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21
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# ANALYTICAL AND SIMULATION STUDIES OF SEVERAL RADAR-VECTORING PROCEDURES IN THE WASHINGTON, D. C., TERMINAL AREA

By

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## TABLE OF CONTENTS



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## SYMBOLS USED IN REPORT

| | |
|---|---|
| A/C | Aircraft |
| ADW RDO | Andrews Radio |
| ADW | Andrews Air Force Base |
| ATC | Air Traffic Control |
| BOF | Bolling Air Force Base |
| FIL | The Franklin Institute Laboratories for Research and Development |
| MM | Middle Marker (on charts only) |
| MTV | Mount Vernon |
| NSF | Anacostia Naval Air Station |
| OM | Outer marker |
| RVD | Riverdale |
| SRI | Springfield |
| TDEC | Technical Development and Evaluation Center of the Civil Aeronautics Administration |
| T O | Take-off |
| WNA | Washington National Airport |
| W O | Wave-off |
| P I S | Piscataway |

| | |
|---|---|
| $G_0$ | Any point in the terminal area and 20 flying miles (statute) from the outer marker |
| $G_1$ | Outer marker, 5 3 statute miles from Washington National Airport Runway 36 |
| $G_{N_0}$ | WNA runway No 36 exit 1970 feet from threshold |
| $G_{N_1}$ | WNA runway No 36 exit 2260 feet from threshold |
| $G_{N_2}$ | WNA runway No 36 exit 3900 feet from threshold |
| $G_{N_3}$ | WNA runway No 36 exit 5000 feet from threshold |
| $G_{N_4}$ | WNA runway No 36 exit 6650 feet from threshold |
| $G_{N_P}$ | Proposed WNA runway No 36 exit 3400 feet from threshold |
| F | Fast aircraft such as DC-6, Constellation, Stratocruiser |
| M | Medium aircraft such as DC-4, Martin, Convair |
| S | Slow aircraft such as DC-3, C-46, Twin Beech |
| VS | Very slow aircraft such as Widgeon, Cessna, Navion |
| s-T | Space-time |
| $V_A$ | Average approach ground speed in mph |
| $V_{TD}$ | Ground speed at touchdown in mph |
| $t_0$ | Minimum average time separation between successive arrivals at the outer marker |
| $\epsilon$ | Loading, or average arrival rate divided by average theoretical acceptance rate |
| $\sigma$ | Standard deviation, the measure of dispersion of a variable so that 68 per cent of the variations lie within $\pm$ one $\sigma$ from the average |

# ANALYTICAL AND SIMULATION STUDIES OF SEVERAL RADAR-VECTORING PROCEDURES IN THE WASHINGTON, D C , TERMINAL AREA

## FOREWORD

The Air Navigation Development Board (ANDB) was established by the Departments of Defense and Commerce in 1948 to carry out a unified development program aimed at meeting the stated operational requirements of the common military/civil air navigation and traffic control system This project, sponsored and financed by the ANDB, is a part of that program The ANDB is located within the administrative framework of the Civil Aeronautics Administration for housekeeping purposes only Persons desiring to communicate with ANDB should address the Executive Secretary, Air Navigation Development Board, Civil Aeronautics Administration, W-9, Washington 25, D C

## SUMMARY

This report summarizes the comparative evaluations of three promising traffic control configurations for the Washington National Airport terminal area, which is approximately 40 miles in diameter This 40-mile diameter represents the expected surveillance-radar coverage Each of the three configurations, identified as phases 2, 6, and 7, uses within this 40-mile area two essentially independent control sectors (East and West), twin stacks to feed the approach gate, and radar-vectoring techniques The three phases differed only in layout of facilities, in twin stacks, in clearance limits, and in procedures A further description of these factors is given in Appendix A

These three phases were analyzed comparatively by the use of three simulative screening techniques ideal, graphical space-time (s-T), and dynamic simulation using the TDEC dynamic simulator Agreement in trends and in the order of magnitude of delays between these three methods for the three phases are shown to be very good The correlation coefficient between the average delays per 15-minute period of the graphical and of the dynamic simulation is 0 98 This means that $(0\ 98)^2$, or 96 per cent of the variation in delays between one 15-minute period and the next on the TDEC dynamic simulator can be conclusively predicted from the graphical-simulation results A statistical analysis of the aircraft delays shows, however, that there is little significant difference between phases This analysis included the powerful analysis-of-variance test The simple and straightforward radar-vectoring procedures permit the random, high traffic rates which are employed to be handled in the terminal area with a relatively low work load and with a minimum of delays, and little flow control en route had to be exercised If the radars are reliable, any reasonable twin-stack system of radar-vectoring control can handle peak instrument-flight-rule (IFR) arrival and departure traffic on a single properly designed runway at a rate of about 50 operations per hour Use of intersecting runways would increase this rate to about 60 to 70 operations per hour

Three random-traffic samples of 2 1/2 to 3 hours in duration were used They are based on a recent traffic survey at Washington National Airport and are considered to be typical of anticipated peak arrival and departure traffic, including aircraft type distributions and rates anticipated for three to five years hence

On the basis of available IFR data on the random spreads of the approach speeds and on the runway performances of different aircraft, it was evident that the use of a standard three-mile radar separation and the use of the present layout of Washington National Airport instrument runway No 36 without some degree of speed control would result in an intolerably high percentage of wave-offs Accordingly, analytical means were used to determine the optimum combination of outer-marker separations and runway-exit modifications which would be consistent with the maximum acceptance rate and traffic This was done for a 1 per cent maximum probability of wave-offs on either the glide slope or the runway The results showed that without some small degree of speed control, nonuniform (called optimum) minimum separations averaging about four miles for each sequence of arrivals at the outer marker would be desirable Use of these optimum separations produces a theoretical maximum acceptance rate of about 36 arrivals per hour, an average interval of 1 minute 40 seconds between successive approaches The results showed further the urgent need for a high-speed turnoff located at 3400 feet from the threshold to runway 36 to serve landing traffic in either direction

# INTRODUCTION

Previous work[1,2] by The Franklin Institute Laboratories (FIL) and by the Technical Development and Evaluation Center of the Civil Aeronautics Administration[3,4] has demonstrated that simulation is a safe, accessible, and inexpensive tool for conducting experiments in air traffic control, which experiments involve controlled flights of groups of aircraft and also involve the operation of existing or of proposed equipment An appreciation of the scale of the simulation tests conducted in the evaluations described herein may be gleaned from the fact that, in just the 54 runs on the dynamic simulator at TDEC, over 5000 simulated flights were flown through the various systems Like any other tool, however, simulation is what its user makes it Properly applied, it can be a powerful aid to the skillful worker Improperly applied, it can result in meaningless or even erroneous conclusions It has been shown that analytical and simplified simulation techniques such as the FIL graphical methods (see Appendix C of this report) are extremely useful and relatively inexpensive means of evaluating and screening on a preliminary basis the many situations, samples, procedures, ranges of variables, and other factors to be investigated However, since it is believed that future air traffic control systems will include human beings monitored by machines or vice versa, it is important that means be employed for realistically representing the rather complex response of the human to his particular situation The response and the duties of the human in air traffic control are mainly functional, attempts to represent him statistically, as a time delay with a normal distribution of delay times about a measured average, for example, are usually weak and unrealistic

The TDEC dynamic simulator[5] is more expensive and more complex to operate than the graphical simulator However, it has a distinct advantage over the graphical simulator in that the human element is introduced into both the air and the ground portions of the simulated system This is done by putting human beings into the system (controllers for controllers and console operators for pilots), giving them proper operational stimuli and equipment, furnishing them with a realistic form of operational tools for their response, and conducting the experiments as they might actually occur on a one-to-one time basis It must be realized, however, that a small number of human beings used in a limited number of situations and experiments does not completely represent the population from which the eventual system operators will be drawn Consequently, care must be taken in properly designing the experiments

