (point B). The trend (trend designations are discussed in Appendix E) designator S_1 (point C) indicates that, in general, the majority of arrivals did experience delay in crossing the inner runway but that a significant number did cross with no hold required (zero delay). The mean total time in the system from outer marker to the apron area was 308 sec. Generally, it was observed that the total time behavior reflected the delay time behavior. The remaining entries in the selected column relate to departure behavior. Continuing, the departure mean total time and taxi time was 492 and 365 sec, respectively, of which 151 sec consitituted delay. The delay trend indicator O (point D) indicates a behavior which reflects the hourly variation in the heavy jet population. The mean runway occupancy time experienced by departures was 75 sec which is somewhat larger than the 35 to 45 sec used for rollout to departure liftoff. The remainder is the time spent holding in position and constitues additional delay time caused in this case, by crossing arrivals and the presence of heavy departure jets. The remaining entry indicates a departure queue length of 8 aircraft at the end of the 4 hour simulation. The departure queue length can only be used as a comparative measure of the various configurations because of the simplistic way the departure runway was loaded. The departures were scheduled to the departure taxiway every 60 $\pm$ 10 sec. The departure queue value does not provide an indication of the maximum queue size one might expect from each configuration with an arbitrary departure traffic loading of 60 aircraft per hour. Instead, it represents the minimum queueing as optimum scheduling (one per minute) was simulated.

The VFR experiments were repeated with interarrival separation reduced to 2.5 nmi simulating an improved ATC environment. The required ATC system improvements to service the increased arrival demand other than high speed exits are not specified. Results of these simulations are presented in Figure 46. Result format is similar to that provided in Figure 45.

Comparitive delay data presented as a function of centerline separation requires some explanation. A graphical illustration of the mean departure delay as a function of centerline spacing and arrival runway preference is presented in Figure 47 (results obtained during simulations runs with 2.5 nmi and 3 nmi arrival separation are indicated by the hatched areas and blank areas, respectively).

Consider the results for departures serviced on the inner runway (arrivals on the outer runway) with 3 nmi arrivals separation. One observes an average difference of 30 sec existing between each configuration with a monotonic increase in departure delay as centerline spacing is increased.

No significance can be made of this result. Data on a second arrival demand modeled (arrival separation reduced to 2.5 nmi) did not exhibit this trend. No predictable difference between the two demands based on pavement demands can be identified. The increasing delay trend as centerline spacing increases as indicated for 3 nmi arrivals (departures on the inner runway) appears to be due to the merging of the arrival and departure streams at different places due to increased centerline spacing. Since the 2.5 nmi arrival results do not follow the same sequence as the 3 nmi, the phenomenon appears to be a function of the simulation dynamics and not attributable to changes in the centerline spacing parameter varied. Considering mean delay values for 2.5 nmi and 3 nmi

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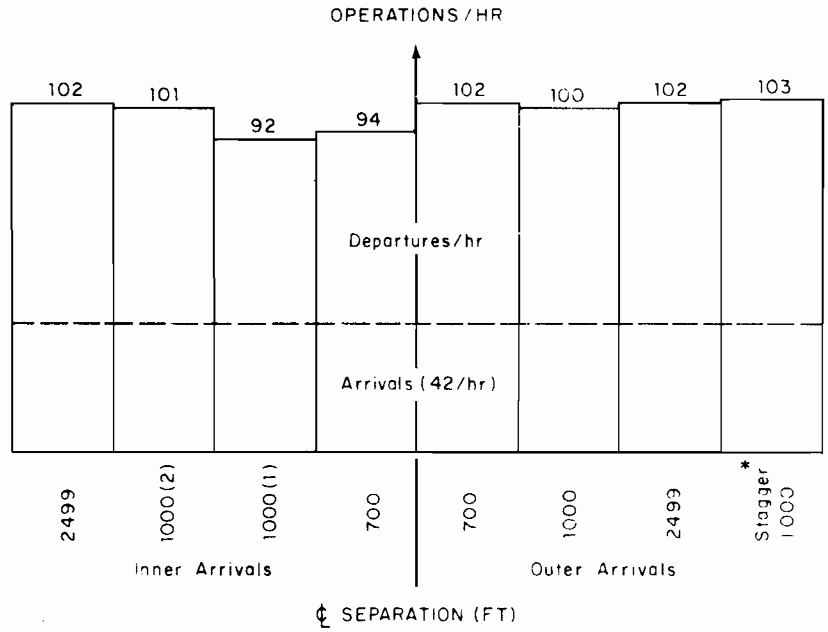


VFR
Arrival spacing 2.5nmi
Arrivals/hr 42
Traffic Type 3 (fig. 55a)
Traffic sample 3.5hr

(1) Hold 1 aircraft between thresholds
(2) Hold 2 aircraft between thresholds

Arrivals	Delay (m/sd)†	—	—	—	—	33/36	41/35	43/36	23/25
	Total time	199/25	199/28	198/22	200/24	288/48	311/44	354/44	281/34
Departures	Delay	77/49	198/82	829/371	624/305	124/79	167/78	141/70	62/47
	Total time	449/73	712/152	1588/564	1307/402	436/117	510/125	462/100	337/64
	Taxi time	336/68	574/138	1476/562	1197/478	308/111	379/120	331/98	215/52
	Runway occupancy time	61/29	63/31	60/25	58/28	76/33	79/33	79/33	71/32
	Queue length	7	14	43	35	10	10	8	5
(Time in sec)									
Departure delay trend		S	I	I	I	O	O	O	O
Arrival delay trend		N	N	N	N	S_1	S_1	S_1	S_1

* 3000-ft stagger
† Mean/standard deviation

Figure 46. VFR Traffic Operations and Delay Profiles (2.5 nmi arrivals).

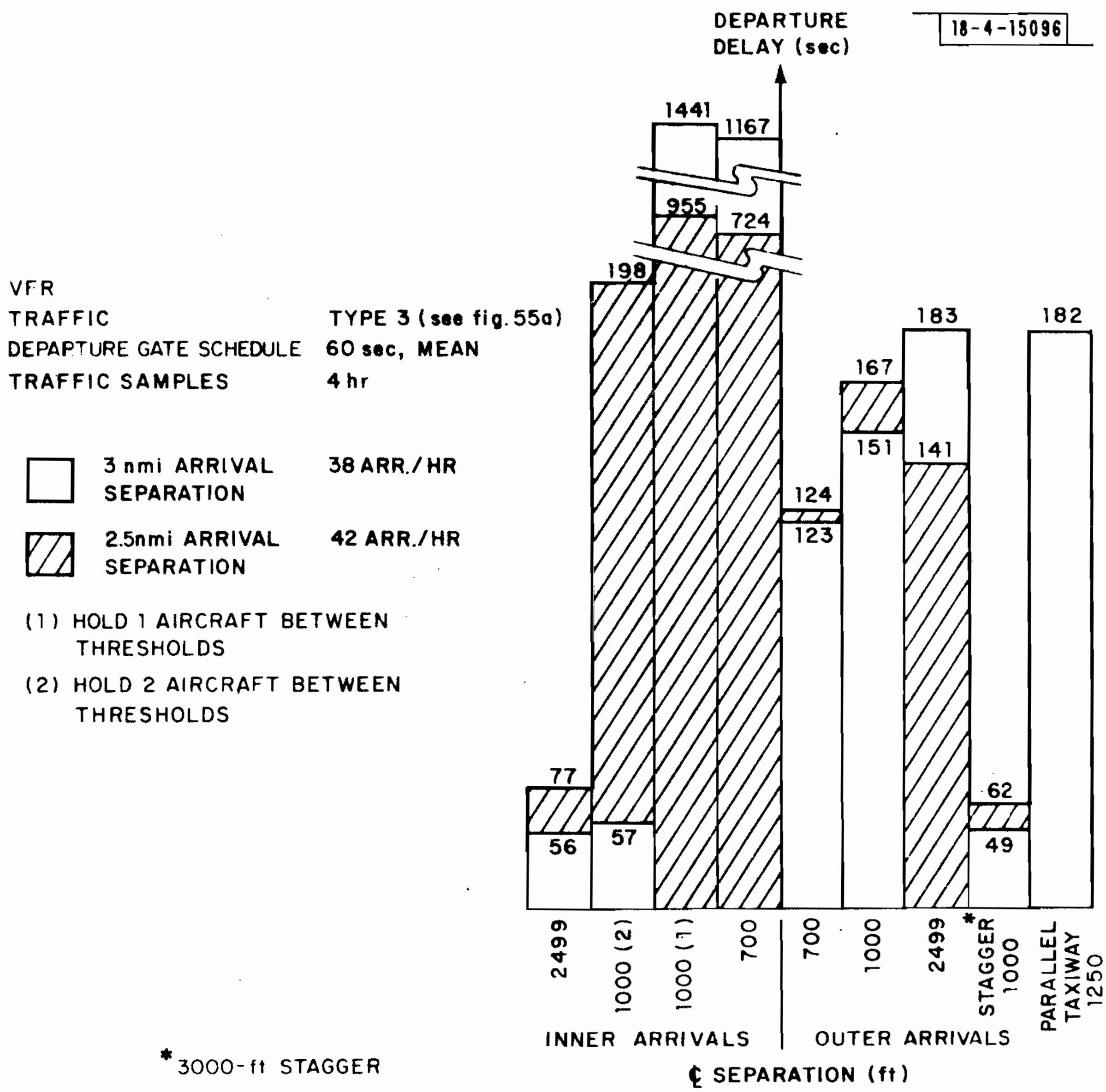


Figure 47. VFR Departure Delay Profiles.

arrival traffic equally valid, we conclude from the value obtained upon averaging these results that the change in departure delay is relatively insensitive to centerline spacing.

The sensitivity of departure delay to centerline separation on the arrival demand rate with departures serviced on the inner runways is discussed under the issue of centerline spacing provided in Section 3.4.3.

Tabulations of the data obtained during the VFR simulation experiments conducted with increased interarrival spacings of 4 nmi and 5 nmi are presented in Figure 48 and 49, respectively.

5.2.2 IFR programmed controller data

The heavy demands imposed by saturation traffic under VFR conditions served to identify pavement requirements needed to handle these levels efficiently. However, equally important is the design requirements of a dual lane system to efficiently handle maximum traffic in IFR conditions. Under conditions of reduced visibility aircraft separation restrictions are imposed on both arrivals and departures to provide the margin of safety lost because of reduced pilot and controller visibility as well as poor runway conditions. Thus, arrival and departure traffic movements become more dependent on each other. The IFR simulation experiments were conducted in order to help in the determination of what design changes may be needed to handle saturation IFR traffic to a dual lane runway system efficiently. The overriding effect of the restrictions imposed by the rules change results in decreased pavement utilization with the corresponding decrease in maximum capacity and an overall increase in delays. The interval between departures scheduled to the departure runway was increased to 90 sec to

18-4-15131

VFR

Arrival Spacing 4nmi

Traffic Type 3 (fig. 55a)

Traffic Sample 3.5 hours

		℄ SEPARATION (FT) Inner Arrivals				Outer Arrivals			
		2499	1000(2)	1000(1)	700	700	1000	2499	Stagger* 1000
Arrivals	Delay (m/sd)†	—	—	—	—	40/33	46/34	48/33	24/27
	Total time	197/27	198/29	200/25	199/29	294/43	313/46	357/45	281/39
Departures	Delay	45/37	54/40	967/534	578/200	98/65	131/69	123/50	56/46
	Total time	397/50	364/50	1750/733	1244/458	394/92	445/105	430/69	329/63
	Taxi time	283/35	251/40	1640/730	1134/455	270/81	317/96	302/64	208/51
	Runway occupancy time	63/29	61/32	59/25	59/25	73/33	77/34	77/34	69/33
	Queue length	6	6	51	32	5	9	5	5
(Time in sec)									
Departure Hourly Count		60	60	48	53	60	59	60	60
Arrival Hourly Count		31	31	31	31	31	31	31	31

* 3000-ft stagger

† Mean/standard/deviation

(1) Hold 1 aircraft between thresholds

(2) Hold 2 aircraft between thresholds

Figure 48. VFR Traffic Operations and Delay Profiles (4 nmi arrival).

18-4-15132

VFR

Arrival Spacing 5nmi

Traffic Type 3 (fig.55a)

Traffic Sample 3.5 hours

		℄ SEPARATION (FT) Inner Arrivals 2499	1000(2)	1000(1)	700	Outer Arrivals 700	1000	2499	Stagger* 1000
Arrivals	Delay (m/sd)†	—	—	—	—	40/31	45/32	40/33	24/24
	Total time	199/24	200/22	198/26	200/24	296/44	314/42	350/43	281/35
Departures	Delay	50/39	50/38	818/459	454/244	59/51	76/55	75/56	36/36
	Total time	403/52	360/42	1564/654	1049/394	334/70	360/77	358/80	300/51
	Taxi time	286/41	243/37	1455/650	945/391	215/57	238/66	236/72	186/35
	Runway occupancy time	65/32	65/29	57/26	53/25	68/32	71/33	70/34	63/28
	Queue length	6	5	44	29	4	4	4	4
	(Time in sec)								
Departure Hourly Count		60	60	50	54	60	60	60	60
Arrival Hourly Count		26	26	26	26	26	26	26	26

* 300-ft stagger

† Mean/standard deviation

(1) Hold 1 aircraft between threshold

(2) Hold 2 aircraft between threshold

Figure 49. VFR Traffic Operations and Delay Profiles (5 nmi arrivals).

alleviate the problem of a long departure queue. This did not relax the constant demand requirement on the pavement. Several experiments were later performed with a departure interval of 75 sec in order to determine the sensitivity of delays to increased departure demand under simulated IFR conditions.

As in VFR, arrivals and departures were assigned separate runways. The arrivals on final approach course were given right of way over all other traffic. Restrictions were imposed on departures in order to maintain safety under weather conditions in which visual separation could not be exercised. In practice, the controller must have adequate assurance (satisfying himself) that the aircraft established on final approach will not execute a missed approach at an inopportune moment and thereby come into potential conflict with a departure cleared for takeoff. This is obtained either through his visual sighting of the aircraft established on final approach path or through pilot communication of his intent to land with runway threshold in sight.

The departures were restricted from takeoff until the arrival was within 1/2 mile from threshold. This simulated the requirement of a visual sighting of the arrival by the controller during relatively poor weather conditions or the provision of pilot assurance to the controller of the landing runway threshold in sight with his intention of landing. Release of a departure when the arrival was at least 2 nmi from threshold did not compromise existing regulation through separation since adequate separation existed between the arrival and departure shortly after takeoff. In the simulation, departure clearances were withheld when the arrival was more than 1/2 mile but less than 2 nmi from threshold.

An additional restriction on departures was the need to maintain a minimum time separation of one minute between successive departures. This restriction provides for the requirement to maintain minimum radar separation between aircraft using the same airspace.

No departures were delayed by the requirement to cross an arrival aircraft which had landed on the outer runway. The arrival traffic was cleared across the departure runway during either of the periods described above at which time the departure traffic was delayed by regulation.

The performance of each configuration tested under IFR conditions with 3 nmi interarrival separation and 90 sec schedule intervals between successive departures is illustrated in Figure 50.

The sensitivity of a dual lane configuration's traffic handling capability to the severity of the IFR weather condition is indicated in Figure 51. The distance from threshold beyond which an arrival must pass before a departure is cleared for release was varied from threshold to a point 2 nmi from threshold. The slight change in the maximum number of operations under these conditions indicates the decrease in departures released as the procedure becomes increasingly restrictive.

As under VFR conditions, we anticipated a reduction to 2.5 nmi interarrival separation. Data obtained on a dual lane runway configuration with 1000 ft centerline separation is presented in Figure 52. Additional configurations were not investigated due to the established insensitivity (Figure 50) of IFR capacity and delay on runway configuration. Figure 52 summarizes the results obtained.

IFR

Arrival Spacing 3nm

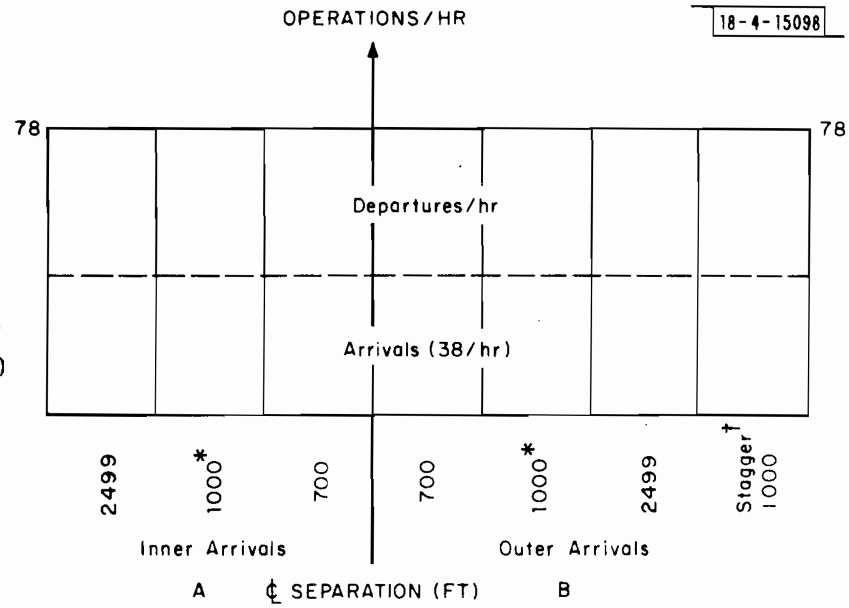
Arrivals 38/hr

Departure separation 90sec

Departures held when arrivals between 0.5 and 2.0nmi from threshold

Interdepartures 1min (minimum)

Traffic Type 3 (fig. 55a)



Arrivals	Delay (m/sd) ‡	—	—	—	24/34	32/34	32/47	17/20
	Total time	200/29	199/27	202/28	280/45	302/43	341/51	270/31
Departures	Delay	66/43	58/44	71/58	56/49	43/41	143/109	73/47
	Total time	415/55	364/54	370/67	322/54	309/49	425/128	338/52
	Taxi time	228/37	234/42	237/50	185/42	179/31	274/114	190/41
	Runway occupancy time	84/29	77/29	80/30	83/31	77/28	98/38	94/33
	Queue length	4	3	4	3	3	3	3
(Time in sec)								
Departure delay trend		S	S	S	S	S	S	S
Arrival delay trend		N	N	N	S_1	S_1	S_1	S_1

* Hold 2 aircraft between threshold

† 3000-ft stagger

‡ Mean/standard deviation

Figure 50. IFR Traffic Operations and Delay Profiles (3 nmi arrivals).

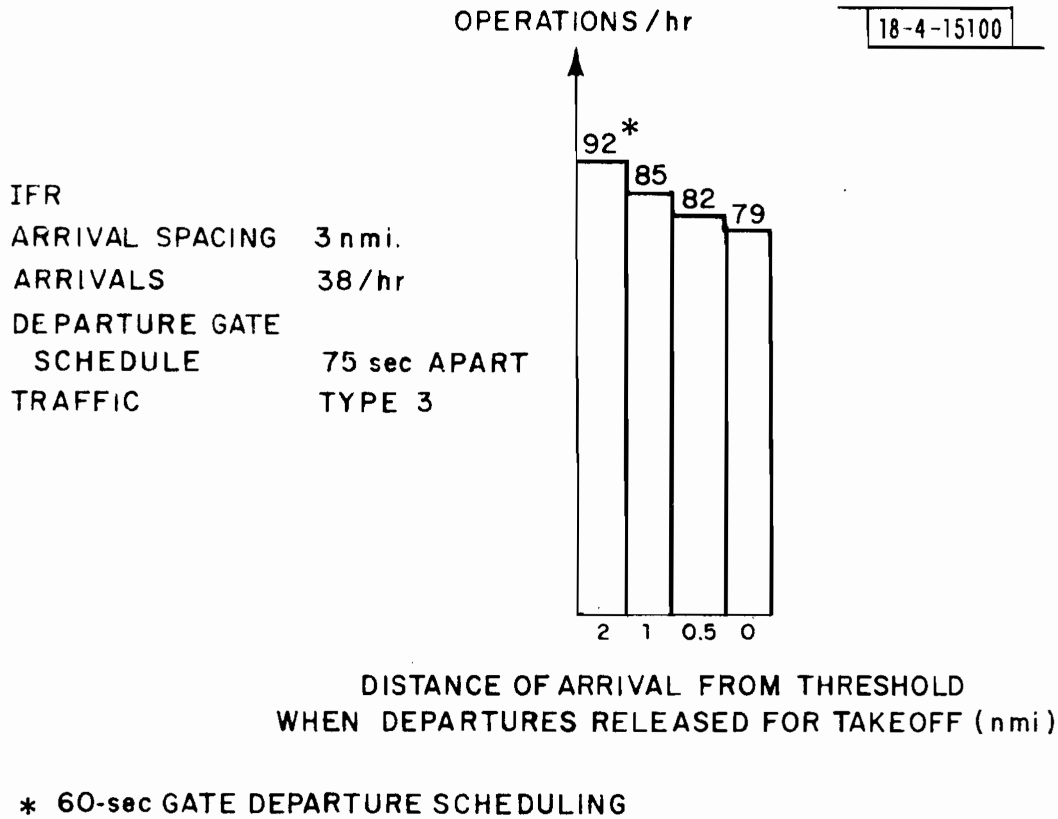


Figure 51. IFR Capacity Achieved when Varying Simulated IFR Weather Conditions (3 nmi arrivals).