The Air Navigation Development Board established at TDEC Project 6 7, the simulation and evaluation of air traffic control Because of the importance of properly designing, conducting, and analyzing the simulation experiments it was realized that there were many traffic samples, situations, procedures, and rules requiring a preliminary screening, a relatively expensive and time-consuming investigation if performed with the TDEC dynamic simulator Under Contract No C13ca-412 with TDEC, the FIL performed a co-ordinated program in which the capabilities of both simulators, the FIL graphical and the TDEC dynamic, were integrated into a logical concerted effort The work performed under this contract was concerned with preliminary evaluations of proposed radar-vectoring techniques at Washington National Airport (WNA), with analysis of the optimum rules for maximum traffic flow and for airport acceptance rates, and with design of the associated experiments This is allied with the general evaluation requirements of ANDB Project 6 7, which specifies a simulation program for determining

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[1] Samuel M Berkowitz, "Analysis of a Fixed-Block Terminal Area Air Traffic Control System," Franklin Institute Laboratories Report No F-2164-2, May 1951

[2] Samuel M Berkowitz and Ruth R Doering, "Comparative Analysis of Terminal Area Air Traffic Control Systems — A Fixed Block System and a Moving Block System," Franklin Institute Laboratories Report No F-2256, October 1951

[3] Richard E Baker, Arthur L Grant, and Tirey K Vickers, "Development of a Dynamic Air Traffic Control Simulator," CAA Technical Development Report No 191, October 1953

[4] C M Anderson and T K Vickers, "Application of Simulation Techniques in the Study of Terminal-Area Traffic Control Problems," CAA Technical Development Report No 192 November, 1953

[5] Baker, Grant, and Vickers, op cit

"1 1 1 The factors which influence the acceptance rate of a terminal area

1 1 2 The quantitative effect of each of these factors and different combinations of these factors on the acceptance rate 'Factors' in the above means both the physical environment (aircraft characteristics, airport characteristics, demand rates, etc ) and operating environment "

The more specific problems (mainly operational on control functions, work loads, controller aids, and so forth) of ANDB Project 6 7 are described in a related Technical Development report[6]

The preliminary investigations of the working period of this contract have demonstrated that this co-ordinated effort and, as such, the order of the screening steps yield a proper perspective to the logical use of simulation in the evaluation of air traffic control Furthermore, the work conducted to date is considered to be primarily of a preliminary-calibration nature and to have laid in it a firm foundation for further and more conclusive study of many other promising fundamental systems and procedures, both en route and terminal-area

## OBJECTIVES

As a part of one of a series of related studies initiated by the ANDB to provide basic information for planning a Common System of Air Navigation and Traffic Control, this investigation was performed under Contract C13ca-412 with TDEC This contract states

"Purpose

The general purpose of this contract is to formulate and perform a co-ordinated program in which the capabilities of the FIL graphical-simulation techniques for analyzing pertinent air traffic control situations are co-ordinated with the corresponding capabilities and experience gained from the TDEC dynamic simulator

The Franklin Institute shall undertake the following three tasks

Task 1

Formulate a detailed program within the broad framework and objectives of the TDEC program for simulation and evaluation of air traffic control (ANDB Project 6 7) for the purpose of evaluating immediate improvements that can be made in airport acceptance rates, at an airport such as Washington National, through the use of new control techniques and methodology applied to existing traffic control aids

Task 2

Perform the simulative analyses as recommended by Task 1, utilizing the graphical technique and including as inputs several combinations of acceptance rates, arrival rates and distributions The results will be used as the yardstick for determining the ultimate that could be achieved under ideal (ultimate) conditions and will also be used as the basis for recommending the follow-up investigations to be conducted as the next step on the TDEC dynamic simulator

Task 3

Provide engineering services and recommendations to TDEC on ANDB Project 6 7 concerning

a Establishment of the simulation experiments, especially as to theoretical and statistical problems

[6] Ibid

"b Measurements (and conduct) during the simulation experiments
c Analysis and interpretation of the results
d Improvements in the operational performance and capabilities of the dynamic simulator '

## ROLE AND INTERPRETATION OF ANALYSIS, SIMULATION, AND STATISTICS

In air traffic control and navigation, it takes about 5 to 10 years from the conception of an idea or of a piece of equipment until its final adoption and operational use How best to shorten and bridge this gap and how best to integrate new ideas and equipment without their usual inherent disadvantages into the rapidly changing requirements warrant more than casual study and top-level committee decisions The manner in which ultimate goals in complex systems can be approached most efficiently can be derived from so-called "systems analysis" in which simulators and properly applied statistical and mathematical techniques are useful aids

To yield the proper perspective while always considering the purposes intended, a systems study should include the following steps

1 Description of system inputs (traffic samples, rates, population, and such factors)
2 Preliminary design
3 Component analysis and operational data
4 System analysis
5 System simulation
6 Analysis of results and modifications toward an optimum system by repeating steps 2 through 5 if found desirable

Step 1, the statement of system inputs is worth more thought than most designers and planners assign to it Certainly the results are no more valid than the input Too often a system finally selected operates best only for inputs which rarely or perhaps never occur in practice Several questions arise, therefore

1 What are the relative merits of simulating air-traffic problems with traffic samples adjusted to conform to a normal cycle of peak traffic rates, as compared with the method of running through several separate problems at various constant average arrival rates (as is done in delay theory)?
2 If a number of peak-traffic samples are chosen by using different parts of a random-number table for each day, how many samples would be required and how would the results of the analysis vary for different days? In other words, are one-, two-, or three-day peak random samples so small statistically that they cause a large variation in day-to-day results?
3 If the one-day peak sample is the preferable input, is it possible to pick a particular random day out of a large number of days and to use only this day to study the effects of varying the significant parameters of the systems? If so, what is the most desirable means for picking the standard sample day? Furthermore, what precautions should be taken if this method is adopted?

Unless reasonable answers to the above questions can be found, the validity of the simulation results will be doubtful Traffic-sample inputs should be representative enough, large enough, and numerous enough statistically but should be consistent with the conditions and with the situations to be evaluated in order to ensure that the results will not be influenced by the samples chosen Thus, there will be obtained reasonably reliable measures of the parameters being evaluated and not merely the variable characteristics of the traffic samples chosen

There are many peculiar circumstances and interrelated variables in this business of air traffic control In view of the preliminary state of the art of simulation of air traffic, the experiences of others in somewhat parallel analyses of telephone traffic problems were examined, and the best answers to the foregoing questions appeared to be

1 "nless the response to a transient of a traffic-control system under study is known beforehand, it will be better to conduct first a number of runs using the one-day peak-cycle inputs Further, it is not safe to assume that the response from one step will settle down before the next step is applied, particularly during the more important periods near the traffic peak Under these conditions, it would be risky to attempt to draw conclusions from the steady-state response to several average arrival rates

2 A one-day peak sample picked at random probably is not large enough to obtain results completely suitable for the design of a traffic-control system or for a conclusive evaluation of various rules or other systems It appears that it will be necessary to run through a number of daily peaks with other randomly selected distributions of entry intervals, sequences of intervals, and sequences of aircraft types It will then be possible to assess the significance that can be attached to the results for any single day

3 However, for rough qualitative comparisons of traffic-control systems or for first rough approximations of the effects of varying certain parameters, it is probably satisfactory to pick a particular typical day and to use it as a constant input For the actual design of a system, it was felt desirable to run through a number of days and to get at least a rough idea of the distribution of the important evaluation characteristics as they vary from day to day

This corresponds to the method the Bell Telephone Laboratories uses in simulating and in validating telephone traffic problems In their case, they are not nearly so much concerned with the transient nature of the daily cycle, even for a short period of peak loading, the transient response settles down rather quickly, and the system assumes statistically a new steady state However, they do not consider it satisfactory to obtain one figure for average delays or for any other pertinent characteristic at a certain loading by extending the time interval so that the result becomes independent of further extension Rather, they take a number of short intervals and derive the distribution of average delays for intervals of the chosen duration The design for the system is based on some arbitrary point on this distribution curve

It was felt that, for any one step in the daily cycle of air traffic, the day-to-day samples for that step would correspond to the short intervals which are studied by the Bell Telephone Laboratories Thus, it was recommended that a number of transient peak periods sufficient to obtain a fairly smooth distribution of the day-to-day results be analyzed For rough comparative studies of other systems, it will probably be satisfactory to pick a particular day's peak from these results and to use it as a constant input Later, if it is desired to study the effect of design refinements or of different rules of a particular traffic-control system, it would be preferable to use enough different days to show again the distribution of each of the important characteristics

Accordingly, three typical random-traffic samples, representative of anticipated peak 3-hour traffic at Washington National Airport several years hence, were selected In order to approach the variability in actual practice of the pilots and controllers in complex situations and in order to average out these variations for comparative purposes, each of the three traffic samples was run three times in the TDEC dynamic simulator The experiments were controlled to insure that the inputs were identical in the repeat runs Controllers and airplane-console operators were rotated from phase to phase and from run to run in order to eliminate learning and thus to be more representative

Step 2, preliminary design, requires little discussion except to state that experienced working-level personnel should have an important role in the setting up of the many problems This step will glean from their knowledge rational procedures and reasonably valid simplifying assumptions

Step 3, component analysis and operational data, logically comes next The tools here are mainly mathematical Rough comparative measures of performance, the output, are then obtained by re-examining the initial preliminary simplifying assumptions, the input Too often in the course of analysis, sufficient operational data are lacking While it is very worthwhile to draw on the knowledge of others, an experimental or operational research program may be required

Step 4, system analysis, follows Here analytical and statistical means or simple analogous solutions can be used to eliminate obviously poor system setups and to indicate regions in which further investigation would be desirable

With all this done, the system must be tried and the degree of correlation between reality and the analytical and analogous-solution techniques established This is necessary in establishing a calibration factor which will be useful in extending and extrapolating the results to other situations and in gaining a further insight into rational methods for integrating new ideas and systems into the over-all scheme of things to come These firm foundations are essential for further and more conclusive studies of the many proposed systems, procedures, and facilities in air traffic control

Step 5 For reasons of safety and economy, no complex operating system should be built, tried, and discarded Here is where simulation is advantageous The system and all its attendant variables can be tried at a large reduction in time and cost over other methods On the other hand, there is no final substitute for the construction and testing of the actual system That system which is finally selected from the many others is tested under conditions as they actually are or as they will occur This is the end result which must be further evaluated to yield the degree of validity of the prior steps to lay the firm foundation for other evaluations

In summary, it can be said that simulation permits the cut-and-try examination of the mathematical representation of a system In the selection of a simulation technique, logical assessment of other means of evaluation should also be considered and should always take into account the purposes intended For some cases which appear to be complex but which are really relatively simple when their fundamentals are studied, analysis and experience can be meaningful and even conclusive When growing complications in the form of nonlinearities, discontinuities, large numbers of interrelated variables, and human beings are somewhere in the system, analytical and statistical techniques can produce only tedious though inexpensive rough approximations It is not intended to imply, however, that analytical and statistical methods serve no useful purpose On the contrary, such methods are extremely useful and sometimes vital in exploring the many situations, conditions, and variables to be studied by simulation, provided their degree of validity and of correlation with reality is known In proportion to the realism of the simulation, the simulator can then further evaluate those items previously screened It can also provide the data for determining the interrelated contributions of the many variables, including the human

With reference to comparative validity and realism, it is often necessary to put real human beings into the system being simulated Several levels of realism must be distinguished For those systems in which decision-making is the human's function, it may be satisfactory to represent his response by a time delay However, it is illogical for the analyst to anticipate what a controller might do in particular complex situations that require snap judgement On the other hand, the response of a pilot to a voiced instruction involves some delay In this case, then, a normal distribution of delay times about a measured average may be adequate However, if the pilots' and controllers' responses are functional as they usually are, the problem becomes difficult, and attempts to represent them statistically are usually weak and unrealistic

This requires putting the human into the simulated system, giving him the proper operational stimuli, and furnishing him with operational controls for his response Unfortunately, a few human beings in a limited number of situations and experiments do not represent completely the population from which the eventual system operators will be drawn or the conditions which may be encountered Here is a problem in the logical design of the experiments and in the interpretation of the results for both the human engineer and the statistician

The preliminary joint FIL-TDEC simulation program follows this proper order of design and screening steps The results indicate that a firm foundation and perspective are being laid for more extensive simulation work on some of the more fundamental aspects of air traffic control, as described in the following sections of this report

## CONDITIONS STUDIED AND METHODS OF EVALUATION

### Construction of Traffic Samples

Three random traffic samples of arrival and departure aircraft were employed in the analysis The characteristics of these samples were based on a recent survey of traffic at Washington National Airport,[7] with the traffic arbitrarily increased by 15 per cent to account for increased aircraft operations with no jets included for a few years hence Peak periods of three typical hours were selected so that two dynamic-simulator runs could be completed in an 8-hour working day The typical 3-hour peak period included sufficient aircraft to make the comparative results conclusive Each 3-hour-period sample consisted of 73 arrival and 68 departure aircraft

The characteristics for the three random samples of arrival aircraft are given in Tables I, II, and III

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[7]Samuel M Berkowitz and Shirley D Gahuse, "Preliminary Survey of Traffic at Washington National Airport," Franklin Institute Laboratories Working Paper No 1 of Project 2269-1 (Unpublished), October 1951

TABLE I

DISTRIBUTION OF ARRIVALS ACCORDING TO SPEED CLASS AND ENTRY ROUTE

| Entry Route (See Fig 1) | | Number of Aircraft and Speed Type | | | |
|---|---|---|---|---|---|
| | | Slow (S) | Medium (M) | Fast (F) | Total |
| A | (Lisbon to Riverdale) | 6 | 6 | 5 | 17 |
| B | (Beltsville to Riverdale) | 5 | 7 | 4 | 16 |
| C | (Dover to Andrews) | 5 | 2 | 2 | 9 |
| E | (Doncaster to Mt Vernon) | 5 | 4 | 2 | 11 |
| F | (Elkins to Springfield) | 3 | 2 | 1 | 6 |
| G | (Arcola to Springfield) | 7 | 3 | 4 | 14 |
| TOTALS | | 31 | 24 | 18 | 73 |

TABLE II

DISTRIBUTION OF ARRIVALS
ACCORDING TO SPEED CLASS AND TYPE OF OPERATION

| Type of Operation | Number of Aircraft and Speed Type | | | |
|---|---|---|---|---|
| | S | M | F | Total |
| Scheduled | 14 | 18 | 15 | 47 |
| Civil-Itinerant | 7 | 4 | 1 | 12 |
| Military | 10 | 2 | 2 | 14 |
| TOTALS | 31 | 24 | 18 | 73 |

TABLE III

ARRIVAL RATES PER HALF-HOUR PERIOD

| Half-Hour Period | Total Number of Arrivals |
|---|---|
| 0 to 1/2 | 7 |
| 1/2 to 1 | 11 |
| 1 to 1 1/2 | 15 |
| 1 1/2 to 2 | 20 |
| 2 to 2 1/2 | 12 |
| 2 1/2 to 3 | 8 |
| TOTAL FOR 3 HOURS | 73* |

*Including 14 military

A listing of the three random samples of arrival aircraft is given in Appendix B, showing for each aircraft the time of arrival at $G_0$ (any point of entry to the terminalarea and 20 flying miles from the outer marker), the speed class (Slow = S, Medium = M, or Fast = F), the route on which it enters, and whether or not it is a military aircraft (hereafter described as "type") DC-3, C-46, and twin-Beech classes are considered to be slow aircraft, DC-4, Martin, and Convair aircraft are mediums, fast include Constellations, DC-6's, and Stratocruisers