IFR

Arrival separation 2.5 nmi
Departure separation 90 sec
Traffic Type 3 (fig. 55a)

(2) Hold 2 aircraft between thresholds

		℄ SEPARATION (FT) Inner Arrivals 1000(2)	Outer Arrivals 1000
Arrivals	Delay (m/sd)*	–	31/30
	Total time	199/26	299/35
Departures	Delay	45/35	53/56
	Total time	349/45	319/65
	Taxi time	225/28	186/46
	Runway occupancy time	71/27	81/36
	Queue length		
(Time in sec)			
Departure hourly count		40	40
Arrival hourly count		42	42

*Mean/standard deviation

18-4-15133

Figure 52. IFR Traffic Operations and Delay Profiles (2.5 nmi arrivals).

The preceding VFR and IFR simulation experiments assumed pilot acceptance of high speed turnoffs. Additional interarrival separation resulting in 4 to 5 nmi gaps may be required under certain conditions such as slippery runways due to heavy rain, snow, etc. Figures 53 and 54 summarize the maximum IFR capacity and delay figures for interarrival separations of 4 and 5 nmi respectively. Inner runway and outer runway arrival servicing were both investigated. The additional time available with increased interarrival separation during which time departures could possibly be serviced is of not much use due to the required IFR spacing between successive departures and heavy jet wake turbulence considerations. Delays under IFR conditions with reduced traffic loading tend to decrease as the arrival demand decreases through larger interarrival separation.

5.3 Sensitivity of Study Findings to Variations in Aircraft Mix

A single traffic mix (type 3 - Figure 55a) was used throughout the simulation experiments. The dual lane runway system with the outer runway serving arrivals and the inner handling departures was then subjected to a number of traffic samples of varying mix. This was done in order to determine the sensitivity of the simulation findings to variations in the traffic mix. Figure 55a indicates the composition of each mix which varied from samples with no heavy type jets to one with 100 percent heavies. The traffic was composed of arrivals with 3 nmi interarrival separation and departures leaving the gate at 60 sec intervals.

The variations in the traffic mix did not result in any changes to the dual lane criteria as established with the intial experiments. However, the mix governed the capacity figures due to the approach speed makeup and number of h 52.es in the traffic sample. For example, a traffic sample composed of a

18-4-15134

℄ SEPARATION (FT)

IFR

Arrival Separation 4 nmi

Departure Separation 90 sec

Traffic Type 3 (fig. 55a)

		Inner Arrivals			Outer Arrivals			
		2499	1000(2)	700	700	1000	2499	Stagger* 1000
Arrivals	Delay (m/sd)†	—	—	—	16/24	19/25	37/30	6/12
	Total time	199/24	198/20	200/29	268/39	288/34	346/40	262/29
Departures	Delay	70/55	55/43	37/29	32/36	52/51	242/94	54/62
	Total time	419/67	364/48	333/37	296/43	317/61	546/109	319/70
	Taxi time	281/44	288/28	210/24	172/25	184/41	381/107	185/56
	Runway occupancy time	85/37	79/32	70/23	71/26	80/32	112/47	80/39
	Queue length (at end of 4-hr runs)	4	3	3	2	3	7	2
(Time in sec)								
Departure Hourly Count		40	40	40	40	40	59	40
Arrival Hourly Count		31	31	31	31	31	31	31

* 300-ft stagger

† Mean/standard deviation

(2) Hold 2 aircraft between threshold

Figure 53. IFR Traffic Operations and Delay Profiles (4 nmi arrivals).

18-4-15135

IFR

Arrival Separation 5 nmi

Departure Separation 90 sec

Traffic Type 3 (fig. 55a)

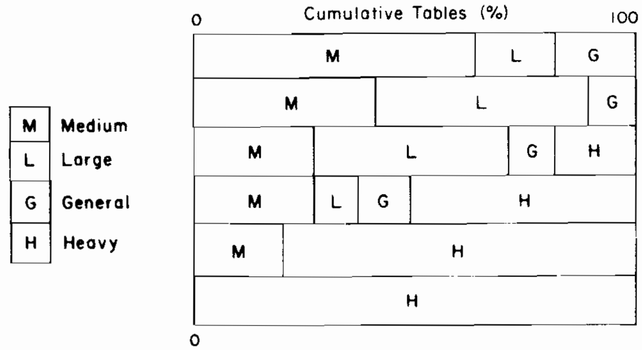
		℄ SEPARATION (FT)						
		Inner Arrivals			Outer Arrivals			
		2499	1000(2)	700	700	1000	2499	Stagger* 1000
Arrivals	Delay (m/sd)†	—	—	—	22/24	21/30	19/22	11/13
	Total time	199/26	200/22	202/27	277/37	288/44	329/40	266/26
Departures	Delay	17/18	17/18	37/33	30/32	23/23	11/12	35/38
	Total time	362/29	321/26	333/38	293/41	287/29	273/21	299/46
	Taxi time	258/21	216/24	213/24	171/17	169/14	166/17	174/28
	Runway occupancy time	51/14	51/16	67/24	69/29	64/24	53/15	72/27
	Queue length (at end of 4-hr runs)	4	3	3	2	2	2	2
(Time in sec)								
Departure Hourly Count		40	40	40	40	40	40	40
Arrival Hourly Count		26	26	26	26	26	26	26

* 3000-ft stagger

† Mean/standard deviation

Figure 54. IFR Traffic Operations and Delay Profiles (5 nmi arrivals).

18-4-15103

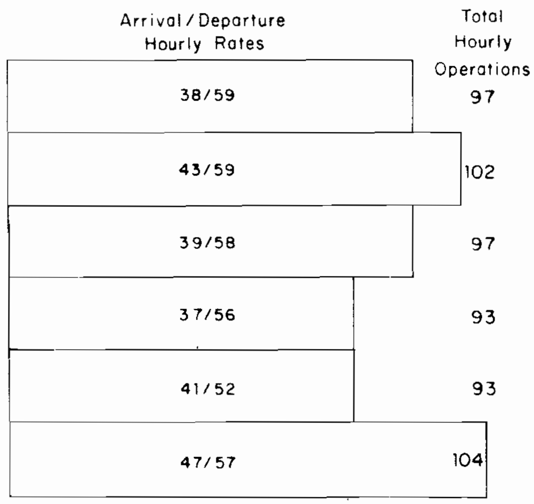


Traffic Types	Heavy	Large	Medium	General
1	0	20	60	20
2	0	50	40	10
3	20	40	30	10
4	50	10	30	10
5	75	0	25	0
6	100	0	0	0

Aircraft (%)

VFR
Arrival Separation 3 nmi
Departure Separation 60 sec
1000 Ft Centline Spacing
Arrivals on Outer Runway

(a)



Traffic Times (sec)

	Runway Occupancy	Taxiway	Delay	Total
A	44/7	123/40	27/26	306/39
D	40/15	167/16	6/8	252/19
A	43/8	142/39	41/31	311/40
D	45/17	168/6	9/11	263/23
A	43/11	141/42	39/34	309/46
D	76/33	313/142	126/98	441/151
A	43/9	138/41	36/33	306/43
D	83/35	507/177	243/108	641/179
A	43/9	111/38	39/30	302/38
D	93/32	734/350	411/240	882/381
A	43/9	155/36	50/30	312/40
D	87/19	465/23	206/70	613/122

A = Arrivals
D = Departures
} Mean/standard deviation

(b)

Figure 55. Capacity Sensitivity to Aircraft Mix.

large percentage of fast aircraft generates a greater number of arrival operations per hour. The heavy jet restrictions behind jet operations is a second factor influencing the change in capacity as a function of the mix. Departure delays are dependent on the heavy separation rule and are quite sensitive to the total number of heavy jet operations. The results of varying the traffic mix on a dual lane configuration are summarized in Figure 55b. Although the mix which contains 75 percent heavy jets appears to cause the lowest number of hourly operations on the dual lane complex, (the results show minimum capacity, maximum departure delays, and longest queue length) one cannot conclude this is the mix which would always present maximum hardships on a given dual lane configuration. The exact sequence of the aircraft types which make up the sample is a primary and governing consideration. For example, minimum capacity is theoretically obtained from a constant demand traffic sample which alternates heavy jet operations with non-heavy jet aircraft. This translates to a mix with only 50 percent heavies.

A pavement's maximum capacity (assuming traffic sample which has an equal number of arrivals and departures and each operation applying a constant demand for service) is obtained by scheduling mixed operations to each runway. Both runways are used to service arrivals and departures on an alternating basis. Runway centerline separation of less than 2500 ft does not provide sufficient separation to run wake turbulence independent simultaneous arrivals and departures in this mixed mode of operation. This is a consequence of the separation requirements behind heavy jet operations as set down in the controller's operation manual. The practice of running saturation arrival and departure traffic to each dependent runway of a dual lane system caused controller workload hardships. The heavy jet dependence requirement which must be applied to aircraft operations both on the same runway and on the adjacent runway decreased the capacity to that possible under dedicated runway usage.

To determine the advantages of providing a minimum centerline separation of 2500 ft with regards to its effect on increasing traffic, a series of simulation runs were performed with independent traffic samples of varying mix to runways spaced 2500 ft apart. In addition, a series of runs were performed on runways spaced somewhat less than 2500 ft apart from which capacity values were derived to illustrate the performance of dependent dual lane runways operated with mixed traffic under saturation traffic conditions.

The maximum capacities obtained for each mix for operations both under 2500 ft and over 2500 ft centerline separations are indicated in Figure 56. The arrival and departure operations are indicated separately. The increase in capacity achieved when centerline separation was increased to greater than 2500 ft, varied from no change when there were no heavy aircraft in the mix (traffic type 1 or 2) to about 20 percent when 50 percent of the mix (traffic type 4) was heavy aircraft.

The rules governing jet operations behind heavy jet operations work to decrease maximum capacity in either of two ways on a dual lane dependent runway system. Separation between in trail arrivals or departures operating to or from a given runway must be increased. This thereby decreases the number of hourly operations possible. In addition, if the runways are considered dependent, a similar separation requirement exists for aircraft operating behind a heavy aircraft on the adjacent runway. The resulting capacity reduction is most pronounced for a random traffic sample which contains approximately 50 percent heavy jets.

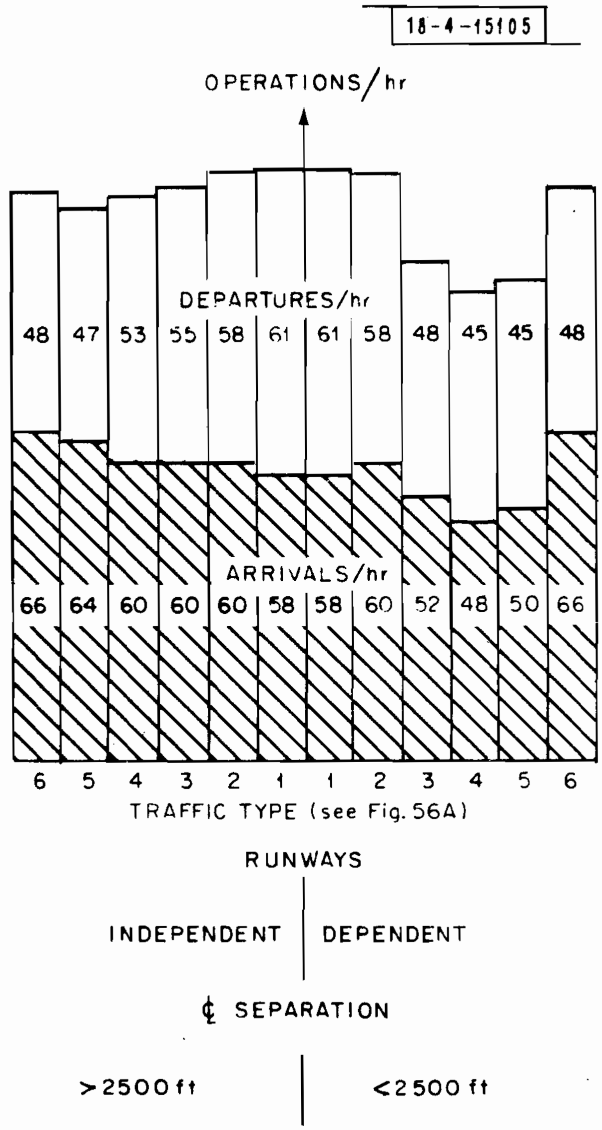


Figure 56. The Number of Fast Time Mixed Departure and Arrival Operations Achieved for the Various Traffic Mixes when Centerline Separation was Varied about 2500 ft.

6.0 CONCLUSIONS

The following major observations and conclusions have been drawn from the issues investigated during the course of the dual lane study. The capacity figures are a function of the traffic mix selected and the simulation parameters used.

(1) The dual lane concept offers substantial VFR and IFR capacity increases over single lane operation while providing a slight increase in controller workload:

- 70 percent increase in VFR operations
- 60 to 100 percent increase in IFR* operations

(2) Dual lane operations offer the flexibility of allowing segregated (arrivals on one runway and departures on the other) operations or mixed operations (arrivals and departures to each runway) to one or both of the runways. Many arrival/departure ratio demands may be handled due to this operational flexibility.

(3) Single lane capacity:

- 60 VFR operations (simulation result)
- 30 to 50 IFR* operations (derived from simulation results)

(4) Dual lane capacity: (Simulation results pp. 42)

- 100 VFR segregated operations
- 110 to 120 VFR mixed operations
- 65 to 80 IFR* operations

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* These figures are a function of weather and runway conditions affecting runway occupancy times and arrival spacings.

(5) Controller workload under constant demand situations:

- Dual lane runways handling segregated operations slightly increased workload over single lane mixed operations.
- Greatest workload occurred when controller handled mixed traffic attempting to interleave departures between a continuous arrival traffic stream (streams).
- Mixed operations to both lanes caused workload to become intolerable under continuous heavy service demand situations.
- A single local controller frequence became saturated with dual lane mixed operations.
- A need for local/ground controller aids was identified to assist controllers during periods of continuous traffic demand situations and particularly under poor IFR conditions.

(6) High Speed Exits

- Conventional angled exits (40 mi/h) are adequate to support present IFR spacing procedures.
- High speed exits became necessary to support one arrival traffic stream of less than 3 nmi spacing.
- High speed exits have the potential to support a 2 nmi arrival stream if some for of speed sequencing or speed control is provided.
- High speed exits have the potential to support mixed traffic operation to a runway with a 4 nmi spaced arrival stream.
- High speed exits have the potential to reduce arrival runway occupancy time by 20 percent.

(7) Parallel Runway Centerline Spacing

- An increase in centerline spacing provides more operational flexibility until 5000 ft separations are achieved.
- A 20 percent increase in capacity was achieved when centerline spacing was increased from 700 ft to 1000 ft in the case where arrivals were serviced on the inner runway and departures on the outer runway.
- The number of operations achieved remained the same for centerline spacing between 1000 ft and 2499 ft.
- At 2500 ft centerline spacing, an increase in operations (dependent upon the number and distribution of heavies in the traffic mix) was experienced due to the lifting of wake turbulence restrictions to the adjacent runway.
- A 1000 ft centerline spacing will support modern heavy jet operations allowing maximum operational flexibility for spacings under 2500 ft.
- The only penalty to increasing spacing above 1000 ft was increased taxi distance.
- A holding area between runway thresholds to accommodate at least two aircraft is needed to adequately feed an outer departure runway in order to achieve maximum capacity.
- A 1000 ft spacing can hold two commercial carrier aircraft between thresholds.

- 1000 ft centerline spacing was found adequate to stay and hold two air carrier aircraft between runways on a high speed exit taxiway segment.
- Approximately 1250 ft spacing needed to permit maximum operational flexibility with a parallel taxiway placed between parallel runways.

(8) Arrival/Departure Preference

- Capacity is the same regardless of which runway is used for arrivals for centerline spacings between 1000 ft and 2499 ft.
- At 700 ft centerline spacing, the maximum capacity was achieved with arrivals on the outer runway.
- ILS glide slope interference is probable when handling inner arrivals and outer departures.
- Arrivals handled on the inner runway (outer departures) minimizes VFR arrival and departure delays.
- Arrivals handled on the outer runway (inner departures) were preferred by operational controllers to minimize workload.
- Jet blast hazard increased with inner arrivals (outer departures).

(9) Inclusive Parallel Taxiway

- Addition of taxiway did not increase number of operations to dual lane runway complex.
- Has the potential to provide operational flexibility thereby reducing departure delays.
- Causes increase in controller workload to resolve taxiway conflicts.

- In poor IFR conditions, use of the taxiway presents potential hazardous situations.

(10) Staggered Runway Thresholds

- Providing threshold stagger did not increase the number of operations handled.
- Threshold stagger of approximately 3000 ft was found to have the potential to minimize arrival and departure delays.

(11) Specific Dual Lane Configuration

- Runway centerline spacing of 1000 ft or more.
- One or more high speed exits on each runway.

Dual Lane Operations

- Segregated operations. (However, mixed operations to one or both runways will permit peak traffic demands to be accommodated.)
- ILS on outer runway.
- Arrivals to outer runway (departures to inner runway).

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APPENDIX A

AN AIRPORT CAPACITY ANALYSIS OVERVIEW

by

Amedeo R. Odoni*

The final approach/runway sequence has (correctly) been identified as the bottleneck of the current ATC system. It is likely to remain so in the foreseeable future, since the number of available runways at major hubs is not likely to increase substantially because of the severe political and economic problems associated with such projects.

With good reason, therefore, very extensive attention has been focused on the runway over the years. In this sequel, we attempt a brief review of the most important available results in the area of airport capacity analysis. In the process, we shall try to indicate the state-of-the-art in terms of analytical results as well as the limitations of the existing techniques. The area will be subdivided into two categories: runway capacity models and queuing models.

A.1 RUNWAY CAPACITY MODELS

The term "runway capacity," strangely enough, has been a controversial one over the years. At the root of the matter seems to be the rather imprecise and un-

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fortunate definition of runway capacity first suggested in (1). According to that definition, the "practical capacity" of the runway is the hourly operations rate at which an average delay of four minutes occurs.

There are several problems with this definition: First, for the definition to be meaningful in practice, some kind of steady-state demand must be assumed for an extended period of time, a situation which is currently observable at only a few airports. Secondly, measurement of delays, in practice, is difficult since a good fraction of delays due to runway congestion is disguised in the form of numerous path-stretching maneuvers in various stages of a flight. Thirdly, and perhaps most importantly, average delay depends, among other things, on the arrival process, as we know from queuing theory. For instance, at a given service system, average delays would differ according to whether arrivals of prospective "customers" occur at random, or in groups, or at regular intervals (although the average number of "customer" arrivals per time unit may be the same in all three cases). One would like "capacity" to be a measure of runway "performance" and the arrival process certainly has nothing to do with the runway as a physical entity.