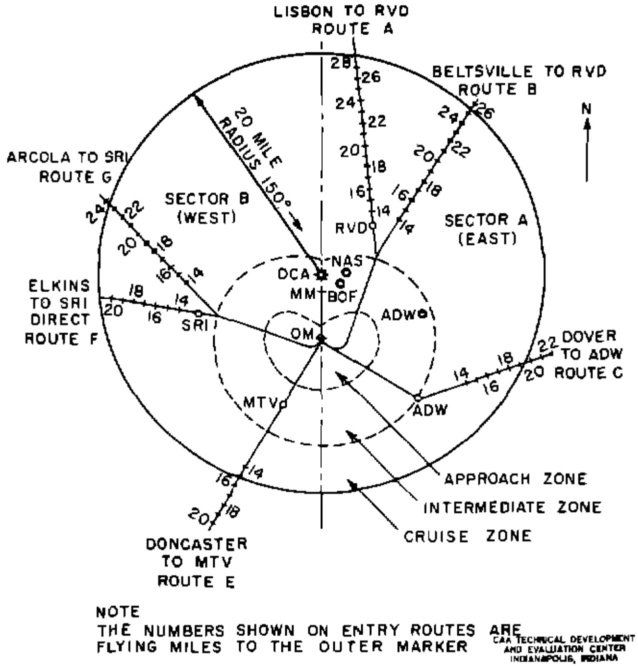


Fig 1 Terminal Area, Entry Airways, and Routes to Outer Marker for Washington National Airport

On the basis of the half-hourly arrival rates shown in Table III, the random times of arrival at $G_0$ were determined by use of the Poisson formula, with exponential distribution and random sequencing of the time intervals This method has been well validated in surveys conducted in the past by FIL and other investigators [8,9,10,11] For large numbers of aircraft, the probability $P_n(m)$ that 1, 2, 3, or n aircraft will appear in a given interval is given by the Poisson formula:

$$P_n(m) = \frac{(m^n e^{-m})}{n!} , \qquad (1)$$

Where

m = average number of aircraft arriving during the interval,
n = any number from zero to infinity,
P = probability,
e = exponential

If over a sufficiently long period of time the average rate of arrivals is m, the probability of one arriving between time t and t + dt is mdt The probability of no aircraft arriving in a time t is $e^{-mt}$ If an aircraft arrives at time t = 0, the probability of the next one arriving between time t and t + dt is

$$P = me^{-mt}dt, \qquad (2)$$

[8] Ibid

[9] Ibid

[10] E G Bowen and T Pearcey, "Delays in the Flow of Air Traffic," Journal of the Royal Aeronautical Society, April 1948

[11] D E. Olshevsky, "Airport Time Utilization Equipment, Phase 1 — Systems Engineering Study," Cornell Aeronautical Laboratories Report No JA-627-P-1, March 1950

Where

P = the probability of an interval of t seconds ( t = 10, 30, 50, seconds) between aircraft arriving at $G_0$,

dt = the differential of time,

m = the number of aircraft arriving during the period, divided by the length of the period (here the length of the period is 1800 seconds, 30 minutes)

Equation (2) produces a plot of the frequency of occurrence of intervals between successive arrivals, and the plot is exponential in form This means the most probable intervals are small ones, and there is a tendency for random arrivals to appear in pairs or in groups more often than expected

Once the probabilities of the possible intervals were computed from Equation (2), the random sequence in which these intervals occur was determined by using Tippetts' Tables of Random Numbers [12] When this sequence was determined, the time an aircraft arrived at $G_0$ was found

The other characteristics of speed class, route, and type were assigned by again using Tippetts' Tables of Random Numbers, the probability of occurrence here being merely the percentage of cases having the desired characteristics These percentages were based on the data given in Tables I and II The speed class and the route were assigned first, in one operation, then the type was assigned in three steps, first to the slow aircraft, then to the medium aircraft, and finally to the fast aircraft

A listing of the three samples of departing aircraft is also given in Appendix B The over-all characteristics of these samples, also based on the traffic survey made at the Washington National Airport and arbitrarily increased by 15 per cent, are shown in Table IV

TABLE IV

DEPARTURE RATES PER HALF-HOUR PERIOD

| Period of Operation (hour) | Total Number of Departures |
|---|---|
| 0 to 1/2 | 5 (including 1 military) |
| 1/2 to 1 | 8 (including 1 military) |
| 1 to 1 1/2 | 11 (including 2 military) |
| 1 1/2 to 2 | 14 (including 3 military) |
| 2 to 2 1/2 | 17 (including 4 military) |
| 2 1/2 to 3 | 13 (including 2 military) |
| 3 to 3 1/2 | 8 (including 2 military) |

The extra half-hour period of departures is given to unload the system, since arrival aircraft of the third hour might well be delayed into the fourth hour The intervals between departing aircraft were drawn from the Poisson distribution, using the data given in Table IV, in the same manner as were the intervals between arrival aircraft The type was assigned randomly according to the percentage of military and nonmilitary types shown

After a number of trial runs were made at TDEC, it was decided to eliminate the first half hour It was found that the elapsed time for running three-hour samples (including briefing, setup, and maintenance time) was such that it was extremely difficult to get in two runs per 8-hour work day without loss of continuity, and further, it was too fatiguing for the simulator controllers and the aircraft-console operators It was also found that, since there are so few aircraft in this period, the dropping of the first half hour had little or no effect on the over-all

[12] See the introduction to these tables for detailed instructions for their use

results Accordingly, the traffic samples finally employed dropped the first half hour and started with arrival No 8 and departure No 6, a total 2 1/2-hour traffic sample which included 66 arrivals and 63 departures, of which 53 are arrivals for Washington National Airport and 51 are departures from it The other operations were in or out of Bolling or Anacostia fields

Conditions Investigated and Traffic Rules

A Conditions Investigated

Initially, it was planned to investigate the following twelve combinations of traffic samples, wind conditions, and arrival and departure traffic

For Zero Wind

1 Sample No 1, arrivals only
2 Sample No 2, arrivals only
3 Sample No 3, arrivals only
4 Sample No 1, arrivals and departures
5 Sample No 2, arrivals and departures
6 Sample No 3, arrivals and departures

For 20-MPH Headwind.

7 Sample No 1, arrivals only
8 Sample No 2, arrivals only
9 Sample No 3, arrivals only
10 Sample No 1, arrivals and departures
11 Sample No 2, arrivals and departures
12 Sample No 3, arrivals and departures

Because of delays in the construction of the apparatus needed to simulate a 20-mph headwind and because of other higher priority work, the analysis of the 20-mph-headwind conditions on the TDEC simulator was postponed beyond the term of this contract The results of the ideal analysis for all conditions are included later in this report

For the purposes of the ideal analysis of the zero-wind conditions, it is immaterial what routes, patterns, or rules other than the rule requiring specified outer-marker separations aircraft follow For the 20-mph-headwind conditons, in addition to the outer-marker separations it is only necessary to know what are the shortest paths on each of the routes in order to determine the length of time it takes to traverse these shortest routes [13]

In the graphical-simulation analysis, however, it is necessary to know the routes and patterns the aircraft follow and to have and follow rules which apply all the way from the 20-mile point of entry to the terminal area $G_0$ to the outer marker $G_1$ In this report, three traffic-control configurations for the Washington National Airport terminal area are considered These configurations, referred to as Phases 2, 6, and 7, are described in Appendix A, and the particular rules which apply to each phase are included there

Graphically, each of the three phases for the Washington National Airport was analyzed for each of the six afore-mentioned zero-wind conditions, making eighteen combinations Each of these eighteen combinations was run three times (54 runs) with the TDEC simulator, and the controllers and the console operators were rotated from run to run in order to eliminate some of the variations due to the human factors

B Traffic Assumptions and Rules

These rules are based on available data applicable to these purposes and on certain arbitrary simplifying assumptions necessary for the meaningful comparative evaluations The average true air speeds for the distance $G_0$ to the runway and assumed for the three aircraft speed classes are listed in Table V

TABLE V

AVERAGE TRUE AIR SPEEDS

| Aircraft Speed Type | Average True Air Speeds | | | |
|---|---|---|---|---|
| | 10-Mile Cruising Zone (mph) | 5-Mile Intermediate Zone (mph) | 5-Mile Approach Zone (mph) | 5 3-Mile Final Approach (mph) |
| F | 290 | 220 | 150 | 150 |
| M | 240 | 190 | 140 | 140 |
| S | 180 | 150 | 120 | 120 |

Based on the average speeds shown in Table V, the undelayed times to traverse the 20 flying miles from $G_0$ to $G_1$ in zero wind are for fast, 326 seconds, for medium, 373 seconds, and for slow, 470 seconds

[13] For a description of the ideal analysis, see Appendix C of this report

With a 20-mph headwind on runway 36 and with the assumption that there is no drift due to the cross-wind components, the undelayed times to traverse the 20 flying miles from $G_0$ to $G_1$ (outer marker) along each of the six designated Washington National Airport entry routes, Fig 1, are presented in Table VI

All military operations will land or take off from either Bolling Field or Anacostia Naval Air Station It is presumed, therefore, that military arrivals will be controlled the same as Washington National Airport commercial arrivals until they pass the outer marker. They will then depart from the final-approach path and will no longer be accounted for Military departures are ignored

TABLE VI

UNDELAYED FLYING TIMES FROM $G_0$ TO $G_1$

| Aircraft Type | Route A (seconds) | Route B (seconds) | Route C (seconds) | Route E (seconds) | Route F (seconds) | Route G (seconds) |
|---|---|---|---|---|---|---|
| F | 306 | 308 | 336 | 356 | 326 | 319 |
| M | 346 | 346 | 384 | 411 | 374 | 364 |
| S | 427 | 427 | 485 | 531 | 471 | 454 |

The minimum outer-marker separations finally are prescribed and yield the maximum theoretical acceptance rate for a minimum probability of wave-offs on the glide path (no more than 1 per cent due to any traffic rules and no pilot errors as such) These are listed later in Table XVIII and are hereinafter referred to as optimum separations at the outer marker The discussion of the derivation of these separations and the considerations leading to their a acceptance are contained in a later section of this report

All operations are for Washington National Airport instrument runway 36

An arrival delay is defined as any additional time required to traverse the 20 flying miles from $G_0$ to $G_1$ in conforming to the outer-marker separations or to any other rules specified

Traffic Rules, Single Runway

A In Zero Wind

1 For a Washington National Airport take-off followed by a Washington National Airport landing an average of 30 seconds is assumed for the time taken by a departure of any type to (a) proceed from its ground checkout point at 100 feet from the live runway, if the ground pre-take-off check is completed, (b) reach the runway, (c) line up, (d) stop, (e) rev up, and (f) barely start rolling at the release of its brakes This 30 seconds is called "line-up time "

The next landing aircraft should be no closer than approximately 3 3/4 miles from the threshold of the runway (that is, no more than approximately 1 1/2 miles past the outer marker) at the time the preceding take-off aircraft just starts its 30-second line-up This will ensure that in the worst possible case the next landing aircraft will be no closer than 2 1/2 miles from the runway at the time the take-off aircraft just starts its take-off roll (This conclusion is based on calculations using the average approach speeds with no speed control ) Therefore, the next landing aircraft cannot be past the outer marker by more than the number of seconds indicated in Table VII prior to or after the 30-second line-up

TABLE VII

MINIMUM TIME SEPARATIONS FOR LANDING AIRCRAFT WHEN INTERMIXED WITH TAKE-OFFS UNDER ZERO-WIND CONDITIONS

| Aircraft Type | Time Past Outer Marker Prior to 30-Second Line-Up (seconds) | Time Past Outer Marker at Time Take-Off Aircraft Starts Roll (seconds) |
|---|---|---|
| F | 36 | 66 |
| M | 42 | 72 |
| S | 54 | 84 |

2 For a Washington National Airport take-off followed by a Washington National Airport take-off, a minimum separation of 55 seconds at take-off clearance is required

3 For a Washington National Airport landing followed by a Washington National Airport take-off, the take-off aircraft cannot start its take-off roll until 60 seconds after the preceding landing aircraft has passed the runway threshold

4 For a Washington National Airport take-off followed by a military arrival, the Washington National Airport take-off is clear to go at any time
5 For a Washington National Airport take-off followed by a military take-off, the Washington National Airport take-off is clear to go at any time
6 For any sequences involving military take-offs and military arrivals (that is, a military take-off followed by a military take-off, a military take-off followed by a military arrival, and vice versa), neglect the military take-off

B In a 20-mph Headwind
1 For a Washington National Airport take-off followed by a Washington National Airport landing, the succeeding landing aircraft should be no closer than approximately 3 1/2 miles from the runway threshold at the time the preceding take-off aircraft starts its 30-second line-up Therefore, prior to or after the 30-second line-up time, this succeeding landing aircraft cannot be past the outer marker by more than the number of seconds shown in Table VIII

TABLE VIII

MINIMUM TIME SEPARATIONS FOR LANDING AIRCRAFT WHEN INTERMIXED WITH TAKE-OFFS DURING 20-MPH HEADWIND

| Aircraft Type | Time Past Outer Marker Prior to 30-Second Line-Up (seconds) | Time Past Outer Marker at Time Take-Off Aircraft Starts Roll (seconds) |
|---|---|---|
| F | 49 | 79 |
| M | 53 | 83 |
| S | 71 | 101 |

2 For a Washington National Airport take-off followed by a Washington National Airport take-off, a minimum separation of 60 seconds at take-off clearance is required
3 For a Washington National Airport landing followed by a Washington National Airport take-off, the take-off aircraft cannot start its roll until 65 seconds after the preceding landing aircraft has passed the runway threshold
4 For combinations of Washington National Airport and military arrivals and departures, the procedures are the same as in rules 5 and 6 for Zero Wind

## ANALYSIS OF PROBABLE GLIDE-SLOPE AND RUNWAY WAVE-OFFS

### Method of Analysis

The method used in this analysis generally followed the method outlined by L R Philpott in ANDB Technical Memo No 3[14] and summarized as follows (1) all the aircraft in a sample are divided into successive pairs, (2) the time at which each aircraft reaches various locations along the glide path and on the runway is computed, (3) the determination of whether the second aircraft of each pair is at a safe distance from the first or of whether it should be waved off is made from the computations of step 2 Some modifications, considered to be less general and accordingly more realistic, were made in the Philpott method These modifications include (1) probable aircraft-performance variations gathered from available IFR operational data, (2) the subjugation of certain variables to others, (3) the use of present minimum separations consistent with safety and with typical random traffic samples, (4) actual rather than idealized glide-path and runway configurations for Washington National Airport, shown in Fig 2

Only those elements associated with the type of IFR traffic represented by the three traffic samples, with the physical layout of the glide path and the runway, with the previously described rules, and with probable aircraft performance variations were considered in the analysis No attempt was made to take pilot errors into consideration, nor was any speed control assumed All variations in speed were variations chosen at random from given distributions

The samples used were the 2 1/2-hour Washington National Airport traffic samples which are discussed previously and are given in Appendix B The particular approach-gate (outer marker $G_1$) arrival sequence and arrival times, along with pertinent departure times, were obtained from the data of the ideal analysis

The variables used in this analysis were presumed to follow a normal distribution, and their sequence was selected at random In those cases where the distributions were not symmetrical about the mean, those parts of the distribution on either side of the mean were considered normal All variables were considered to be independent of the particular random

[14] LaVerne R Philpott, "The External Acceptance Rate of an Airport, An Analysis," ANDB Technical Memo No 3, June 22, 1951

selection of the other variables with the exception of the touchdown point, the probability of which was assumed to be a function of the touchdown speed These variables include the error in arrival time at the approach gate, $G_1$, the average approach speed from $G_1$ to the wave-off point, the touchdown speed, the touchdown point, and the deceleration rate on the runway