Because of the faults of the above definition, a variety of other terms have come into being, such as "peak hour" capacity, "sustained" capacity, "yearly" capacity, "theoretical" capacity, etc. By far, the most natural definition, however, is the one first suggested by Blumstein (2) who defined capacity as "the hourly rate of accepting aircraft under continuous saturation conditions." In other words, assuming that aircraft seeking service are always present, capacity is equal to the hourly rate at which such aircraft can be served.

This definition has been gaining increasing acceptance over the years and most of the recent work in this area is aimed at estimating the "maximum throughput rate" or "saturation capacity" of the runway.

Because of the well-defined sequence of events in this portion of the flight and the fact that all aircraft have to follow the same path, one at a time, it is possible to construct quite realistic models of the landing and departure processes from a single runway. In addition to the earlier models of IFR landing at a runway due to Blumstein (2), more recent work includes reports by Harris (3), NBS (4), and Odoni (5). All these models recognize the dependence of the throughput rate of a runway on such parameters as:

(1) Length of final approach path.

(2) Aircraft mix - described by the distribution of approach speeds and runway occupancy times.

(3) Separation standards in the air and on the ground.

(4) Priorities for runway use.

In addition, the most recent models take into consideration the very considerable effects on capacity of "buffer times" and "errors" due to such diverse items as controller and pilot performance, navigation and surveillance inaccuracies, weather conditions, etc. A "delivery error" at the gate of the final approach is usually postulated in order to describe the aforementioned variety of factors. The missed approach probabilities as a function of increasing runway capacities can also be included.

Several common features of the capacity models can be identified: they are all analytical in nature; they recognize the stochastic nature of the problem by using probability distributions to describe the various parameters; they provide explicit and rather simple mathematical expressions for the throughput capacity, thus being particularly well-suited for sensitivity analyses; and, finally, they produce estimates that correlate very well with observed runway throughput rates.

An illustration of the type of results that can be obtained by means of the approach outlined above is provided by Figure A-1. The outcome of a parametric analysis of landing capacity as a function of runway occupancy times is depicted there. (For details about Figure A-1, the reader can consult (5)). As shown in Figure A-1, the varying parameters used in this analysis are the minimum longitudinal separation requirement on final approach and the accuracy of aircraft delivery at the final approach gate. The bottom curve on the figure is probably typical of today's ATC system while the other three apply to increasingly improving hypothetical future systems.

As with any analytical model, several simplifying assumptions about the "real world" are always necessary in order to maintain mathematical tractability. Thus, it is simple in principle but cumbersome in practice to include for additional realism such considerations as wind effects, local noise abatement regulations, load factors, etc.

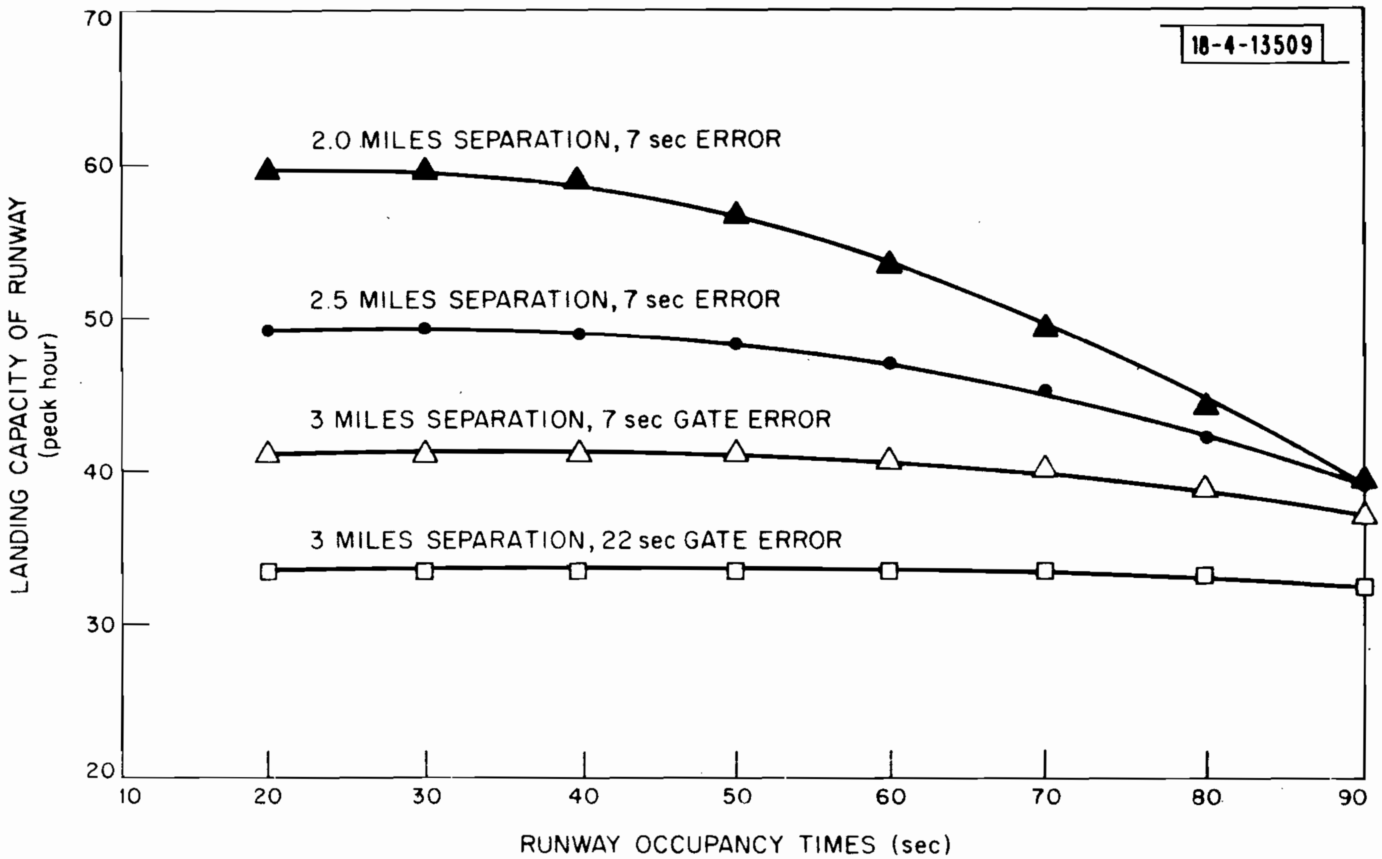

Fig. A-1. Sensitivity of the landing capacity of a runway (landings only) to average runway occupancy time and average spacing error.

On the other hand, the very need of excluding too much detail from the models forces the analyst into the highly useful exercise of identifying what the important and what the unimportant variables are. Moreover, once an analytical model is completed, it is then easy to investigate the effects of such suggested future improvements as better runway designs (fast entry/fast exit), new separation standards, computer-aided spacing and sequencing, and as possible changes in priority rules (see, for example, (6)) come into being.

A.2 QUEUING MODELS

The queuing models available are much less satisfactory than the capacity models mentioned above. An excellent introduction to the various issues in this area is provided in the paper by Oliver (7). In general, we can distinguish here between steady-state models and analyses with time-dependent arrival rates, with the great majority of the reports falling into the former category. It may also be added that, for analytical purposes at least, departure schedules at major airports display a highly irregular pattern (with most departures scheduled on the hour or the half-hour). Consequently, most of the analytical work on the present subject concentrates on queues of landing aircraft.

Let us summarize a typical steady-state model for a landing queue: It is clear, first, that as in all queuing analyses, the following information must be provided:

(1) A probabilistic description of the arrival process at the final approach/runway sequence.

(2) A probabilistic description of the service time per aircraft.

(3) Any available data on the maximum length allowed for the queue, the priorities for the use of the runway, etc.

With regard to item (1), it is typical to assume that the instants of aircraft arrivals at the periphery of the terminal area can be accurately modeled by a Poisson process. Previous studies (see (8) for references) have shown this to be substantially true for high density terminal areas. Good theoretical arguments (8) can also be offered in support of this proposition.

As for the service times, it should be noted that the capacity models of the preceding subsection deal with the problem of estimating the distribution of the time-gap between successive landings under saturation conditions, or, in effect, the time during which the server is "occupied" by an aircraft. Thus, the capacity models can serve as "building blocks" for the queuing analysis.

In conclusion, we have a queuing situation with Poisson arrivals and a "general" service time distribution. As service is provided on a first-come, first-served basis and as the maximum length of the queue can be considered infinite for all practical purposes, the usual steady-state expressions from the analysis of M/G/1 queues can be applied to this case. Thus, for instance, the average time spent in the queue per aircraft is given by:

$$W_q = \frac{\lambda E[t_s^2]}{2(1 - \lambda E[t_s])} \quad \text{for } \lambda\, E[t_s] < 1 \quad ,$$

where,

λ = average number of arrivals per unit of time,

$E[t_s]$ = average length of a service time;

$E[t_s^2]$ = second moment of service times.

This type of analysis has been used very widely in the past (see (2), (3), (5)). In a more recent paper (9), and M/G/1 queue with state-dependent service times (to account for interactions among aircraft in the final approach) has been used to obtain some correction terms to the aforementioned steady-state expressions.

Figure A-2 (from reference (5)) illustrates the type of results obtainable through the steady-state queuing models. The figure shows average delays at a runway used only for landings as a function of the number of aircraft that demand use of the runway each hour. The most important characteristic of these curves for operational purposes is, of course, the dramatic increase in delays that occurs at high demand levels. Excessive utilization of the runway can thus result in unacceptable delays for its users. Figure A-2 also shows how the practical hourly capacity (PHCAP) of the runway (level of operations at which an average delay of four minutes is expected) can be obtained by using the delay curves.

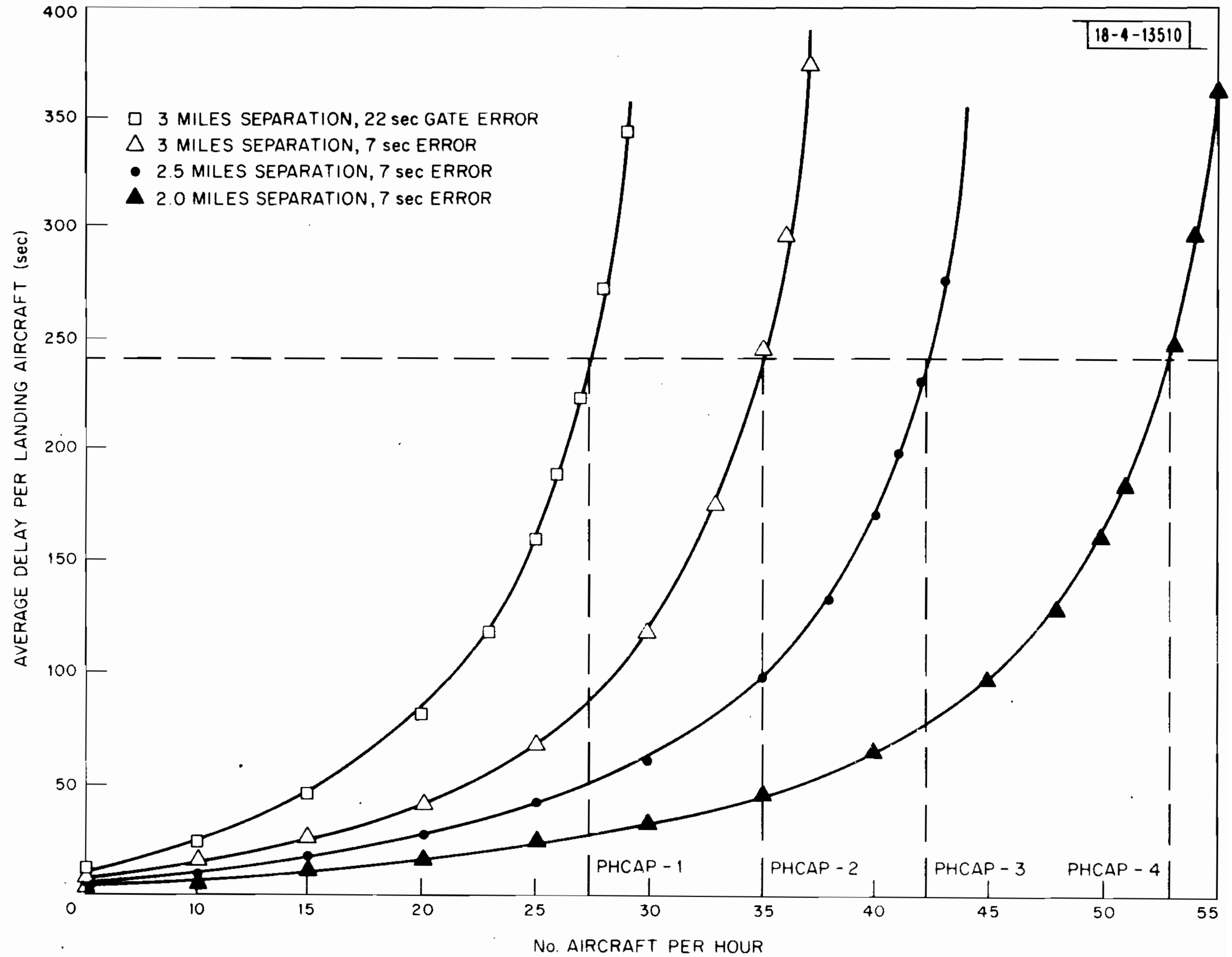

Fig. A-2. Average delays to a runway (landings only) as a function of the number of aircraft demanding use of the runway each hour for four ranges of spacing error.

The steady-state models are helpful in two respects: first, they can demonstrate graphically to airport administrators the drastic increase in expected delays at high utilization rates and the severe consequences of even minor degradations in service; secondly, for planning purposes, they are useful in identifying potentially troublesome situtations that can result from chronic overscheduling. However, the models also suffer from strong limitations that are a consequence of using steady-state assumptions for queues which, in reality, have strongly time-dependent inputs.

Until recently, the only available time-dependent queuing analysis which referred directly to ATC was the one reported in (10). During the last year, Koopman (11) has investigated queues under time-dependent conditions by using "computer implemented analytical methods." With considerable success, a landing queue of finite capacity with time-dependent arrivals has been analyzed by expressing the status and probabilities of the queue in terms of a system of the well-known first-order differential equations for birth-and-death processes. Subsequently, solutions were evaluated numerically through the use of the computer. A rather surprising conclusion of this study has been that the (time-dependent) average waiting times are rather insensitive to the precise form of the service-time distribution, but highly sensitive to the expected length of service times. This promising method has been expanded most recently by Istefanopoulos (12) in work which was supported, in part, by Lincoln Laboratory. This latter study shows not only that the above approach can be extended to the case of multiple runways, but also that it is computationally efficient and that the remarkable insensitivity of average waiting times still holds under a very wide variety of conditions.

Koopman (11) has also tried to extend his technique to the case of runways which are used for mixed operations. Several difficulties, however, arise in this case, the most severe of which is a rapidly increasing number of differential equations which greatly complicate the computational solution.

A.3 LIMITATIONS OF ANALYTICAL METHODS

In the preceding paragraphs, we have indicated the extent of the available analytical results on runway capacity. Some of the shortcomings of these techniques were also mentioned. We would now like to discuss the latter point a little further.

As noted above, one important difficulty with the analytical approach is that, in order to maintain the mathematical analysis within tractable limits, it is often necessary to omit from models many details which at the local level (to airport managers, for instance) may be very important. A second, more important and crucial problem with the type of mathematical analysis outlined in this introduction, is its inability to consider all of the large number of complex interactions that continually take place among the various elements and subsystems of the airport complex. In other words, it is possible to analyze capacities and delays at a single runway which is assumed to operate isolated from the rest of the system, but it is extremely difficult to account in the analysis for the constraints and perturbations that, say, the taxiway system or other operations at different runways or the workload of the controller, to name a few, impose on the runway in question.

It is at this system-wide level that the simulation approach can be most useful. After the operation of individual elements of the airport complex have been modeled and understood, a simulation can aid the planner to obtain information about the operational characteristics of the airport with all of its elements functioning simultaneously. The simulation of dual runway operations which is described in this report was undertaken with this objective in mind.

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APPENDIX B

RUNWAY SIMULATOR COMMANDS AND FLOW CHART

COMMANDS FOR RUNWAY SIMULATOR — SIMULATE MODE

Drawn	Recognized	Meaning
∣	h	Put measurement file on storage tube
DO	⊃	Create snapshot file
RI	⊂	Read in snapshot file
\	∪	Turn right at next intersection
/	∩	Turn left at next intersection
Q	Q	Back to edit
TR	α	Go to trainer
///	B	Transition (i.e., stepover)
—	—	Cleared for departure
\	∣	Cleared into position and hold
?∣∣	?	Query
/	/	Flip gridplot
H	t	Halt immediately
∣	≺	Proceed to second intersection and halt
→	→	Proceed
═	2	Proceed to next intersection and halt

COMMANDS FOR RUNWAY SIMULATOR — SIMULATOR MODE

Drawn	Recognized	Meaning
M	3	Waveoff
↑	5	Scale
↓	6	Magnify
□	7	Reset center
RT	8	Set frame rate
○	9	Blow up selected area
O	#	Re-initialize center and scale
P	‖	Start traffic from distribution
	z	End playback
SC	G	Start traffic from a script

COMMANDS FOR RUNWAY SIMULATOR — EDIT MODE

Drawn	Reported	Meaning
Q	Q	Quit
S	S	Simulate
F	F	Read in version before last change
//	ε	Enter Ruler Mode
\\	λ	Delete Ruler
///	β	Enter Protractor Mode
\\\	γ	Delete Protractor
X	X	Delete object
R	R	Enter Runway mode

COMMANDS FOR RUNWAY SIMULATOR — EDIT MODE

Drawn	Reported	Meaning
d	D	Place departure fix
A	A	Place approach fix
—	t	Enter touchdown mode
T	T	Enter taxiway mode
+	+	Select object for move
TR	α	Go up to trainer
/	/	Flip gridplot
↑	5	Scale
↓	6	Magnify
□	7	Reset center
○	#	Re-initialize center and scale
○	9	Blow-up selected region

The program is currently 5200 lines of code in BCPL,[6] a high-level language in use on TX-2. When compiled, the machine code comprises approximately 33500 instructions. In addition, approximately 6000 words of data storage for the airport map and plane status are required. The 4100 lines of code may be divided roughly as follows:

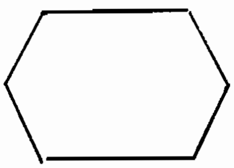
Global declarations, allocation of storage	629
Parameter specification	110
Edit mode	1400
Display routines to paint map	400
Simulate mode	1750
Routine to calculate plane motion	50
Display routines to paint planes	100
Miscellaneous utility routines	200
Snapshot facility	350
Playback facility	200

A flow chart of this program follows.

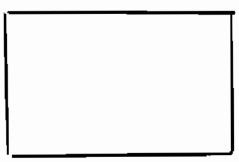
Flowcharts

The flowchart (Figure B-1) indicates the sequence of steps for each plane as it goes through the system. Usually several planes will be at various points in the flowchart simultaneously. The flowchart (Figure B-2) indicates the logical steps which the programmed controller logic follows in directing aircraft in the dual lane system.

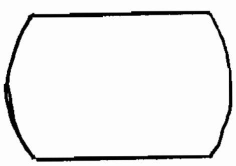
The boxes with pointed ends represent instantaneous actions. The rectangular boxes represent actions which proceed over intervals. These actions are terminated either by reaching the end of the interval (i.e., taxi to end-of-segment terminates when the plane reaches the end of the current taxiway segment) or by an interactive command, indicated by a line coming out of the side of the box rather than the bottom. The commands the controller can give are indicated by boxes with rounded ends. Decision points (always instantaneous) are represented by diamonds.



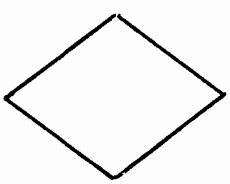
Instanteous actions



Action over interval



Controller commands



Decision

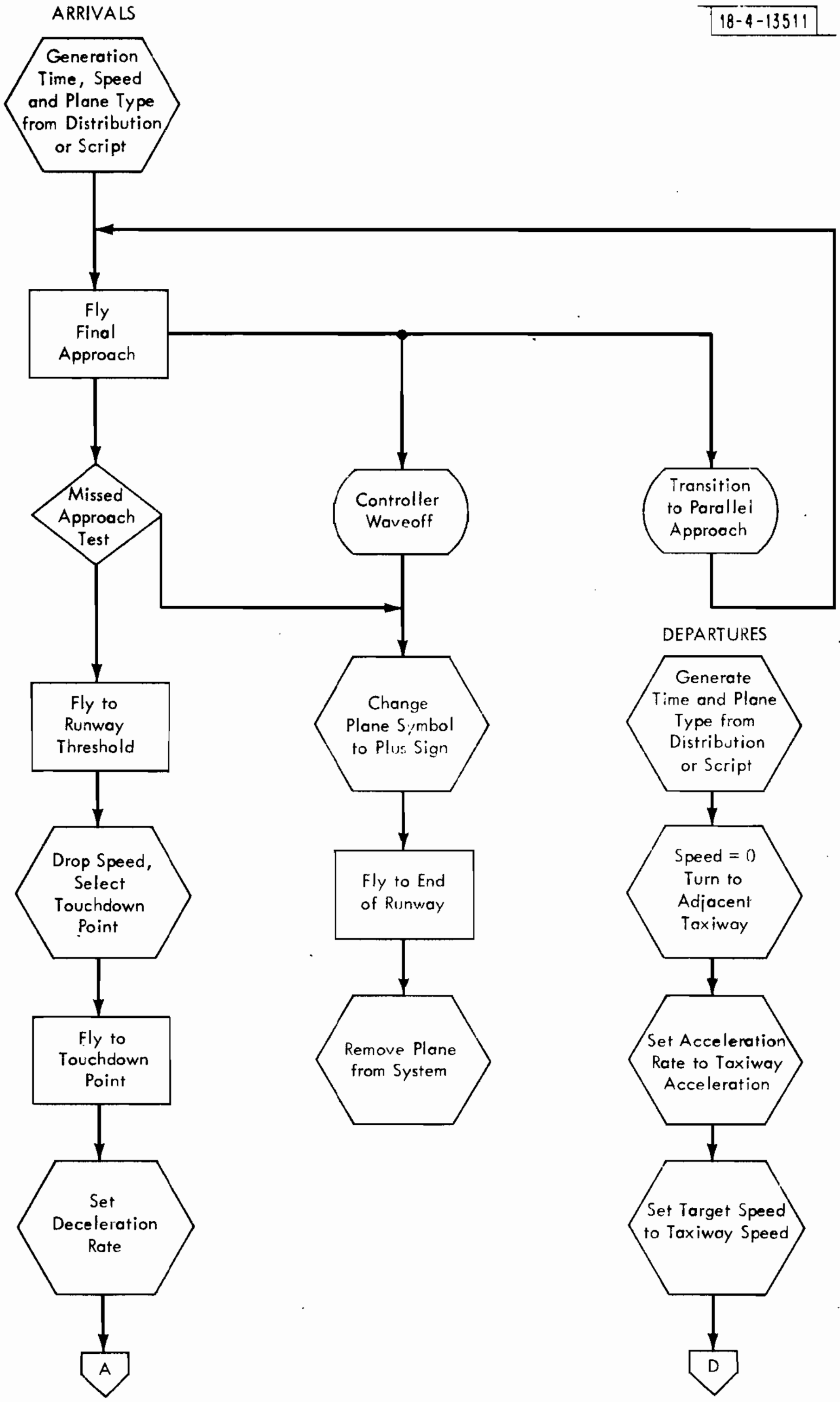


Fig. B-1. Arrivals/departures flowchart (Sheet 1 of 4).

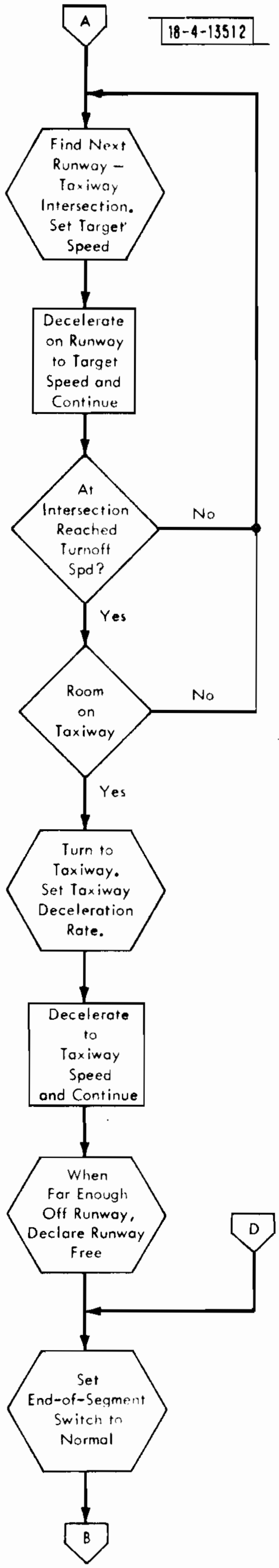


Fig. B-1. Continued (Sheet 2 of 4).

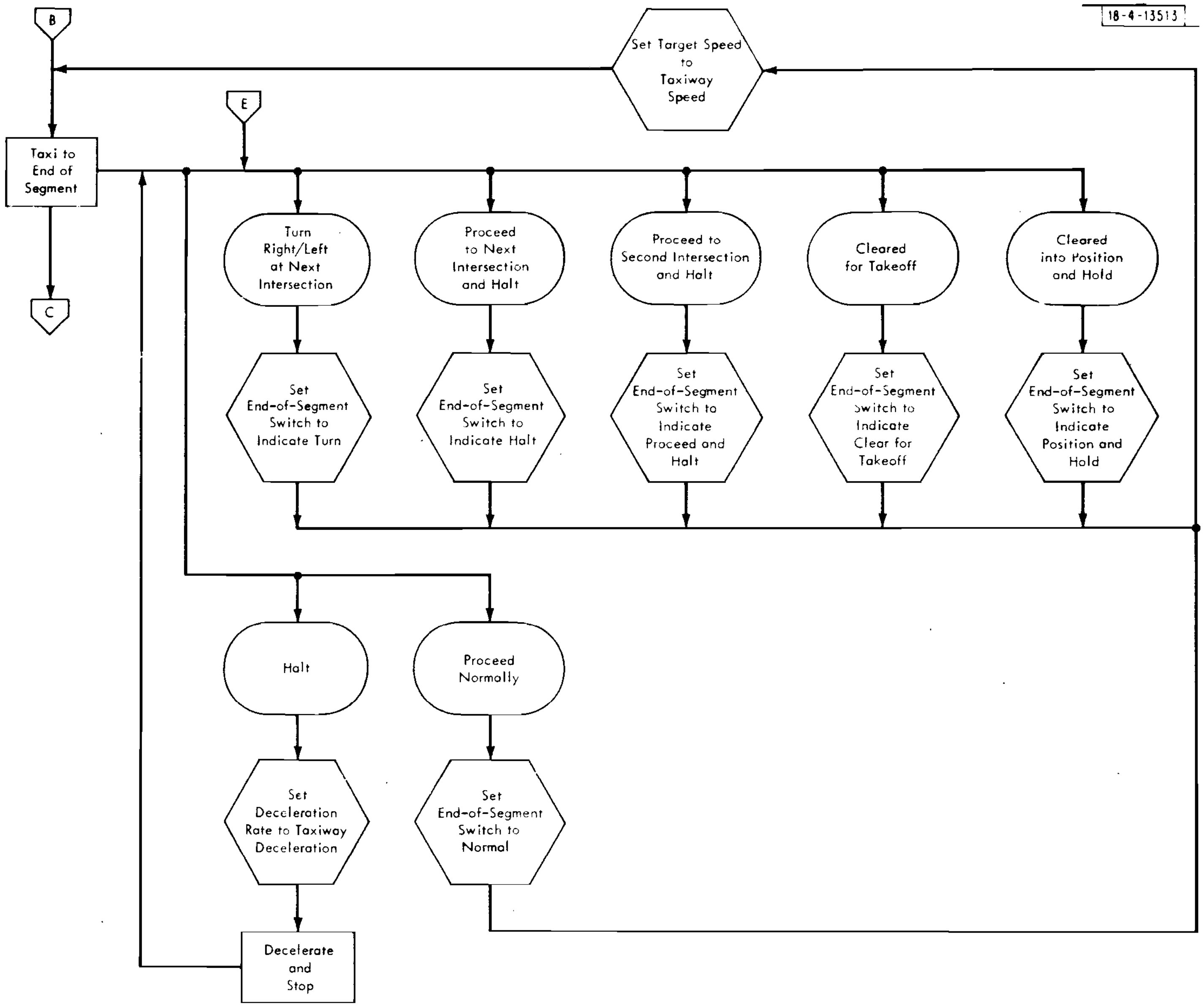


Fig. B-1. Continued (Sheet 3 of 4).

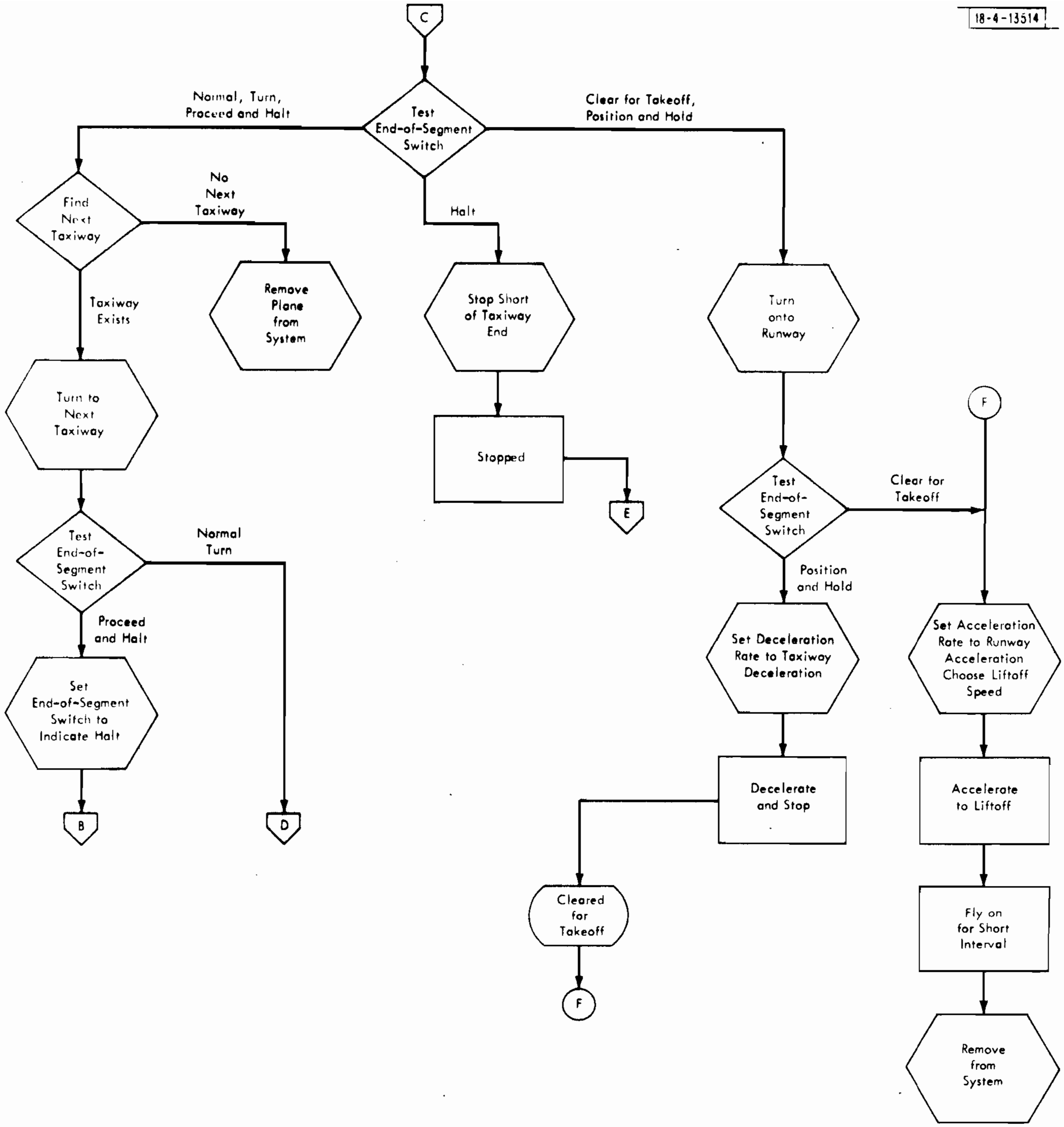


Fig. B-1. Continued (Sheet 4 of 4).

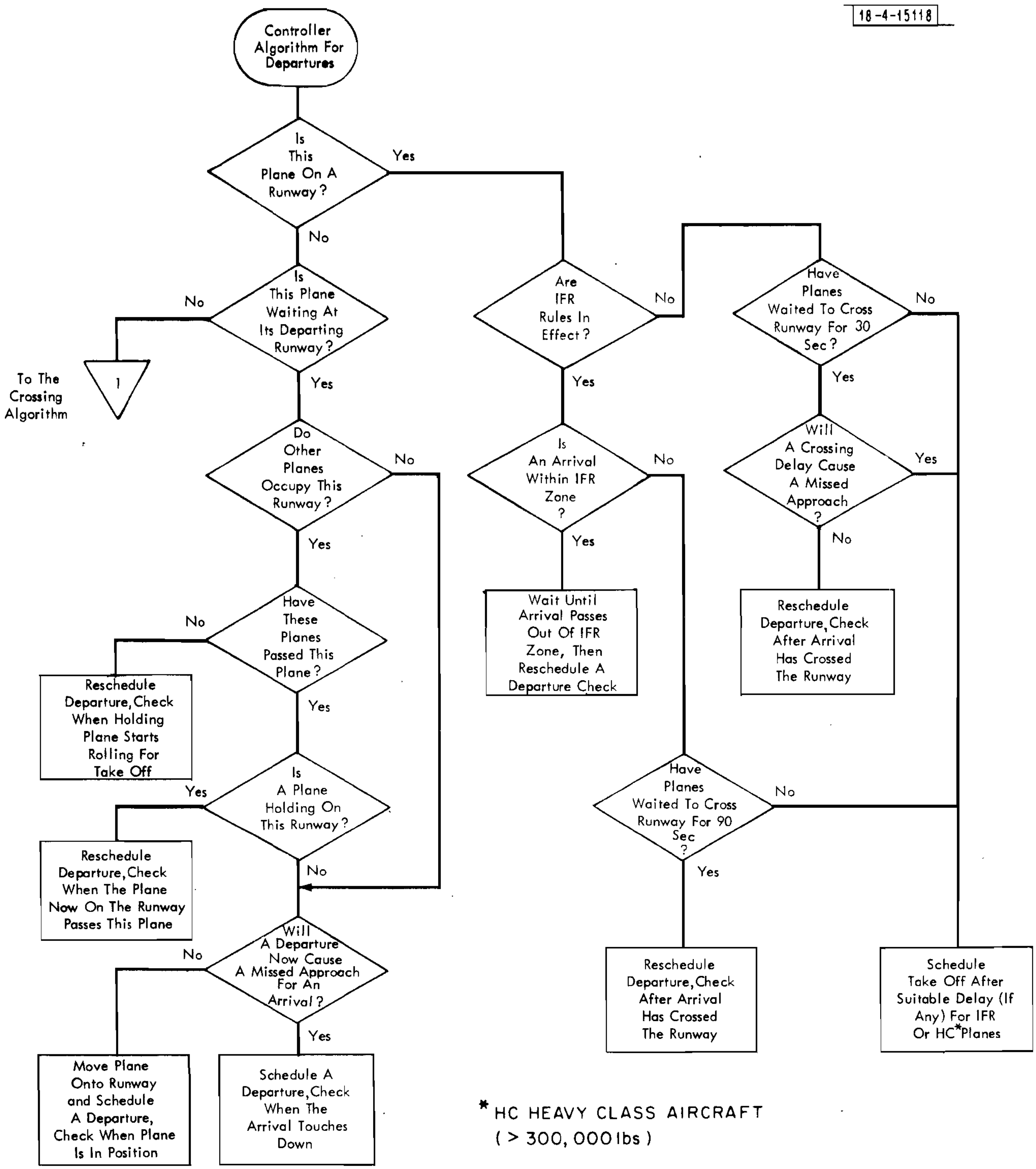


Figure B-2. Controller Logic Flow. (Sheet 1 of 2)

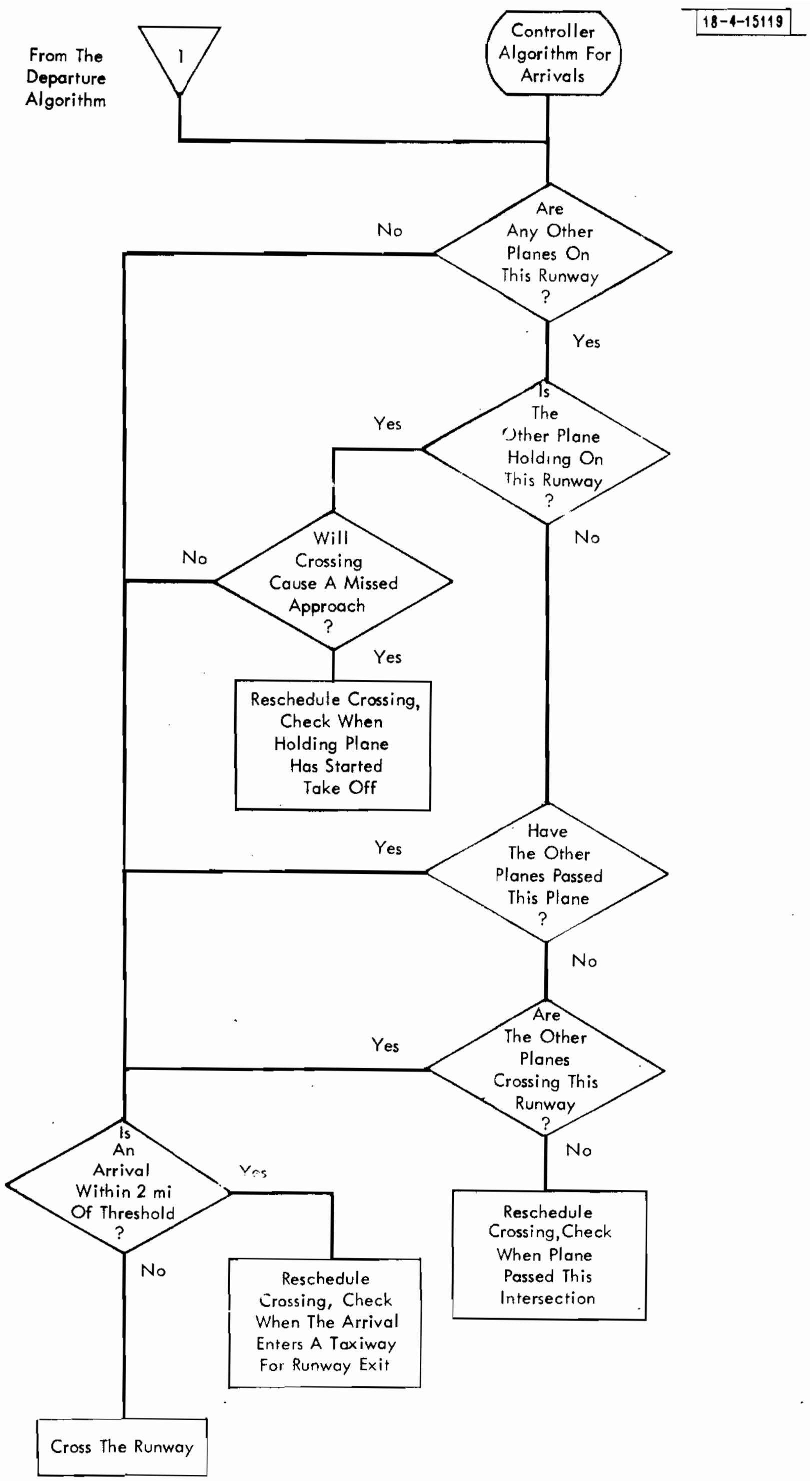


Figure B-2. Continued (Sheet 2 of 2).