Data on the glide-slope and runway performance distributions were obtained from published and unpublished CAA stop-watch, photo-recorded, and National Advisory Committee for Aeronautics (NACA) type V-G-H recorder data obtained under a wide variety of IFR conditions at many busy airports, including Washington National Approach-speed data, for instance, were based on V-G-H records of 1170 Martin 2-0-2's, 163 Convair-240's, 131 Douglas DC-6's, and 176 Boeing Stratocruisers Factual data on aircraft-landing and runway performances were obtained from CAA raw data from the stop-watch records of 996 landings of all aircraft types under both IFR and visual-flight-rule (VFR) conditions at Washington National, LaGuardia, Chicago Midway, Willow Run, and Cleveland airports With the use of these data where applicable, the random performance distributions used for the previously mentioned variables are shown in Table IX The first number given is one extreme of the normal distribution cut off at one 0 01 probability level, the second is the mean, and the third number is the other extreme cut off at the other 0 01 probability level (that is, the first and third numbers represent 2 1/2 standard deviations, 2 1/2 $\sigma$, below and above the mean)

TABLE IX

DISTRIBUTION OF PERFORMANCE VARIABLES

| Aircraft Type | Error in Time of Arrival at $G_1$ (seconds) | 0 Wind: Approach Ground Speed $V_A$ (mph) | 0 Wind: Touchdown Ground Speed $V_{TD}$ (mph) | 0 Wind: Touchdown Point (Function of $V_{TD}$) (feet) | 0 Wind: Runway Deceleration Rate (g's) | 20-MPH Headwind: Approach Ground Speed $V_A$ (mph) | 20-MPH Headwind: Touchdown Ground Speed $V_{TD}$ (mph) | 20-MPH Headwind: Touchdown Point (Function of $V_{TD}$) (feet) | 20-MPH Headwind: Runway Deceleration Rate (g's) |
|---|---|---|---|---|---|---|---|---|---|
| S | -5 | 95 | 79 | 500 | 0 040 | 75 | 59 | 500 | 0 040 |
| | 0 | 120 | 82 | 1000 | 0 165 | 100 | 62 | 1000 | 0 165 |
| | 5 | 145 | 88 | 2000 | 0 290 | 125 | 78 | 2000 | 0 290 |
| M | -5 | 110 | 92 | 500 | 0 040 | 90 | 72 | 500 | 0 040 |
| | 0 | 140 | 95 | 1000 | 0 215 | 120 | 75 | 1000 | 0 215 |
| | 5 | 170 | 102 | 2000 | 0 390 | 150 | 82 | 2000 | 0 390 |
| F | -5 | 118 | 98 | 500 | 0 070 | 98 | 78 | 500 | 0 070 |
| | 0 | 150 | 102 | 1000 | 0 235 | 130 | 82 | 1000 | 0 235 |
| | 5 | 182 | 109 | 2000 | 0 400 | 162 | 89 | 2000 | 0 400 |

The average ground speed from Wave-off to touchdown is $\frac{V_A + V_{TD}}{2}$ miles per hour

The Washington National Airport instrument-landing-system (ILS) glide-slope and runway No 36 configuration are shown in Fig 2 The final-approach, landing, runway, and runway-exit sequences are broken down into seven stages

Stage 1 Approach gate $G_1$ to wave-off, variable
Stage 2 Wave-off to touchdown, variable
Stage 3 Touchdown to start of braking and reverse thrust, constant at five seconds for all types and conditions
Stage 4 Start of braking to release of brakes at the particular taxi speeds, variable
Stage 5 Taxi interval on the runway, dependent on runway exit available for the particular exit speed
Stage 6 Process of leaving the runway,
Use constant 8 seconds for exit from $G_{N_0}$ and $G_{N_1}$ for all types

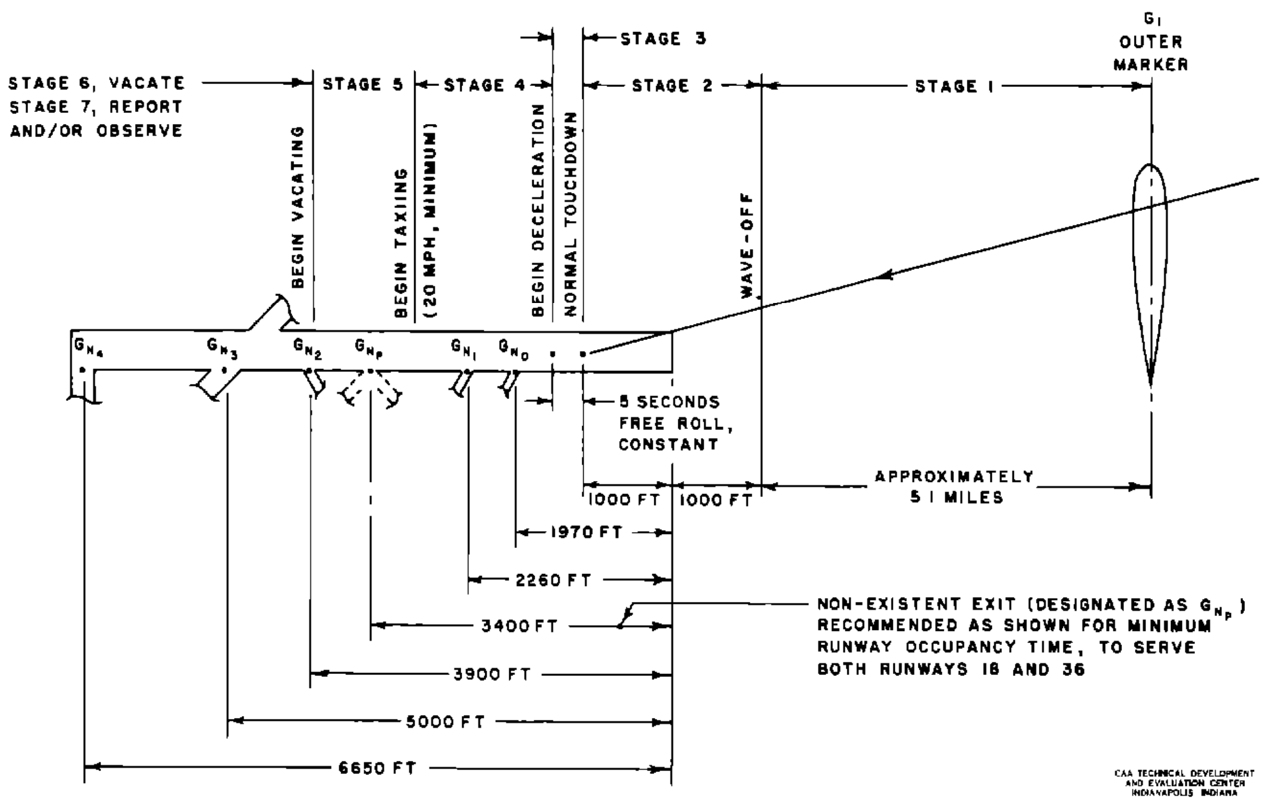


Fig 2 7-Stage Breakdown of Approach to Runway 36 at Washington National Airport

Use constant 12 seconds for exit from $G_{N_2}$ for all types
Use constant 5 seconds for exit from $G_{N_3}$ and $G_{N_P}$ for all types
Use constant 10 seconds for exit from $G_{N_4}$ for all types

Stage 7 Report and observation of an aircraft clear of the active runway and issuance of clearance to the next operation, constant at 6 seconds for all exits and all aircraft