APPENDIX C

HIGH DENSITY TERMINAL OPERATIONS

High density airport terminal operations were investigated to establish pilot and controller techniques utilized at major hub airports. The real time and fast time simulations were developed to reflect techniques employed in directing high density operations.

The three trip reports in Appendix C were written subsequent to visits to the following major hub airports:

(1) O'Hare International Airport, Chicago.

(2) JFK International Airport, New York and Atlanta Airport.

(3) Los Angeles (LAX) and San Francisco International (SFO) Airports.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

7 August 1972

Subject: Trip Report to O'Hare International Airport, Chicago, Illinois, (June 1-2, 1972).

The pupose of the trip was to become familiar with pilot and controller technique when operating at a high density hub airport such as O'Hare Airport in Chicago. Pilots and controllers were observed and interviewed while performing their specific functions. O'Hare is currently the busiest air carrier airport in the world. This report will cover flights from Logan to O'Hare and return. A description of the operations observed at O'Hare is also covered in this report.

The trip to O'Hare from Logan Airport, Boston was flown on the flight deck of an American Airlines B747 jumbo jet. The three aircrew members include pilot, first officer (co-pilot), and flight engineer. The trip from gate to gate was scheduled for two hours and twenty minutes with one hour and fifty-one minutes in the air. It is the first officer's job to compute the expected fuel required for the trip. His calculations were:

point to point	44,000 lbs
reserve	16,500 "
alternate	---
instrument approach	3,600 "
missed approach climbout	7,000 "
	71,100 lbs

The dispatcher also calculates the fuel required and is generally more conservative in his estimate normally calling for more fuel than the crew calculates. The dispatcher's total came to 84,000 lbs with an additional 4,000 lbs being added at takeoff time to balance the load. The pilot signed off on the 88,000 lbs of fuel at flight time. No alternate landing site was provided due to the excellent weather in Chicago. Normally, 45 minutes of flying time to an alternate airport is figured.

The first officer preceded the pilot to the aircraft and manually loaded the latitude and longitude of the waypoints into the Litton LTN-51 inertial area navigation system.

Heading In	VOR	Freq.	Heading Out	W.P.	Lat.	Long.
	BOS	12.7			42 21.8	71 01.0
298	CAM	15.0	285	1	42 59.7	73 20.7
285	SYR	17.0	274	2	43 0916	76 12.3
270	BUF	16.4	282	3	42 55.7	78 38.8
279	XU	17.2	287	4	43 02.3	81 08.9
284	ECK	14.0	253	5	43 15.3	82 43.1
252	FNT	16.9	258	6	42 58.0	83 44.5
253	PMM	12.1	261	7	42 27.9	86 06.3
257	OBK	13.0		8	42 13.4	87 57.0
	ORD	13.9		9	41 58.5	87 53.9

There presently is no area navigation route from Boston to Chicago so the inertial navigation system was used to fly the VOR jet route, in this case J 547. The clearance was obtained by the first officer from clearance control and was approved as filed.

A single engine was started at the gate before pushback for emergency power. A clearance from the ground controller was obtained to pushback. A tug pushed the aircraft away from the gate where the other three engines were started. The aircraft was cleared to taxi to runway 22L and hold short. The aircraft taxied at or less than 15 knots as read on the inertial ground speed readout. The ground was wet and when the pilot attempted a right angle turn the nose wheel skidded at 8 knots. The turn was completed at approximately 5 knots. The controller cleared the aircraft to taxi into position on the runway and hold. This was refused by the pilot as he had not received final confirmation of his takeoff weight calculations from the company dispatcher. The aircraft was cleared and took off on a Merimack departure. The jet route, J 547, was intercepted and the course to O'Hare followed. The flight proceeded north of Albany, over Syracuse, Buffalo, and Flint, Michigan and on into O'Hare. A mach number of .84 (270 knots IAS) equivalent to a TAS of ~500 knots at 39,000 ft was flown. The fuel flow was approximately 5200 lbs/hr for each of the four engines (20,800 lbs total/hr).

The O'Hare approach controller requested that we keep our airspeed over 160 knots until outer marker to expedite traffic in the area. At the outer marker the pilot started reducing speed to 130 knots TAS. The radio altimeter activates at 2500 ft and was used to indicate altitude on approach. We passed the runway threshold at 50 ft altitude and 130 knots TAS. The sensation experienced at touchdown was complete surprise as to our touchdown point. Due to the height of the cockpit above the landing gear (~45 ft) and the slight noseup attitude, it appeared as if we would touchdown in the middle of the runway instead of close to the threshold. The pilot later stated that this was the hardest part of the transition to the B747 aircraft. The pilot applied thrust reverse and speed brakes to slow the aircraft. The main landing gear were "unlocked" at about

60 knots at which time the pilot started to steer the aircraft. The main gear trucks swivel hydraulically in a turn similar to the hook and ladder fire engines where the rear wheels are turned opposite to the front wheels to effect a turn. A gradual turn was made with the aircraft negotiating the angled turn 4600 ft from threshold at 17 knots. We proceeded to taxi at 20 knots with the speed going to 28 knots on a long straight stretch of taxiway. A right angle turn into the gate area was negotiated at 7 - 8 knots.

Later, in an interview, the pilot revealed that when landing he does not unlock the main gear for steering until the aircraft is below 60 knots. He feels he would never take a high speed exit at 60 mi/h in a 747. He states that the maximum speed he would consider would be 45 mi/h. Later observations revealed no 747 aircraft taking the 4600 ft exit at O'Hare as all were proceeding to an exit at about 6000 ft. It is suspected that the pilot reacted to our inflight discussions of runway occupancy and therefore took the first exit at 4600 ft instead of the more normal 6000 ft exit. This confirmed our suspicion that a 5000 ft exit could be used by heavy class aircraft given the incentive.

The return flight was made in the cockpit of an American Airlines DC-10 aircraft.

The DC-10 is considered a heavy aircraft (>300,000 lbs) for wake turbulence effects. Its maximum gross takeoff weight is 410,000 lbs and its maximum gross landing weight is 337,000 lbs. We landed at Logan with a gross weight of 275,000 lbs. There is apparent confusion about this aircraft by the controllers presumably due to its recent introduciton and to its maximum landing weight being below that of the heavy classification. However, it is to be considered a heavy aircraft on takeoffs and landings requiring controllers to enforce wake turbulence separation rules. The pilot stated that the controllers at Los Angeles realizing their error in clearing the heavy DC-10 to land on a weight restricted runway (due to insufficient tunnel stress) made him go around resulting in a loss of eighteen minutes on landing.

This DC-10 aircraft was not equipped with an inertial navigation system. The DC-10 lifted off in 25 sec from start of roll and made a steep climb out at 4500 ft/min. The aircraft was overtaking another company aircraft flying a similar course out of O'Hare. The en route controller gave the pilot an "S" maneuver to fly to increase the airspace between aircraft. However, once back on course it was found that we were still overtaking the preceding aircraft. A few comments were passed between the two pilots and en route controller to the effect that we were flying too fast. This was confirmed by our pilot who stated he would rather fly at 0.85 mach number than the company recommended 0.82.

We were subsequently vectored over the company jet we had been overtaking. This confused the en route handoff from Chicago Center to Cleveland Center as we were shifted back and forth three times before the confusion was resolved. The cruise portion of the trip from O'Hare to Logan was made at 0.85 mach and 37,000 ft altitude. We arrived about ten minutes ahead of schedule and had used less fuel than had been anticipated at the 0.82 mach number.

O'Hare and Midway control towers were visited. Chicago-O'Hare International Airport (see Figure C-1) is essentially run as two separate airports. The North Complex consists of runways 32R-14L, 27R-9L, 36-18, 22R-4L while the South Complex consists of runways 32L-14R, 9R-27L, 22L-4R. There is a local controller for the North Complex and one for the South Complex. Two ground controllers coordinate ground traffic; one for arrivals and the other for departures. O'Hare traffic averages 1700-1900 operations per day, 90 percent of which are air carrier with 10 percent general aviation and air taxi. The number of departures and arrivals handled by each runway are tabulated for 1971.

Runway	Departures	Arrivals (x1000)
27R	3.1	55.9
27L	121.9	14.5
14R	17.6	73.4
14L	11.5	44.7
32R	58.9	9.9
32L	17.5	71.1
9R	24.5	10.5
9L	47.9	2.1
22R	1.1	37.1
22L	.6	.3
18	-	-
36	4.5	-
4R	-	-
4L	6.9	.5
	316.0	320.0

The airport handled 636,000 operations in 1971, or, an average of 73 operations per hour per day for the entire year. During their peak loading in the rush hours, they normally handled 135-150 VFR operations per hour with this going close to 200 during extraordinary periods. They schedule 135 IFR operations per hour. The main departure runways are seen to be 27L, 32R, and 9L while the main arrival runways are 14R, 32L and 27R. The four major runways are, therefore, 27L-9R, 32R-14L, 27R-9L, 32L-14R, which is basically the configuration we observed in use on our visit.

The air carrier percentage breakdown by aircraft that O'Hare handled in 1971 is as follows:

Aircraft	Percent (%)
B747 and DC10	6
B727 all	31
DC9 all	16
B720	9
B737	9
B707 and B320	8
DC8 all	8
CV 880	4
CV 580	7
FA 22	2
	100

The breakdown shows that the bulk of the traffic (56 percent) is made up of the short haul B727, B737 and DC9 type aircraft. The figures show that the heavy class aircraft (B747 and DC10) make up 6 percent of the total. However, the DC8 and B707 categories contain stretch versions which are classified as heavy aircraft (>300,000 lbs) thereby, conceivably making the heavy aircraft 10-15 percent of the mix.

The runway configuration in use when we visited the field was: North Complex - 32 R departures and 27R arrivals; South Complex - 32L departures and arrivals. Runway 27L was temporarily closed for repairs. The weather was VFR with good visibility.

It was observed that none of the active controllers were seated during the rush hour period. The result of operating with three runways instead of the more customary four was a queuing of the departure aircraft at runway 32L on the South Complex and 32R on the North Complex. The South Complex controller was landing and departing aircraft on 32L. The arrivals came in a steady stream with 4-5 nmi spacing between aircraft. The South Complex local controller was constantly talking to the departure aircraft telling them his intentions and the current traffic situation. He would ask if they would accept intersection take-offs where the aircraft would depart the runway other than at the runway end. The smaller air carrier aircraft tended to accept the intersection takeoffs while the larger aircraft refused. The intersection takeoffs resulted in less time in control of the runway for departures as they were further away from the threshold and the incoming arrival when they were cleared for takeoff. The arrivals were asked to vacate the runways as soon as possible. The departures were not generally put into position after an arrival passed as the controller did not know how long the arrival would be on the runway. The controller would generally give the departure a clearance to taxi into position and not to plan on stopping. He would give the takeoff clearance while the aircraft was taxiing into position when, in his judgment, the previous arrival was committed to an exit. This type of operation (continual streams of arrivals and departures) lasted close to two hours. One missed approach was observed when the B707 arrival elected to go around even though the controller cleared him to land. The pilot felt that the departure lifting off was not sufficiently clear of the runway to allow him to land. The North Complex local controller landed aircraft on 27R and departed aircraft on 32R. The departures were cleared for takeoff when the arrivals cleared the 27R-32R intersection. Arrivals were spaced in a steady stream anywhere from 4-5 miles apart. Departures were queuing with the line extending to over ten aircraft at times. The North and South local controllers continually coordinated departures between themselves as the departures were on parallel paths from 32R and 32L. If both departures were West bound, the South controller would have the 32L departure make a sharp left turn while the North controller would have the 32R departure making a gradual left turn. Both departures were appraised of the situation and were on the lookout for the other aircraft.

The rush hour operation observed at O'Hare was busy but always under complete control by the tower. Arrivals were touching down on runways 27R and 32L every two minutes with one or two departures between arrivals on 32R and departures on 32L when they could be accommodated. This type of operation requires absolute confidence between controllers and pilots to be effective.

Midway tower was a complete contrast from O'Hare. Midway traffic is approximately one fourth that of O'Hare or about 500 operations per day. However, the mix of general aviation and commercial is reversed from O'Hare. Midway has a preponderance of general aviation traffic, approximately 75 percent general aviation traffic and 25 percent air carrier and air taxi operations. The air carrier operations at Midway are restricted to the short haul aircraft due to the lengths of the runways.

Due to the short runways at Midway and traffic pattern interference with O'Hare patterns, it does not appear that Midway is a logical choice as an alternate airport to alleviate O'Hare air carrier traffic jams.

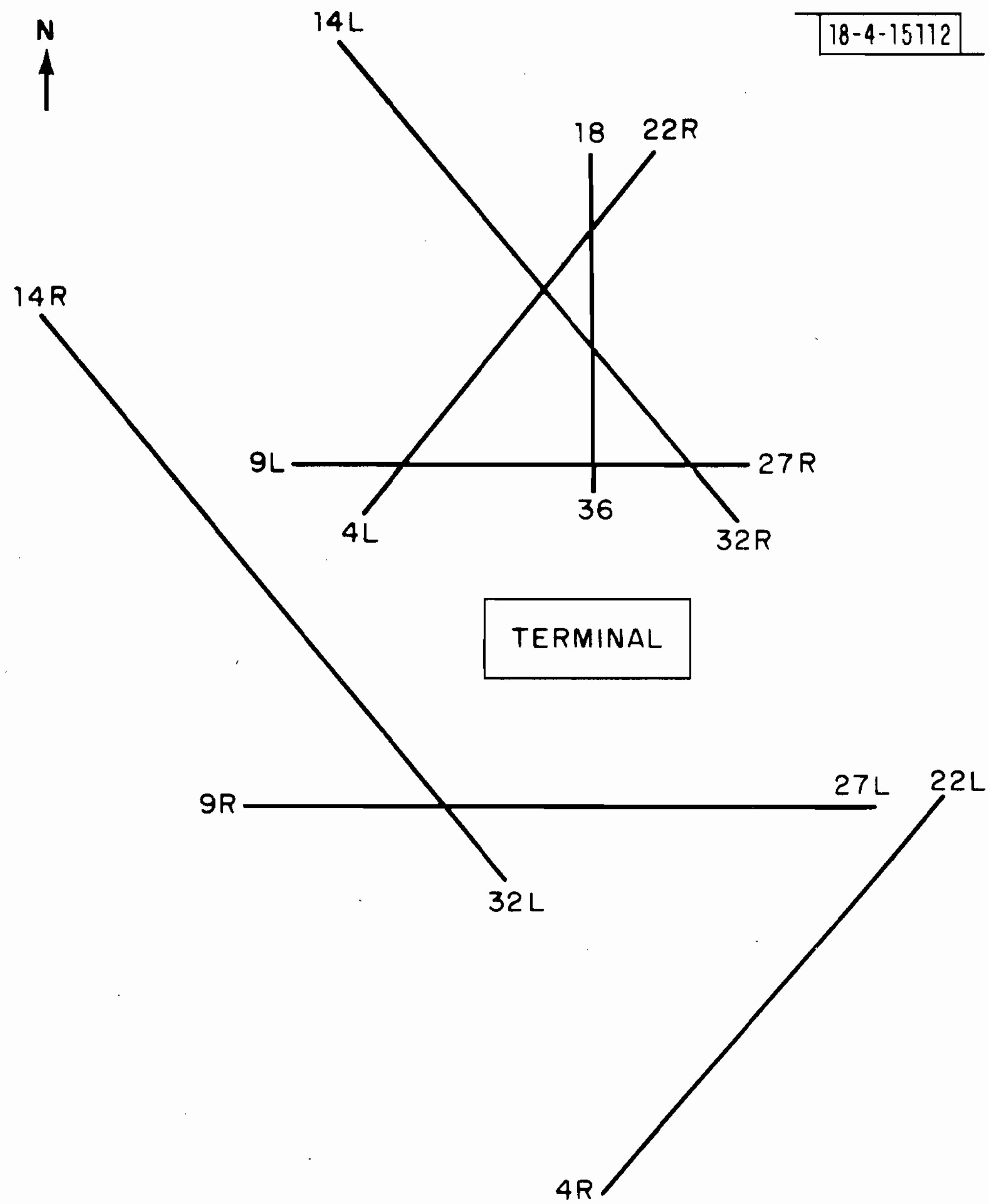


Figure C-1. O'Hare Airport, Chicago, Illinois.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

20 September 1972

Subject: Trip Report: a) Jump Seat Flight Providence to JFK (8/22/72)
b) Jump Seat Flight Boston to JFK (8/22/72)
c) Visit to JFK Tower and IFR Room (8/22/72)
d) Visit to Atlanta Tower and IFR Room (8/23/72)

a) Flight AA655 is a Boeing 727S (stretch) aircraft scheduled to depart Providence, Rhode Island at 7:15 a.m. and arrive at John F. Kennedy Airport at 7:58 a.m. The departure clearance from Theodore F. Green State Airport was for runway 16 using a southern departure route (Quonset departure). The assigned route was V167 to Sterling intersection then V16 to Bohemia intersection where the flight would be radar vectored into JFK (references:

1. Jeppesen Low Altitude En Route Chart (#26),

2. Standard Instrument Departures (SID's), Eastern United States, and

3. Low Altitude Instrument Approach Procedures, Northeast United States (VOL-7)).

The critical engine failure speed (V1) below which an aircraft can come to a safe stop on the runway was calculated as 115 knots. The rotate speed (VR) at which speed the pilot lifts the nose wheel off (rotates the aircraft) is always less than V1 in the B727 aircraft so V1 is used as rotate speed. The flying speed (V2 or 1.2 stall velocity was calculated as 134 knots. Present noise abatement climbout procedures recommend climbout velocity to be V2 plus 10 knots. Once airborne, the Providence departure controller instructed the pilot to climb to 2,000 ft, at which point, he was to execute a right turn to 270 degrees. Once established on this heading, the aircraft was cleared direct to Norwich VOR. A cruising altitude of 10,000 ft was assigned. At the 10,000 ft cruising altitude, the aircraft maintained an indicated air speed of 395 knots and an estimated 455 knot ground speed due to an estimated 60 knot tail wind component. Shortly after being cleared direct to Norwich, the aircraft was cleared direct to Riverhead VOR. Before reaching Riverhead VOR, the aircraft was again cleared direct to Deer Park VOR under JFK common IFR room control. Approximately 20 miles east of Deer Park VOR, the aircraft was requested to descent to 7,000 ft and reduce speed to 250 knots. After calling in at 7,000 ft, the aircraft was cleared to 4,000 ft. The pilot descended to 4,000 ft and reported to the approach controller that he had a heading reading on the outer marker. The final approach controller then expedited the approach by giving the pilot a heading vector to intercept the extended runway centerline about a mile before the outer marker.

The aircraft was cleared for an ILS approach to runway 31R. The pilot made a request of the tower to go long on the runway in order to take an exit convenient to his American Airline terminal. The request was approved by the local controller. The pilot landed at the normal ILS touchdown zone, but kept his speed up to exit further down the runway at approximately his normal runway occupancy time.

The touchdown was made one minute ahead of the published schedule. This was a surprise due to the path we actually followed versus the planned route. The aircraft was expedited throughout its entire flight plan by controllers clearing the aircraft directly instead of over the VOR routes. The pilot stated that the short hop scheduled flying times were very tight and extremely hard to beat. The scheduled flying time is 28 min (depart 7:21 and touchdown at 7:49) which flight AA655 made in 27 min. We arrived at the American Airlines terminal gate at 7:52, about six minutes ahead of schedule, and had to wait about four minutes for airline ground personnel before we could dock. If the wind had been out of the East, a Canarsie VOR approach to runway 13L would have to be made causing an additional 10-15 min of flying time. There is approach path interference with LaGuardia Airport routes requiring rigid speed and heading restrictions on this approach creating delays to the runway.

The flight crew were young and had an intense interest in their jobs. The flight crews relationship with the JFK and en route controllers was excellent. The pilot and the various ATC controllers worked together expediting the flight whenever possible.

b) Flight deck operation on a 727S (extended version of the basic 727) equipped for oceanic flight and Category II instrument approaches was viewed from the vantage point of the jump seat on Flight AA621 from Boston to New York (JFK).

Normally, the routine flying from one airport to another is handled on an alternating basis between pilot and first officer. This enables both to remain proficient in all assignments. During this particular flight, it was the captain's task to fly and navigate. Takeoff was initiated at rotation speed V_r (calculated by the second officer) as called out by the first officer upon passing it on rollout. The Weston standard instrument departure route was followed with an early lifting of the altitude restrictions by the departure controller allowing a climb to the assigned en route altitude (16,000 ft). Boston and en route weather at altitude were clear with some restriction to visibility due to early morning haze.

The required navigation and communication frequency changes, map, and chart selection as the flight progresses, plus the task of obtaining reports such as the automatic terminal information service (ATIS) and en route weather are among the duties of that member of the crew not currently engaged in the flying assignment. On this flight, these duties were handled by the first officer, leaving the pilot free to do the required flying unhampered. All three members of the flight crew monitor the ATC frequency, thereby, decreasing the chance of a missed transmission or frequency change assignment.

The second officer monitored the engine instruments after takeoff making small changes in the power setting while climbing to altitude and while en route. Trim changes made by the Captain were frequent things during the climb/descent phase of flight. The climb to altitude was made at rates ranging from 2000 ft/min to 3000 ft/min. It appeared as if no special attempt to fly a steady rate was made.

An altitude alert warning indicator set at the desired altitude allows activity to continue within the cockpit without constantly monitoring the altimeter and altitude requirements and without fear of passing through the assigned altitude. The alert instrument signals at an altitude approximately 1000 ft before the desired altitude. At this point, the climb/descent rate is reduced to approximately 500 ft/min in preparation for a transition to a level configuration.

En route flight was performed with the autopilot in the manual mode (the mode appears to be preferred by a large number of pilots). In this mode, manual inputs by the pilot are made to the flight control surfaces via the autopilot panel. This provides a smoother flight over that possible through control inputs via the control column. However, some difficulty was experienced through altitude excursions of several hundred feet before a level altitude was held by the autopilot.

The flight was expedited through the issuance of clearances direct to a succeeding VOR prior to VOR passage, thereby, cutting off "dog leg" turns over the VOR. During this en route phase, the crew found time to briefly demonstrate the Loran navigation equipment used in oceanic flight.

Following a short en route phase, the flight was vectored for an ILS approach to JFK on runway 31R. JFK's weather was clear with one mile in haze and smoke. The crew was thoroughly familiar with the approach and the New York TCA. Vectors were given to intercept the localizer course with a final turn of 20° onto final approach course. The three members of the flight crew later commented on the fact that the New York controller is consistent in this issuance of small angles for final interception of the localizer and goes a long way into decreasing localizer overshoot. A coupled ILS approach was made until the runway was visible through the haze, at which time the pilot completed the appraoch manually. His approach speed was 140 knots which he carried until the flare at which time it dropped approximately 15 knots. The approach speed as calculated by the second officer for the aircraft's weight and existing weather conditions was 126 knots. Both turnoff and rollout were well planned following a smooth landing so as not to linger on the active runway surface.

c) Visit to JFK Tower and Common IFR Room

Visits were made to the JFK Control Tower and to the JFK Common IFR Room. JFK personnel were interviewed about JFK operations. The steady decline in the total number of operations since 1967 (see table) was discussed.

Year	Total Oper. (x1000)	Total Instrument Operations (x1000)
57	202	-
58	217	-
59	240	-
60	275	-
61	290	-
62	319	-
63	339	-
64	367	-
65	390	305
66	439	319
67	481	380
68	465	390
69	436	365
70	397	335
71	380	338

The 21 percent decrease in total operations from a high of 481,000 in 1967 to 380,000 in 1971 is attributed to the increase in the number of heavy jet operations and the decline in the number of general aviation aircraft operations. A heavy jet is defined as a jet aircraft weighing over 300,000 pounds. They include stretch versions of B707 and DC8, jumbo B747, DC10, and L1011. Depending on the configuration, these aircraft are capable of carrying between 200-500 passengers. The airlines have been able to reduce the total number of scheduled flights by the number of heavy jets scheduled at JFK. Heavy jet operations presently account for approximately 40 percent of the total number of operations at JFK. This is due to the fact that JFK is a long haul airport. It is an international terminal handling overseas flights from all Eropean and South American airlines. A typical example of the efficiency of jumbo jet operations is given by Lufthansa Airlines, which has substituted a B747F cargo aircraft for two B707 freighter aircraft flying round trip from JFK to Frankfurt daily six days per week. A daily round trip payload for the B747 results in a 36 percent increase in cargo payload over the two B707 daily round trips (Reference AW & ST, August 14, 1972, p. 32). A twenty-five dollar landing fee is charged to all general aviation aircraft. This has had the effect of reducing general aviation aircraft to only a few percent of the total number of operations. The reduction of general aviation VFR flights is apparent in that 338,000 or 89 percent of the total operations were instrument operations in 1971.

The JFK Control Tower was visited during the morning and afternoon. Runway configurations in use were changed three times in that period due to wind changes and noise abatement procedures. Two local controllers and one ground controller were directing traffic. One local controller, using a BRITE (bright radar indicator tower equipment) television display system, was directing traffic within the terminal control area (TCA). The tower TCA responsibility extended over an eight-mile radius from the ground to two thousand feet altitude. This same local controller had responsibility for the short general aviation runway 32/14 when it was in operation. The other local controller directed traffic to a pair of runways depending on the configuration being operated 31L/31R, 13L/13R, 4L/4R, or 22L/22R. One ground controller handled ground traffic except in heavy situations where one ground controller handled arrivals and another handled departures. A computerized noise reduction system is used to spread the noise. When the wind speed is less than or equal to 15 knots, a computer printout (see sample) provides the recommended arrival and departure runways to alleviate the noise in some sectors. The printout varies with the time of day and can be obtained at anytime upon request by tower supervisor. When the wind velocity exceeds 15 knots, the tower supervisor is free to select the configuration he feels that best meets the situation.

Computerized Noise Reduction System (Wind Factors 5-15 knots)

Wind heading (degrees)

221/311	311/041	041/131	131/221	0-4 knots	arr. runway	dep. runway
-	-	I	-	I	4	13
I	-	-	-	I	31	22
X	-	-	X	X	22	22
-	X	-	-	X	4	31
-	-	-	I	I	13	22
-	X	x	-	X	4	4
X	X	-	-	X	31	31
-	-	X	X	X	13	13

The horizontal dashed entry means that with this wind heading, the listed arrival/departure runways would never be used. The I entry states that these runways are impractical for these wind conditions. The X entry means that these runways are practical for the listed wind headings. For a given wind heading (e.g., 221/311) and a wind velocity between 5 and 15 knots, the first column would be chosen. The first X is the recommended choice of runways (e.g., arrivals 22, departures 22) to reduce noise at the given hour of the day normally stated on the computer printout. However, as happened when we were there, runway 22L was closed for repair. Then the next recommended choice (follow down column to next X) was arrivals 31 and departures 31. This noise reduction system is closely adhered to by tower personnel.

The airport surface detection equipment (ASDE) radar was turned on for our benefit while in the tower. It was being repaired most of the period we spent in the tower. It is displayed on a PPI BRITE display in the tower by closed circuit television. When it was finally properly adjusted, it was found to have some excellent features. Airport runways, buildings, and hangers were clearly discernable. A B747 aircraft could be distinguished from the smaller aircraft due to size and outline of fuselage and wing surfaces. However, the aircraft was lost as soon as it moved faster than taxi velocity. Departing aircraft could be followed through the taxiway system, onto the runway and soon after starting their takeoff roll, they would disappear from the screen. This was evidently a malfunction of this particular ASDE. We visited downstairs and saw the actual 3" diameter CRT from which the closed circuit TV obtained its picture. A normal PPI indicator was viewed downstairs. This had excellent quality and did not drop the aircraft as soon as they started takeoff roll. The aircraft were lost a few hundred feet after liftoff. The Tower personnel felt that the properly aligned ASDE has a definite place in the tower under IFR conditions. However, they warned that the reception was degraded in wet conditions when they really needed it.

The New York area is sectored and stratified so as to handle the IFR traffic to the three major terminals within the area. Both noise abatement procedures and the airspace restrictions dictated by the near proximity of these large terminals make some approaches rather long and involved. Within the terminal control area (TCA) no airspace is shared by traffic landing at different airports. The space restrictions are quite limiting in that occasional minor violation of reserved airspace does occur when wind conditions require certain approach configurations. In addition to this traffic, the NY Common IFR controllers must handle traffic to a number of satellite general aviation (G/A) airports. A dedicated radar position handles all VFR terminal and en route traffic within the TCA. These aircraft are radar controlled through the area so as not to conflict with the normal approach path airspace reserved for the three major terminals.

In general, complaints voiced of the G/A Sunday flyer (not the air taxi's and such) were directed toward ccomments on his lack of knowledge of the TCA procedures and the non-professional radio technique and phraseology used by him.

Two of the three controllers observed, issued instructions based on landmarks and not headings and VOR references. A third controller cleared aircraft with heading references used in IFR flights.

Handling G/A at this position appeared to frustrate controllers on several occasions. At one time, a second controller observing, suggested to the controller at the position to calm down and to simply issue a simple clearance through the area to an aircraft he was having problems with.

d) Atlanta Tower and IFR Room

Flight information about Atlanta Airport is to be found in publications under the name of The William B. Hartsfield Atlanta Airport. The basic Atlanta Airport configuration consists of two parallel runways separated by 4,400 ft (Fig. C2). This centerline separation is not enough to allow independent IFR operations. A modified or stagger approach is followed under IFR conditions. Arrival aircraft are vectored in with four nautical miles in trail separation. Aircraft for the parallel approach are also vectored in with four nautical miles in trail separation 2 nmi from the aircraft on the adjacent final approach. When one of the aircraft is a heavy jet and wake turbulence requirements dictate 5 nmi spacing, the trail separation is increased 1 nmi to 5 nmi. The staggered aircraft on the adjacent final approach is unaffected as its lateral spacing is greater than the 2,500 ft wake turbulence requirement.

Lester Shipp, the Atlanta Tower Chief, was interviewed for his comments on the dual lane runway due to be completed in December of this year. A third parallel runway is being added 1,050 ft outside of the south runway 9R/27L. A parallel taxiway between the 1,050 ft spaced runways is also being added. Mr. Shipp stated that he expected to land aircraft on 9L and 9R (new runway) and depart 9C (old 9R runway). Complete flexibility would be maintained such that under VFR conditions, aircraft could depart or land on any of the three parallels. Under IFR conditions, operations to 9R (new runway) and 9L would be independent due to the 5,450 ft runway separations.

Atlanta's traffic of 1,300-1,400 operations per day ranks third for commercial airports behind O'Hare and Los Angeles and ahead of JFK's 900-1,000 operations per day. The mix of aircraft includes approximately 10 percent general aviation and 5 percent heavy jet operations. Atlanta is a hub airport where short haul or feeder aircraft operate. About 80 percent of the traffic is attributed to two airline operations, Eastern and Delta, Southern airways operates short haul piston (Martin 404) and turbo-prop (Japanese YS-11) aircraft as a feeder airline. The busiest one hour period to date this year totaled 107 operations. One of the busiest hours we observed and recorded (see Number of Operations table) handled 100 operations. This included 60 air carrier arrivals and 8 general aviation arrivals plus 32 departures.

Number of Operations - Atlanta Airport 8/23/72

Hour	Air Carrier		General Aviation		Air Taxi		Total		Total All
	I	0	I	0	I	0	I	0	
4-5	24	33	11	10	3	0	38	43	81
5-6	60	23	8	9	0	0	68	32	100
6-7	18	51	2	5	1	1	22	57	79

I - Inbound
0 - Outbound

The dual lane runway simulation results compare favorably to these figures. The capacity limit found from the simulation for two independent runways handling IFR spaced traffic is 120 operations per hour which is broken down as 60 operations per runway per hour. Half (30) of these operations are arrivals which translates into a steady stream of arrivals 4 nmi in trail separation to each runway with a departure after each arrival.

The interesting thing to note (Figure C-3) is the alternate peaking of arrivals in the first hour and then the departures in the subsequent hour. This is explained by the fact that Atlanta is a hub airport where the feeder aircraft arrive, are turned around within an hour, and become departures the next hour. A graph plotting the number of Atlanta Airport arrivals and departures versus time of day for 8/1/72 shows this alternate peaking clearly (see Atlanta Airport Traffic plot. Figure C-3.)

Atlanta Tower does not have an ASDE. In IFR weather, when they cannot see aircraft on the outboard runway, the nearest portion of which is over a mile from the tower, the controllers must rely on the pilots to notify them when they have landed or departed and when they are clear of the runway. This mode of operation reduces capacity as the controllers are operating blind, relying on the pilots to indicate their relative positions on the airport.

During peak period operations, arrivals and departures were handled concurrently on each of the two parallel runways. The arrival longtitudinal spacing was a nominal 4 nmi. The local controller attempted to alternate a departure after each arrival. This was accomplished through the controller's knowledge of the various aircraft performances and the information shown on the ARTS I tower BRITE display. The BRITE display showed the arrival aircraft on final approach, their relative positions, their tracks, their ground speeds and altitudes, and their identification. The controllers know the type of aircraft and hence, its performance characteristics from the flight identification number. When in doubt, they call the pilot and ask the type of aircraft. Armed with this information, the local controller decides whether to put a departure into position and hold after an arrival goes over the threshold. This decision is based on the controller's judgment of how long both the arrival and the departure he is putting in position will occupy the runway. The next arrival spaced four miles (80-120 sec) from the runway must be accommodated. The local controller solicits the pilots help by advising them of his intention to get a departure out between the two arrivals. The first arrival pilot is then expected to clear the runway as soon as possible. The departure pilot is expected to expedite his takeoff as soon as he is cleared for takeoff. The second arrival pilot, knowing the situation and seeing the runway activity, may be requested to slow his speed and, in some cases, to make an "S" maneuver on final to allow the departure to liftoff before the arrival sets down on the runway. The four mile spacing using the existing conventional exits is the minimum which will permit a departure to be taken off between two arrivals. With the consistent use of high speed exits, the spacing could possibly be reduced to 3 nmi with departures alternated to effect a potential 30 percent increase in the overall capacity of a single runway.

9 20 September 1972

A missed approach occurred because a pilot refused to land behind a departing B747 jumbo jet due to the turbulence effects of jet blast. The controller had the jumbo jet just starting its takeoff roll when the four engine DC8 was 3 nmi from the threshold. The pilot stated he could not land that close to a departing heavy jet due to the turbulence generated. The controller vectored him around to intercept the extended runway centerline about 9 nmi out where the DC8 again began its approach.

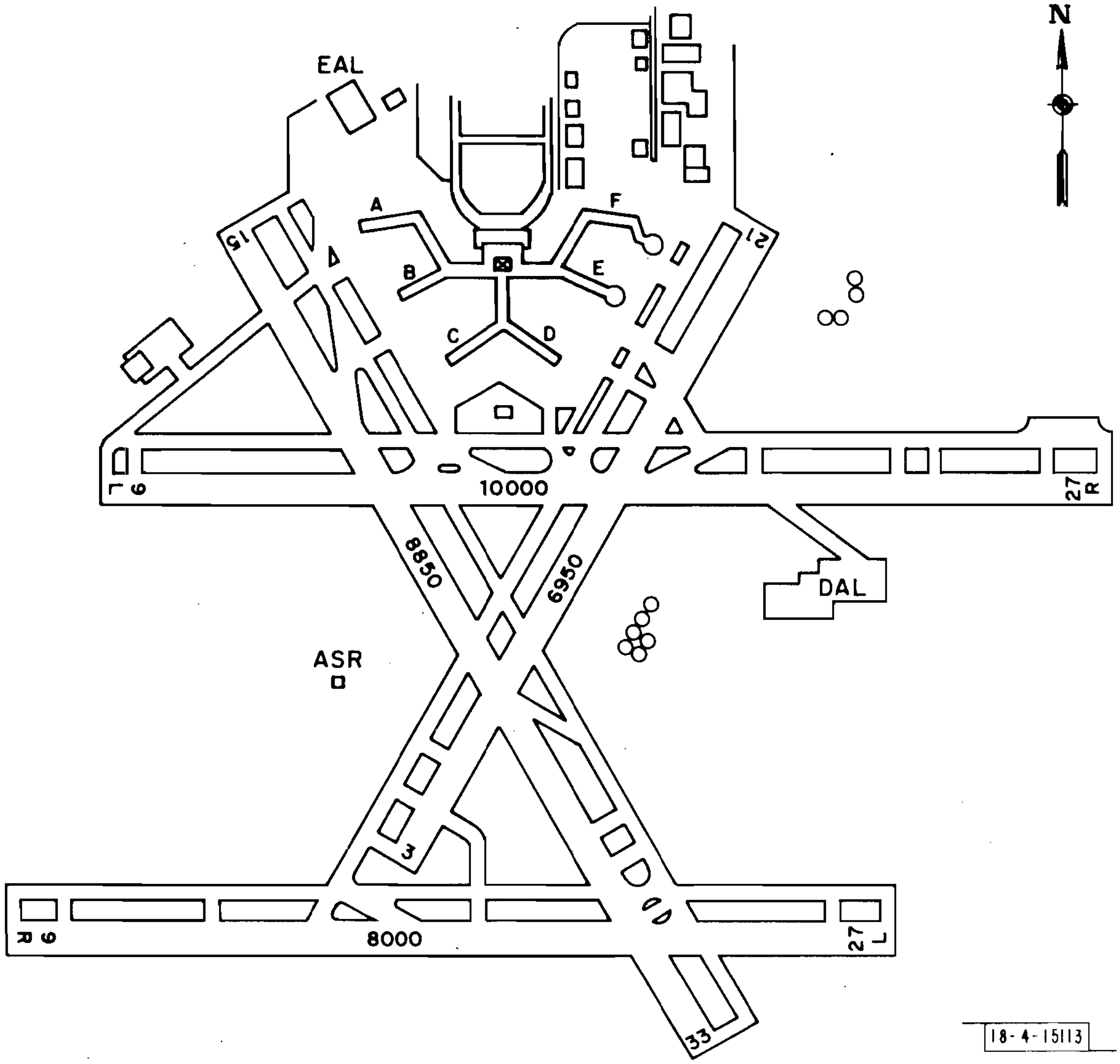


Figure C-2. Atlanta Airport.