Rules Assumed for the Experiment

The following rules are pertinent to this analysis

a The wave-off point is 1000 feet from the runway threshold and 2000 feet from normal touchdown Overshoots up to 200 feet beyond the wave-off point will be permissible

b Runway-exit overshoots up to 50 feet are permissible except in the cases of those aircraft using the exits designated at $G_{N_3}$ and $G_{N_P}$, where 100-foot overshoots are permissible

c Runway exits are located as indicated in Table X, with maximum runway-exit speeds as shown

d Where a runway exit can be made where the maximum runway-exit speed is 5, 10, 15, or 20 mph, the minimum taxi speed is 20 mph for all types

e Where a runway exit can be made where the maximum runway-exit speed is 30 mph, the minimum taxi speed is 30 mph

f Aircraft with less than 2 1/2 miles of separation from the preceding aircraft on the ILS glide slope will be waved off (glide-slope wave-off) Two and one-half miles is approximately half the distance from the outer marker to the wave-off point

g Only one aircraft at a time is permitted to occupy the block between the wave-off point and the runway exit, including aircraft being observed or those reported clear of the active runway A violation of this rule will probably result in a runway wave-off

h For analytical and computational purposes, waved-off aircraft will be reintroduced into the system by executing a 180° turn at the wave-off point, climbing back to 1500 feet of

TABLE X

LOCATIONS OF RUNWAY EXITS

| Runway Exit | Distance From Normal Touchdown (feet) | Exit Speed F (mph) | Exit Speed M (mph) | Exit Speed S (mph) |
|---|---|---|---|---|
| $G_{N_0}$ | 970 | 15 | 15 | 15 |
| $G_{N_1}$ | 1260 | 15 | 15 | 15 |
| $G_{N_2}$ | 2900 | 5 | 5 | 5 |
| $G_{N_3}$ | 4000 | 30 | 30 | 20 |
| $G_{N_4}$ | 5650 | 10 | 10 | 10 |
| $G_{N_P}$ (proposed) | 3400 | 30 | 30 | 20 |

altitude for approximately 51 miles at their average approach speed, and executing another 180° turn back to $G_1$ On the basis of first-come, first-served arrangements at the outer marker, either the reintroduced wave-off aircraft or succeeding aircraft may be delayed to suit the prescribed outer-marker minimum separation for that particular sequence

Results

In order to explore the effects of the use of the present CAA uniform minimum radar-separation rule of three miles, an analysis was made of the probable wave-offs due to the glide-slope and runway-block-occupancy rules previously specified It utilized the three random 2 1/2-hour samples of arrivals only for the condition of no wind The three-mile uniform-separation rule establishes at the outer marker separations sufficiently large to ensure that at all times all aircraft have a minimum separation, based on their average approach speeds, of three miles between the outer marker and the runway, thus, faster aircraft following slower aircraft require more than three miles of separation at the outer marker, and slower aircraft following faster aircraft require a minimum of three miles of separation at the outer marker The three-mile, uniform, minimum separations used for the nine sequences of slow, medium, and fast aircraft are given in Table XI On the basis of the distribution of the three aircraft types (42 per cent slow, 33 per cent medium, 25 per cent fast) and on condition that there are no wave-offs, this gives a computed maximum acceptance rate of 41 3 aircraft per hour, an average interval between aircraft of 1 minute 27 seconds It should also be noted that the proposed exit, $G_{NP}$, was not considered in this or in the immediately following analyses The use of this exit is discussed later

The total number of probable wave-offs out of the 198 landing aircraft of the three samples, including those wave-offs reintroduced into the arrival traffic samples, was 75, as summarized in Table XII Because this was a prohibitively high percentage of wave-offs, the three arrival samples were analyzed for four-mile, uniform, minimum separations as shown in Table XIII The maximum theoretical acceptance rate was 31 9 aircraft per hour, an average interval between aircraft of 1 minute 53 seconds

The results showed no glide-slope wave-offs, however, there were 42 total runway wave-offs, as summarized in Table XIV

In order to obtain the maximum theoretical acceptance rate and still conform to the prescribed glide-slope 2 1/2-mile minimum-separation rule, a 3 1/2-mile uniform minimum separation was explored It was found that the probability of glide-slope wave-offs was still too high, being approximately 10 out of the 198 landings Therefore, in an effort to obtain the maximum glide-slope acceptance rate for a wave-off probability of no greater than one per cent,

### TABLE XI

OUTER-MARKER 3-MILE UNIFORM MINIMUM SEPARATIONS WITH ZERO WIND

| Sequence* | Time Separation at Outer Marker** (seconds) | Distance Separation at Outer Marker (miles) |
|---|---|---|
| FF | 72 | 3.0 |
| MM | 77 | 3.0 |
| SS | 90 | 3.0 |
| MF | 81 | 3.4 |
| SM | 100 | 3.9 |
| SF | 104 | 4.3 |
| FM | 77 | 3.0 |
| FS | 90 | 3.0 |
| MS | 90 | 3.0 |
| | Average | 3.3 |

* MF means Medium followed by fast, SM means slow followed by medium, SS means slow followed by slow, etc

**Based on average approach speeds of 150, 140, and 120 mph for F, M, and S, respectively

### TABLE XII

TOTAL PROBABLE WAVE-OFFS FOR 3-MILE UNIFORM-SEPARATION RULE

| Aircraft Speed Class | Number of Wave-Offs Due to 2 1/2-Mile Glide-Slope Minima | Number of Wave-Offs Due to Runway-Occupancy Rule | Total Number of Arrivals | Total Number of Landing Aircraft |
|---|---|---|---|---|
| F | 5 | 19 | | |
| M | 10 | 31 | | |
| S | 2 | 8 | | |
| Total | 17 | 58 | 273* | 198** |

* This includes those wave-offs reintroduced (198 + 58 + 17)
**Including 40 military

### TABLE XIII

OUTER-MARKER 4-MILE UNIFORM MINIMUM SEPARATIONS WITH ZERO WIND

| Sequence | Time Separation at Outer Marker (seconds) | Distance Separation at Outer Marker (miles) |
|---|---|---|
| FF | 96 | 4.0 |
| MM | 103 | 4.0 |
| SS | 120 | 4.0 |
| MF | 105 | 4.4 |
| SM | 126 | 4.9 |
| SF | 128 | 5.3 |
| FM | 103 | 4.0 |
| FS | 120 | 4.0 |
| MS | 120 | 4.0 |
| | Average | 4.3 |

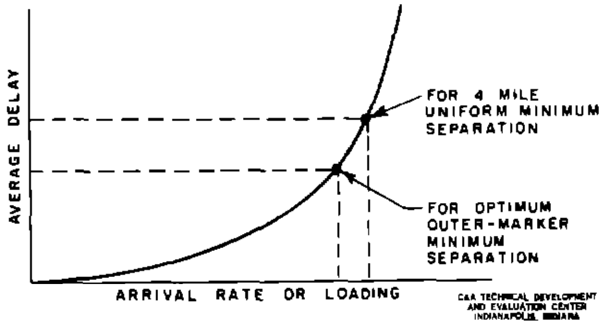


Fig 3 Delay as a Function of Loading

TABLE XIV

TOTAL PROBABLE WAVE-OFFS FOR 4-MILE UNIFORM-SEPARATION RULE

| Aircraft Speed Class | Number of Wave-Offs Due to 2 1/2-Mile Glide-Slope Minima | Number of Wave-Offs Due to Runway-Occupancy Rule | Total Number of Arrivals | Total Number of Landing Aircraft |
|---|---|---|---|---|
| F | 0 | 10 | | |
| M | 0 | 25 | | |
| S | 0 | 7 | | |
| Total | 0 | 42 | 240* | 198** |

* 240 = 198 landings + 42 wave-offs reintroduced
**Including 40 military

TABLE XV

OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS WITH ZERO WIND

| Sequence | Time Separation at Outer Marker (seconds) | Distance Separation at Outer Marker (miles) |
|---|---|---|
| FF | 97 | 4 0 |
| MM | 104 | 4 0 |
| SS | 122 | 4 1 |
| MF | 108 | 4 5 |
| SM | 130 | 5 1 |
| SF | 131 | 5 7 |
| FM | 92 | 3 6 |
| FS | 83 | 2 8 |
| MS | 94 | 3 1 |
| | | Average 4 1 |

a theoretical probabilistic analysis was undertaken using a theoretically infinite sample of arrivals to determine optimum nonuniform outer-marker minimum separations for each of the nine sequences of slow, medium, and fast aircraft