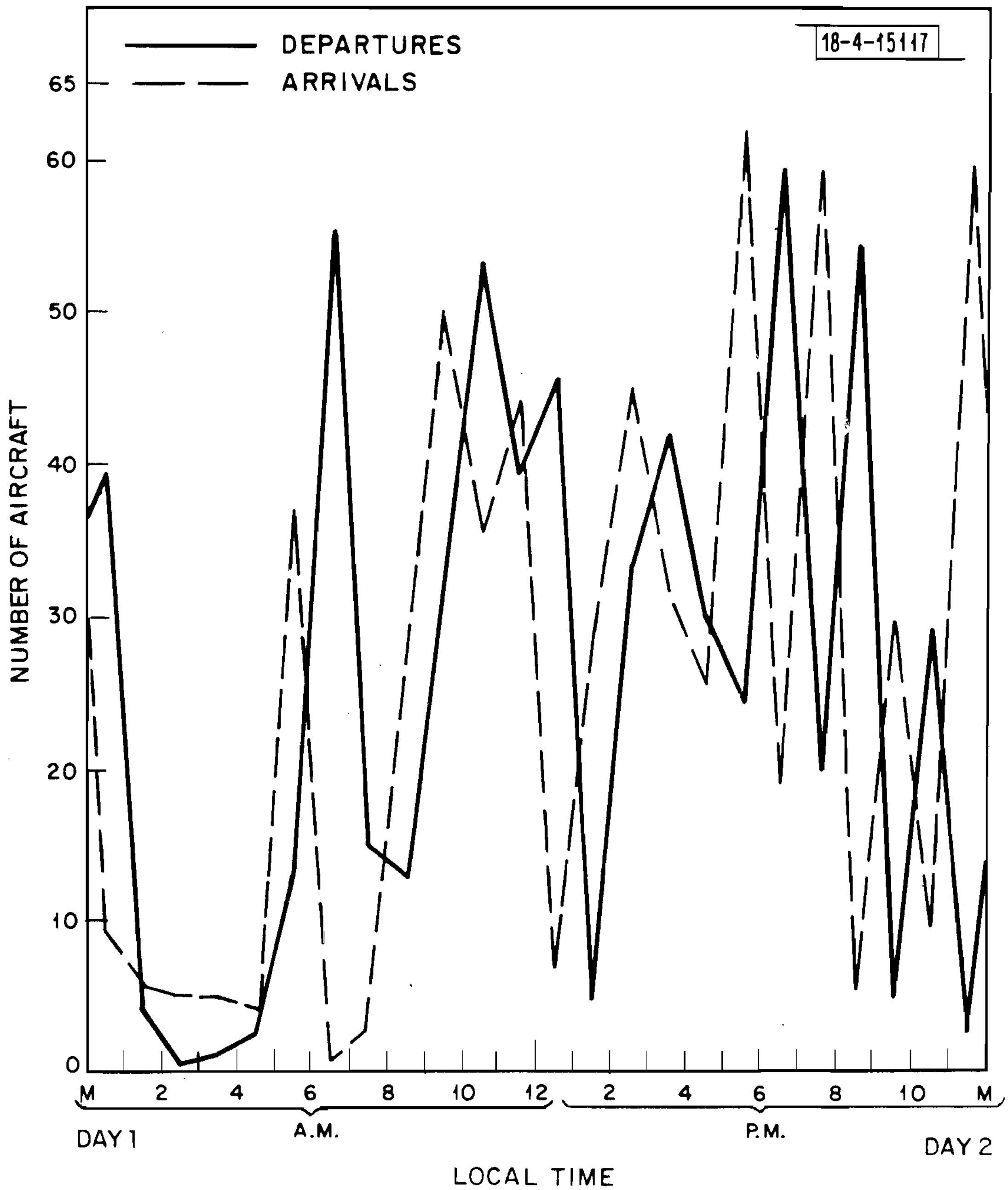


Figure C-3. Atlanta Airport Traffic.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

19 October 1972

Subject: Trip Report to Los Angeles (LAX) and San Francisco International (SFO) Airports (October 1972.)

The purpose of the trip was to discuss with ATC specialists familiar with dual lane systems areas of dual lane runway operation brought into question during the course of our simulation investigation. Both LAX and SFO have dual lane runway configurations (Figure C4, & C5). The trip also provided observation of crew work loads and discussions of ATC problems with pilots. The dual lane runway was one area of discussion.

The American Airline flight flew from Logan to SFO via LGA, CLE, DAX, CVG, DAL, PHX, and OAK. The flight was scheduled for a 10:30 a.m. departure from Logan and an 8:30 p.m. arrival at SFO. Three scheduled crew changes would occur before trip completion. The flight was one hour late in departing due to fog related delays at Logan.

The fog burned off by late morning leaving relatively good visual flying conditions to LGA. En route, the autopilot was demonstrated in VOR tracking mode. An ILS autopilot approach to LGA was executed in order to demonstrate the autopilot's good and bad features in this mode of operation. The good feature is its ability to bring the aircraft down a glide slope to a point about 50 ft over the runway while the bad feature is its abrupt control movement commands to keep the aircraft on the glide slope.

Without fail, the approach on landing at each of the stops was made approximately 10 knots above reference speed as calculated by the flight engineer. At these approach speeds, a relatively large flare distance results when a soft landing is attempted. The relatively short runway at LGA necessitates touchdown near threshold and thus the pilot has small margin when trying to make a soft landing out of one that may be relatively hard. Twice we ended up using the full length of long runways following soft landings in which we floated a relatively long way down the runway.

The approach to PHX was made in a heavy rain shower resulting in reduced visibility approach. The onboard weather radar was used to pick our way between strong returns en route to PHX. The pilot flew the ILS approach manually.

The landing at OAK provided an opportunity to observe a runway exit at a relatively high speed at night. The high speed exit was assisted by runway centerline and exit entry centerline lights. This lighting arrangement is much less confusing than the runway edge and taxiway lighting system in usage elsewhere.

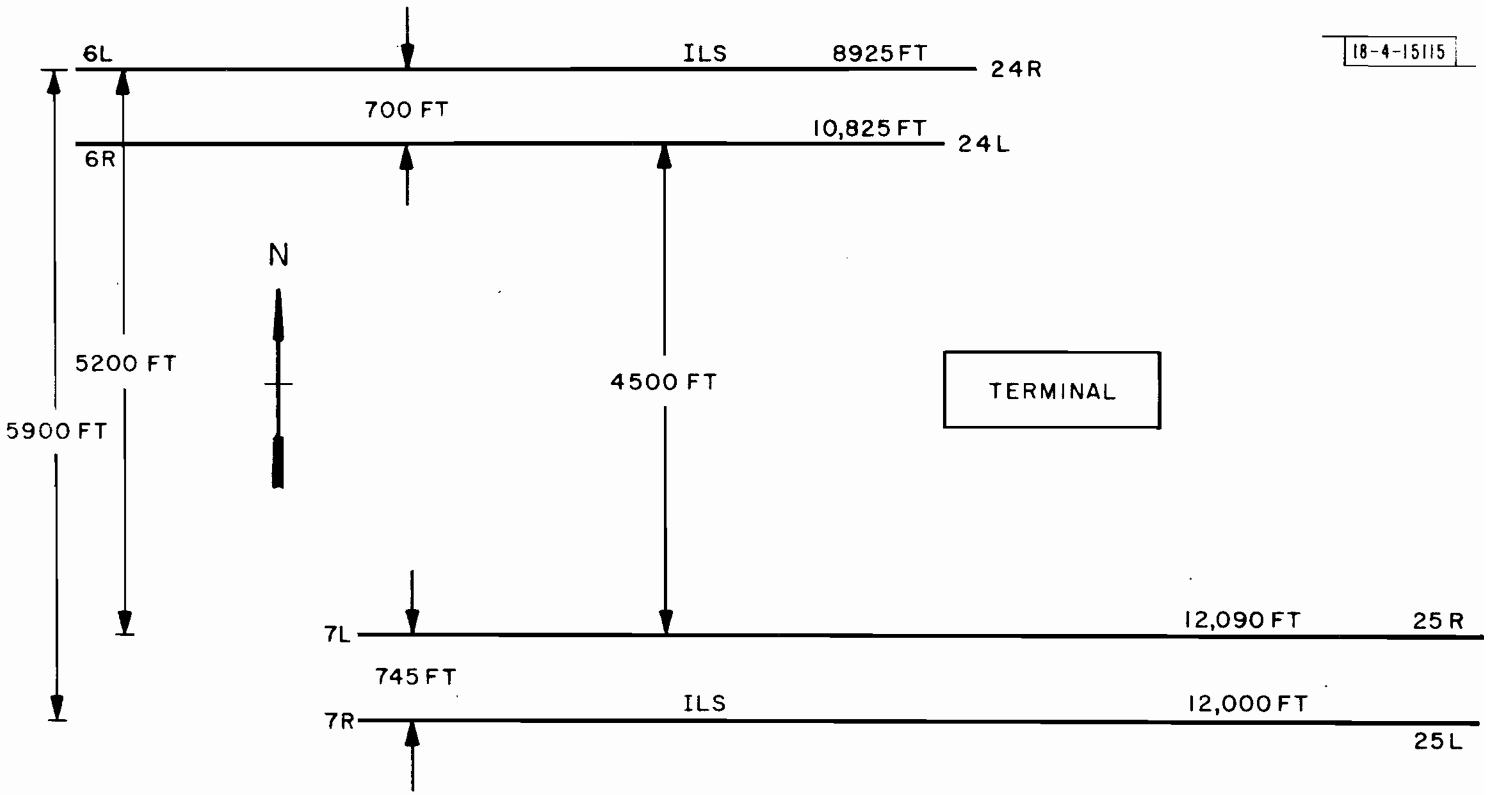


Figure C-4. Los Angeles International Airport.

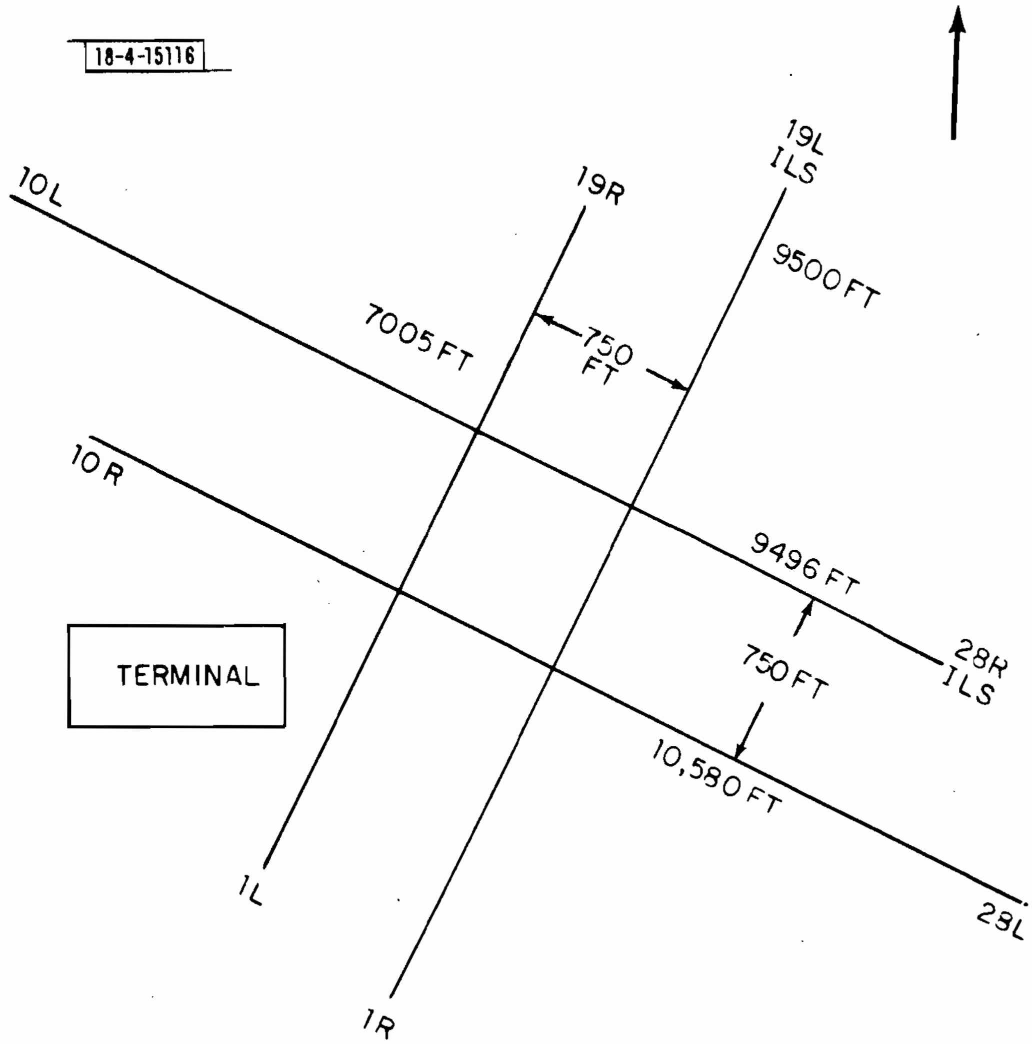


Figure C-5. San Francisco International Airport.

The final leg of the flight, the ten miles from OAK to SFO, required nine communication frequency changes before completion. SFO was using simultaneous visual approaches to 28L and 28R. The approach controller communicates to the pilot the traffic and when sighting of traffic is confirmed by the pilot, he is cleared for a simultaneous visual approach. The pilot is concerned about the preceeding traffic on either of the two runways spaced 750 ft apart. If either is a jumbo type airplane, his concern is to maintain extra separation and to remain above its glideslope. Side by side approaches are routine and do not unduely concern pilots as long as the weather is good VFR. They do, however, feel that simultaneous approaches are sometimes authorized by controllers in less than desirable weather conditions.

The return trip was flown on a DC10. It was hoped that RNAV routing would be used during this non-stop flight from LAX to Boston. However, for economic reasons, American Airlines had removed such navigational equipment after an initial experimental period.

The DC10 modern features include the autopilot--flight director, and the digital readout of all relevant aircraft data. Crew work load is decreased through the automated monitoring and control of functions previously performed manually. En route climb and cruise in the DC10 is performed at a mach number of 0.85. The crew suggested that the DC10's performance at much different speeds is noticeably reduced. Cruise routing at FL370 along the J airways was close to a great circle route; the small dog leg sections were cut by direct clearances to succeeding VOR's.

A potential en route conflict was resolved by an altitude change as volunteered by the conflicting traffic. The initial solution suggested by the controller was a 10 knot speed reduction by the DC10. No other traffic problems or weather problems were encountered over the remainder of the flight.

The landing in a DC10 is made with the radar altimeter as the primary vertical position reference. The pilot used the co-pilot's countdown and judged the landing from the rate at which countdown proceeds. Discussions with SFO and LAX controllers and watch supervisors centered on dual lane operations. The following set of questions directed the discussions.

1. a. In general, which is the preferred mode of runway operation?
   b. What problem is associated with each mode?

2. Under conditions of heavy demand by both arrivals and departures, which aircraft are given ground movement priority? What are the circumstances?

3. a. What level of traffic (mixed or otherwise) can be handled by one controller of a dual lane runway? What are the problem areas?
   b. Single runway?

4. Do you feel each runway of a dual lane system could be handled by a separate controller? Do any outstanding problem areas exist which come to mind?

5. a. Can two aircraft be held between the parallel runways at the threshold end?
   b. At points of crossing?

6. Is there any problem in clearing an approach to land (one that is within 3 nmi) immediately behind a heavy departure? We have witnessed a go around on one occasion which was due to this.

7. Is there any advantage associated with staggered runways?

8. Are there any operational restrictions associated with simultaneous heavy arrivals or departures under good visibility conditions?

9. How and who sets up the simultaneous approaches witnessed at SFO.

10. How are heavy jet operations identified? Is there, in fact, any effort made to identify each type of aircraft.

In addition to the above questions, the following questions were asked at LAX.

11. What runway configuration and traffic routing is used at LAX under conditions of reduced visibility?

The above questions received the following answers respectively:

1. Due to decreased ground control work load and coordination, it is best to arrive on the outer runway. As it is, two ground controllers are currently used (both at SFO and LAX) to route traffic and they are kept quite busy during the peak periods of the day. In addition, pilots do not like having an aircraft hold between runways, especially if it is one of the jumbo types. For the situation of an inner arrival and an outer departure holding between thresholds, the controller must concern himself with the arrival crossing threshold and thrust management of the aircraft holding. He must communicate to both the arrival and the holding aircraft the situation at hand and remind the holding aircraft to remain at idle power until the arrival has passed his position.

2. Generally, the arrival will be held short of a runway to keep a certain rhythm going in the departure stream. The arrival can usually be crossed behind a departure and thus traffic does not build up between runways. Occasionally, two aircraft are held in line when departure traffic is heavy. However, they generally like to get jumbos out from between runways and thus tend to let these types cross without a hold.

3. a. About 90 operations per hour is the point at which the average controller (at SFO) starts to reach a limit. Voice communication starts to become the limiting factor in the traffic load handled. Pilot performance also starts to enter in when operations start to reach this number.

A controller cannot work heavy traffic for any great length of time over a long period. For one day, maybe six hours of extra heavy traffic can be handled, but if this demand was to continue day after day, it would not take long before he could handle but one or two hours. When taken off a demanding position even with the current traffic loads the tendency is to go to a position at which one can relax some.

b. Some time ago, the general feeling was that 30 operations/hour would be doing good on a one runway operation. Due to runway problems, this single runway mode was used occasionally. At one time, the demand was such that they handled 43 operations/hour during the first hour and 55 operations/hour in the second hour. This was close to the limit.

4. LAX personnel felt that certain installations could (cited Denver as an example) but felt that there would be no way for this to happen at LAX. The reasons given were based on traffic patterns in use and loss of flexibility which one did not care to give up.

Some at SFO felt that separate controllers could handle each runway and some didn't. The ones that did, gave Oakland as an example as where it works and grant that it is a special case (air carrier runway is separate and a good distance from each of the two parallel general aviation runways). They emphasized that it required supervisors and control personnel with the right attitude to make it work. SFO has tried it in a number of different ways:

a. Separate controllers for each pair of parallels; an arrival controller on one and a departure controller on the other. Coordination problems existed at crossings and broke up the smooth flow of departures. Concern was noticeably increased and at a constant high level.

b. Separate controllers on each runway of one dual lane system. The operations were mixed on both. Each controller handled arrivals and departures to his runway. A big problem was the lack of the big picture. Each aircraft, in general, wants to know what type of aircraft is on final ahead of him to either of the adjacent runways. One controller must lean over to ask the other his traffic and relate this to the pilot. This increases communication by the controller to an unacceptable level. This desire to know who is in front on either of the runways was also learned first hand during the flight from OAK to SFO. Another problem area is the runway crossing which must be coordinated between controllers.

c. Separate arrival controllers to each of the parallel arrival runways (28L and 28R) at SFO and a departure controller on the crossing runways (1L and 1R). The operation is too tight to delegate responsibility to several people. It did not come close to working.

The operation which works best in a dual lane set up is to have one controller with a coordination position to assist him. How a pair of parallel runways is used changes depending on demand make up. Operations (arrivals and departures) always appear to happen in bunches. How the traffic picutre is evolving can be kept clearly in mind by the coordination man and he can determine which should be given priority.

5. a. Pilots are mostly against this. At times, it has caused go arounds when a controller does elect to put one between closely spaced runways.

b. Two are occasionally held between the runways spaced 750 ft apart.

6. No problems like this had come up at either SFO or LAX.

7. No advantages could be identified. In fact, there is the disadvantage that an aircraft can be approaching below the glide path of a jumbo type landing on the parallel non-stagger runway.

8. There is no special handling used by the controllers. On occasion, two 747's do make side-by-side approaches (at SFO; jumbos are segregated to one runway at LAX) to the 750 ft separated runways. Depending on the pilots, they may or may not fall behind a proceeding aircraft to avoid a side-by-side situation.

9. Approach control sets up the simultaneous approaches.

10. Flight strips carry the aircraft's type designation. Tracon puts in the required separation behind jumbo jets and on handoff to tower they notify the local controller of the type designation.

11. They try to run the parallels in the same manner as during VFR as long as possible. Wind may cause them to turn the airport around and land toward the East.

APPENDIX D

REAL TIME DATA SUMMARY

A summary of the 52 real time data runs which were performed using four different ATC controllers is given in Figure D-1. The VFR and IFR experiments were performed to investigate: single lane, centerline spacing, arrival/departure preference, parallel taxiway, threshold stagger, and mixed dual lane operations. Various interarrival spacings mainly employing high speed exits (60 mi/h) were explored. The figure gives the mean and standard deviation for arrival and departure: runway occupancy times, delay times, taxi times, and total time in the system. Scatter diagrams depicting each aircraft serviced by the various dual lane configurations were furnished by the TX-2 computer for each of the variables listed above. These diagrams were analyzed to establish trends in the data. A complete time history of the events for each aircraft operating within the dual lane system is available upon completion of each of the computer runs. The number of arrivals and departures per hour along with the missed approaches executed over a one-hour period are listed.

-4-15543

Legend (each cell): Number Arrivals | Number departures per hour / Total number aircraft per hour — e.g. "24 36 / 60".
Mean Arrival time (sec) | Mean departure time (sec) / Arrival time standard deviation (sec) | Departure time standard deviation (sec) — e.g. "42 62 / 10 14".

DUAL LANE RUNWAY REAL TIME EXPERIMENTS	VFR or IFR	Centerline Spacing (ft)	Runway A-Arrivals D-Departures Inner	Outer	Nominal Arrival Spacing (nmi)	Exit Velocity (mi/h)	No. Arrivals Per Hour / No.* Departures Per Hour / Total I	II	III	IV	Missed Approaches I	II	III	IV
SINGLE LANE	V	-	A/D	-	5	60	24 36 / 60	22 44 / 66	- / -	-	2	4	-	
	V	-	A/D	-	4	60	22 36 / 58	24 42 / 66	26 34 / 60		8	6	4	
	V	-	A/D	-	3	60	36 24 / 60	30 28 / 58	36 18 / 54		2	8	2	
	V	-	A/D	-	4	40	22 36 / 58	20 42 / 62	28 24 / 52		8	10	2	
	V	-	A/D	-	3	40	28 30 / 58	26 30 / 56	36 18 / 54		10	12	2	
CENTERLINE SPACING AND ARRIVAL/DEPARTURE PREFERENCE	V	700	A	D	3	60	36 50 / 86	38 60 / 98			2	0		
	V	700	D	A	3	60	38 46 / 84	38 44 / 82			0	0		
	V	1000	A	D	3	60	38 54 / 92	38 58 / 96	38 62 / 100	38 54 / 92	0	0	0	0
	I	1000	A	D	3	60	36 36 / 72				2			
	V	1000	D	A	3	60	38 42 / 80	36 58 / 94	38 52 / 90	38 46 / 84	0	2	0	0
	I	1000	D	A	3	60	36 28 / 64		38 38 / 76	38 28 / 66	2		0	0
	I	1000	A	D	5	60		26 26 / 52				0		
	I	1000	D	A	5	60	26 38 / 64	26 24 / 50			0	0		
	V	2499	A	D	3	60	38 64 / 102	38 60 / 98			0	0		
	V	2499	D	A	3	60	38 56 / 94	38 48 / 86			0	0		
CENTER PARALLEL TAXIWAY 1	V	1250	D	A	3	60	38 50 / 88	38 44 / 82			0	0		
2	V	1250	D	A	3	60	38 58 / 96	38 58 / 96			0	0		
2	I	1250	D	A	3	60	38 34 / 72				0			
STAGGERED THRESHOLD I	V	1000	D	A	3	60	38 56 / 94	38 50 / 88			0	0		
II	V	1000	D	A	3	60	38 62 / 100	38 64 / 102			0	0		
MIXED DUAL LANE OPERATION	V	1000	A/D	A/D	5	60		36 68 / 104				6		
	V	1000	A/D	A/D	4	60	48 58 / 106		50 62 / 112		6	4	4	
	V	2499	A/D	A/D	5	60	42 56 / 98				2			
	V	2500	A/D	A/D	5	60	48 58 / 106	48 58 / 106			4	4		

Experiment	VFR or IFR	Centerline Spacing (ft)	Inner	Outer	Runway Occupancy Time (sec) Arrivals Mean Std. Dev. / Departures I	II	III	IV	Delay Time (sec) Arrivals Mean Std. Dev. / Departures I	II	III	IV
SINGLE LANE	V	-	A/D	-	42 62 / 10 14	47 65 / 12 20	-		0 236 / 0 56	0 122 / 0 67	- - / - -	
	V	-	A/D	-	50 59 / 11 18	47 51 / 10 18	47 59 / 11 14		0 205 / 0 94	0 82 / 0 40	0 217 / 0 70	
	V	-	A/D	-	48 51 / 10 18	47 59 / 5 18	50 63 / 14 12		0 560 / 0 171	0 156 / 0 65	0 962 / 0 106	
	V	-	A/D	-	52 57 / 7 15	61 51 / 12 20	56 64 / 9 17		0 269 / 0 96	0 93 / 0 67	0 484 / 0 122	
	V	-	A/D	-	56 50 / 5 14	56 67 / 10 16	54 51 / 11 12		0 118 / 0 122	0 436 / 0 118	0 647 / 0 119	
CENTERLINE SPACING AND ARRIVAL/DEPARTURE PREFERENCE	V	700	A	D	54 69 / 28 27	50 52 / 27 25			0 255 / 0 86	0 103 / 0 39		
	V	700	D	A	47 89 / 12 84	44 75 / 9 22			21 283 / 32 62	9 212 / 14 69		
	V	1000	A	D	48 56 / 11 25	47 45 / 13 21	42 65 / 9 18	44 86 / 9 33	0 219 / 0 66	0 47 / 0 27	0 57 / 0 39	0 210 / 0 51
	I	1000	A	D	48 95 / 9 29				0 155 / 0 80			
	V	1000	D	A	46 87 / 8 30	45 67 / 9 24	43 76 / 7 26	43 92 / 8 34	27 377 / 37 164	11 126 / 16 41	13 272 / 23 76	13 340 / 14 73
	I	1000	D	A	48 111 / 13 35		44 91 / 7 32	42 133 / 6 51	40 374 / 50 169		6 525 / 12 175	52 565 / 40 116
	I	1000	A	D		41 132 / 8 43				0 546 / 0 175		
	I	1000	D	A	42 101 / 7 23	45 150 / 14 52			41 120 / 30 45	48 684 / 20 188		
	V	2499	A	D	45 61 / 11 20	44 63 / 8 26			5 116 / 17 46	0 170 / 0 38		
	V	2499	D	A	45 69 / 10 19	44 82 / 11 37			77 155 / 77 98	8 277 / 19 85		
CENTER PARALLEL TAXIWAY 1	V	1250	D	A	45 86 / 12 29	44 85 / 7 34			25 346 / 31 69	13 378 / 22 181		
2	V	1250	D	A	46 77 / 9 25	44 74 / 9 32			26 115 / 27 79	11 161 / 34 48		
2	I	1250	D	A	44 105 / 11 42				52 435 / 41 182			
STAGGERED THRESHOLD I	V	1000	D	A	43 73 / 7 18	45 82 / 11 32			56 184 / 60 42	3 142 / 10 59		
II	V	1000	D	A	43 69 / 6 20	45 58 / 11 24			0 81 / 0 38	0 43 / 0 35		
MIXED DUAL LANE OPERATION	V	1000	A/D	A/D		46 74 / 9 31				40 344 / 67 98		
	V	1000	A/D	A/D	51 63 / 34 25		44 62 / 10 19		45 354 / 67 146		- 394 / - 154	
	V	2499	A/D	A/D	42 65 / 10 23				70 389 / 113 130			
	V	2500	A/D	A/D	44 67 / 8 17	42 62 / 9 19			28 456 / 53 139	28 398 / 59 116		

Experiment	VFR or IFR	Centerline Spacing (ft)	Inner	Outer	Taxi Time (sec) Arrivals Mean Std. Dev. / Departures I	II	III	IV	Total System Time (sec) Arrivals Mean Std. Dev. / Departures I	II	III	IV
SINGLE LANE	V	-	A/D	-	32 397 / 8 67	34 253 / 6 73	- - / - -		212 512 / 44 67	- 372 / - 70	- -	
	V	-	A/D	-	29 368 / 10 98	35 192 / 7 42	34 370 / 9 79		214 476 / 32 107	209 297 / 30 43	213 481 / 28 86	
	V	-	A/D	-	31 744 / 10 177	32 296 / 9 64	31 1181 / 10 103		212 847 / 29 177	211 406 / 30 69	212 1290 / 28 86	
	V	-	A/D	-	30 443 / 7 99	31 229 / 7 67	30 658 / 8 131		215 552 / 21 104	224 334 / 35 70	216 773 / 27 139	
	V	-	A/D	-	28 266 / 7 132	27 590 / 8 125	29 844 / 6 167		216 370 / 28 132	217 709 / 22 128	217 943 / 30 166	
CENTERLINE SPACING AND ARRIVAL/DEPARTURE PREFERENCE	V	700	A	D	39 447 / 31 90	36 282 / 14 41			223 567 / 49 101	215 385 / 36 49		
	V	700	D	A	96 442 / 44 70	83 389 / 31 95			276 580 / 49 82	256 516 / 34 96		
	V	1000	A	D	31 387 / 8 69	34 179 / 12 41	32 225 / 8 59	32 434 / 7 53	212 494 / 34 73	211 275 / 37 35	199 341 / 15 58	199 571 / 17 53
	I	1000	A	D	33 250 / 9 81				210 397 / 37 97			
	V	1000	D	A	110 487 / 59 168	102 249 / 34 62	104 545 / 36 114	113 593 / 19 130	285 624 / 62 178	276 367 / 31 57	268 672 / 41 110	279 734 / 23 125
	I	1000	D	A	140 455 / 51 198		102 760 / 22 212	154 715 / 49 150	318 617 / 63 199		269 899 / 23 208	319 901 / 54 146
	I	1000	A	D		32 643 / 6 213				196 825 / 22 204		
	I	1000	D	A	147 175 / 31 49	147 731 / 26 242			- 392 / - 59	315 931 / 30 202		
	V	2499	A	D	48 326 / 54 61	31 413 / 7 44			223 438 / 62 70	- 529 / - 42		
	V	2499	D	A	211 313 / 88 116	137 455 / 35 117			385 434 / 85 123	312 588 / 43 114		
CENTER PARALLEL TAXIWAY 1	V	1250	D	A	101 540 / 37 114	86 545 / 26 213			279 678 / 44 106	- 681 / - 198		
2	V	1250	D	A	154 253 / 65 102	137 320 / 56 50			329 380 / 74 111	- 445 / - 54		
2	I	1250	D	A	248 589 / 61 233				424 746 / 40 236			
STAGGERED THRESHOLD I	V	1000	D	A	144 375 / 66 54	82 276 / 19 76			- 498 / - 49	256 410 / 24 74		
II	V	1000	D	A	63 219 / 11 54	63 168 / 12 37			- 338 / - 52	237 277 / 37 45		
MIXED DUAL LANE OPERATION	V	1000	A/D	A/D		110 475 / 89 102				291 601 / 92 110		
	V	1000	A/D	A/D	115 497 / 92 165		141 552 / 55 183		301 611 / 97 173		307 665 / 64 178	
	V	2499	A/D	A/D	152 596 / 157 147				327 711 / 161 150			
	V	2500	A/D	A/D	109 665 / 97 176	111 609 / 96 146			288 782 / 108 176	288 723 / 104 145		

1 Normal Crossing
2 Threshold Crossing

*VFR 60 sec mean departure gate schedule.
IFR 90 sec mean departure gate schedule.

Fig. D-1. Real Time Data Summary Chart

APPENDIX E

SIMULATION DATA OUTPUT PACKAGE

Included is a typical time graph (Figure E-1) representative of the output available on each simulation run. The total output for each run is composed of a playback file, a raw data file, scatter diagrams of performance parameters measuring runway occupancy time, taxi time, total time in the system, and delay time for both arrivals and departures. The mean value and standard deviation of each parameter is also part of the output. Graphs illustrating the instantaneous counts on departures and arrivals proceding through the dual lane system were made at three minute intervals. These data were further broken down to reflect runway assignment.

During the course of the fast time simulation effort, the time graphs of the delay data were observed to fall into various groupings indicating certian trends. Thus, we find it instructive to provide a general trend designator to further the comparative evaluation of the dual lane configurations. Figure E-2 contains representative illustrations of the various trends observed. Each time point represents one aircraft and corresponds to the time it was introduced into the simulated airport system. The trends described by the five designators, S, S_1, O, I. and N are described briefly.

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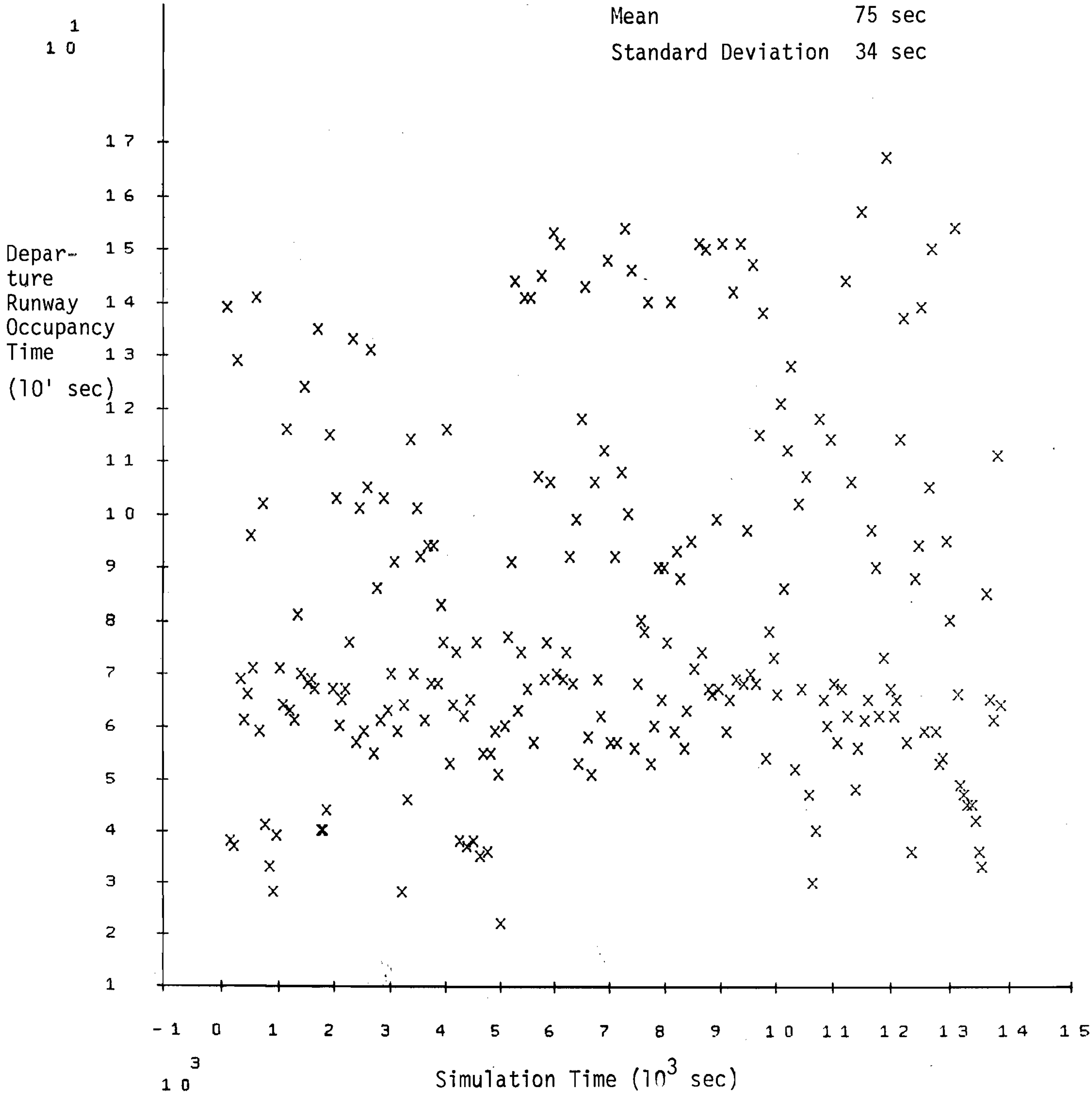

Figure E-1. Runway Occupancy of Departures on Runway 1.

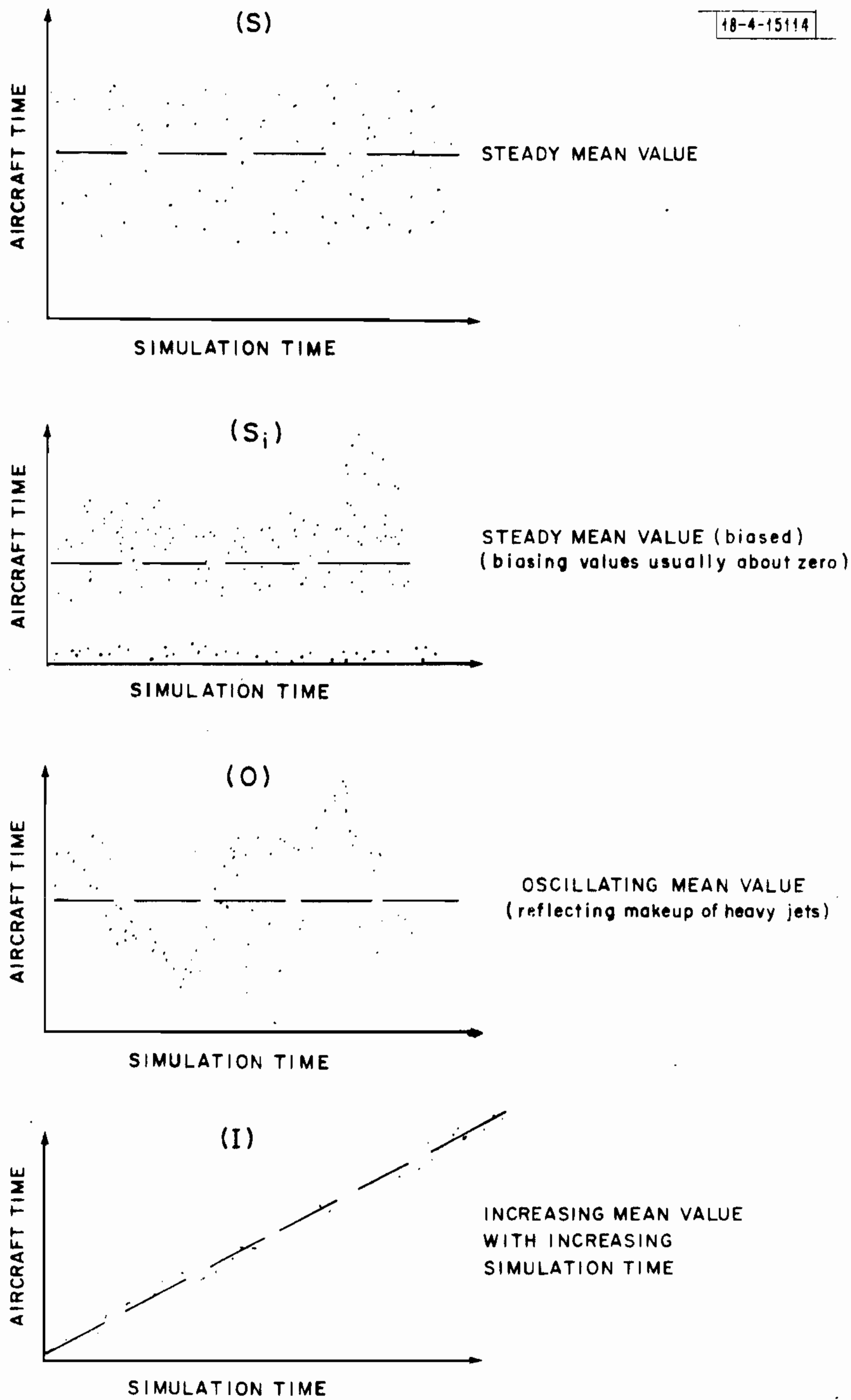

Figure E-2. Time Graph Trends Observed in TX-2 Output.

S - The mean value is independent of the duration of the simulation and is approximately constant over any interval of time considered. The individual values relating to single aircraft obtained for this output data are scattered about the mean and do not tend to any particular value. It is independent of any particular segment looked at provided the interval is large enough. Over a small interval, this mean can vary appreciably and is caused by the application of the two minute rule associated with jumbo jets. The delays to those departures immediately behind the jumbo traffic are increased. This additional delay decays off to zero as successive aircraft are considered.

S_1 - As above, except that the individual data points do show some tendency to take on a particular bias value. In reference to delay times, this bias value tends to be zero. The runway occupancy time data for arrivals tends to be biased toward values corresponding to the time it takes the average aircraft to reach each of the three high speed exits provided.

O - The mean value varies reflecting gross variations in the average heavy jet population and over any time interval, the mean can vary appreciably and is caused by the application of the two minute rule associated with heavy jets and the exact mix structure. The delays to departures immediately behind the heavy traffic are increased. This additional delay decays off to zero as successive aircraft are considered unless, of course, the system is again perturbed by the presence of a second heavy jet.

I - The mean value increases steadily as the simulation progresses.

N - No delay is experienced.

Travel distance on each dual lane configuration was standardized wherever possible in order that taxi time and total time in the system became additional valid performance indicators. Departure taxiway paths to the runways measured identical lengths apart from the segment linking the runway thresholds. Centerline separation between runways dictated the length of this segment. With the exception of the parallel taxiway configuration, arrival travel distance was similarly affected only by the centerline spacing.