This analysis assumed that aircraft were being fed through the outer marker as fast as prescribed minimum-distance separations would permit Then, for each of the nine possible sequences of slow, medium, and fast aircraft all possible combinations of the performance variables with their associated probabilities were examined for glide-slope wave-offs This process was repeated for each sequence until the minimum outer-marker separation which yielded closest to 1 per cent wave-offs was found

On the assumption that all arrivals including the military land at Washington National Airport, optimum minimum separations at the outer marker were determined as shown in Table XV

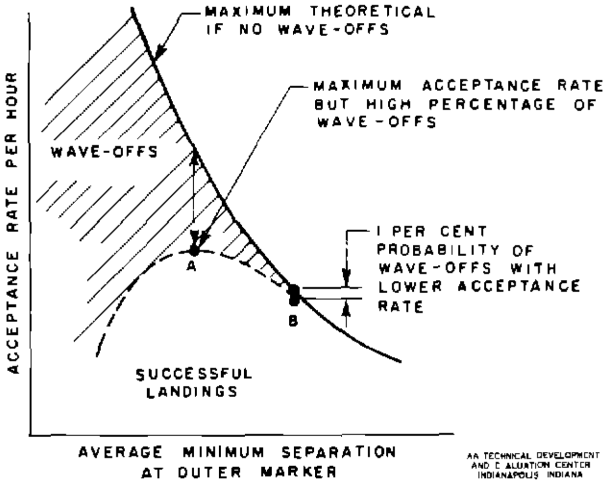


Fig 4 Acceptance Rate as a Function of Separation

The maximum theoretical acceptance rate using these optimum zero-wind, outer-marker separations is 33 8 aircraft per hour, as compared with 31 9 per hour for the 4-mile uniform-separation rule

It may be argued that such an increase of approximately two aircraft per hour in the acceptance rate is insignificant when the mental gymnastics required of the controllers in properly vectoring aircraft (while remembering the separations for the nine sequences of S, M, and F aircraft among the many other interrelated functions of the controllers) is compared with the relatively simpler task of maintaining the uniform 4-mile minimum separations However, it will be recalled that traffic inputs which are of appreciable duration and which approach or exceed a loading of 100 per cent (loading = arrival rate divided by the acceptance rate) can result in intolerable delays which approach infinity, as shown in Fig 3 It should be pointed out that in actual operational practice the delays would be even worse since it is physically impossible for the controllers and the pilots to approach the degree of perfection of the analytical studies For a given arrival rate, the lower the acceptance rate is, the higher will be the loading, and the higher the acceptance rate, the lower the loading Consequently, as small a decrease as two aircraft per hour in the acceptance rate could result in a significant increase in delays if the traffic rates were highly saturated and were of appreciable duration This condition is further illustrated qualitatively as points A and B in Fig 3 Such a condition is most undesirable from the standpoint of maximum utilization, consistent with the rules and safety criteria, of both the facilities and the airspace

It could be argued that the maximum acceptance rate should be determined on the basis of the maximum number of successful landings per hour, regardless of the number of probable wave-offs Fig 4, although out of scale, is presented for discussion purposes

The shaded portion of Fig 4 denotes probable wave-offs and the unshaded portion the successful landings It is apparent that the greatest number of successful landings per hour, and therefore the maximum external acceptance rate, is obtained at point A However, this is accomplished by "force feeding" and results in an intolerably high percentage of wave-offs These wave-offs are chargeable to the traffic control system itself and do not include the probable wave-offs caused by lack of pilot proficiency These probable pilot wave-offs, although not analyzed here, must also be reintroduced They thus cause a further backing up of the already saturated loading parameter and consequently introduce a further chain reaction of higher delays Certainly, these additional delays and the high percentage of wave-offs are intolerable in actual civil operations, although military operations might tolerate them, depending on the type of operation and the calculated risk

The next step concerned the use of the zero-wind optimum outer-marker separations of Table XV to determine for the same three 2 1/2-hour samples of arrival-only traffic the probable wave-offs due to the runway block-occupancy rule The zero-wind results are given in Table XVI

TABLE XVI

PROBABLE WAVE-OFFS FOR OPTIMUM OUTER-MARKER SEPARATIONS WITH ZERO WIND

| Arrival Sample | Number of Wave-Offs Due to 2 1/2-Mile Glide-Slope Minima | Number of Wave-Offs Due to Runway-Occupancy Rule | Total Number of Arrivals* | Total Number of Landing Aircraft |
|---|---|---|---|---|
| 1 | 0 | 8 | 74 | 66 (incl 13 mil ) |
| 2 | 0 | 12 | 78 | 66 (incl 14 mil ) |
| 3 | 0 | 11 | 77 | 66 (incl 13 mil ) |
| 1 + 2 + 3 | 0 | 31 | 229 | 198 (incl 40 mil ) |

*Includes wave-offs reintroduced (229 = 198 + 31, etc )

Although the total of 31 runway wave-offs for the three arrival samples is significantly less than the 42 runway wave-offs computed for the 4-mile uniform-separation rule, it is still intolerably high Accordingly, the resulting runway-time and -distance distributions were examined, and it became evident that the exits to Washington National Airport runway 36 were poorly angled and located Further, it was seen that this runway bottleneck could be alleviated simply by adding a high-speed exit at 3400 feet, shown on Fig 2 as $G_{NP}$ This exit could serve both runways 36 and 18 and could accommodate approximately 70 per cent of the landing aircraft on an over-all probability basis Figs 5 through 8 show these theoretical runway-time and -distance distributions Note on Figs 6 and 8 the excellent agreement between the CAA stop-watch operational data and the corresponding average results obtained from the probability analyses

The next, and more conclusive step in the analysis involved the use of these optimum outer-marker minimum separations for zero wind, a theoretically infinite saturated sample of arrival-only traffic (consisting of 42 per cent slow, 33 per cent medium, and 25 per cent fast aircraft), the assumption that all aircraft including military land at Washington National Airport, the previously prescribed rules and variables, and the assumption that the afore-mentioned 3400-foot runway exit exists in calculating the probability of runway wave-offs The results are shown in Table XVII

Although the 3 3 per cent total probability of runway wave-offs and glide-slope wave-offs is now greater than the originally prescribed 1 per cent and in view of the assumption that the traffic sample is infinitely saturated (and actual traffic samples are most decidedly not), the assumption that the military aircraft land at Washington National Airport (when in reality all but the most important personages land at Bolling or Anacostia), the fact that some of the probable runway wave-offs were caused by a matter of a few seconds (mathematical analyses make no provision for exercising judgment as in actual practice), this 3 3 per cent wave-off figure is believed acceptable for the analytical purposes intended

On the basis of the 1 per cent maximum probability of glide-slope wave-offs, optimum outer-marker minimum separations were also computed for the 20-mph-headwind conditions Further, since the rules previously outlined specified that all military arrivals land at either Bolling or Anacostia, 3-mile rather than optimum separations were established for all sequences involving military arrivals Table XVIII summarizes the outer-marker separations for all possible sequences of aircraft arrivals under both the zero and 20-mph wind conditions Note that the weighted acceptance rate is 36 1 arrivals per hour for zero wind with an average interval of 1 minute 40 seconds and is only 29 8 per hour for the 20-mph wind condition because of the additional time involved in traversing the 5 3-mile glide slope This implies that higher acceptance rates can be achieved with shorter glide slopes, a fact borne out by simple arithmetic

Accordingly, with the utilization of the stated optimum separations and of the assumed 3400-foot runway exit, the wave-off probabilities for the three 2 1/2-hour traffic samples were analyzed for the rules and for the twelve conditions outlined previously The results are shown in Table XIX It will be noted that the only probable wave-off occurred in Sample No 2 for the zero-wind condition This was due to the runway-occupancy rule

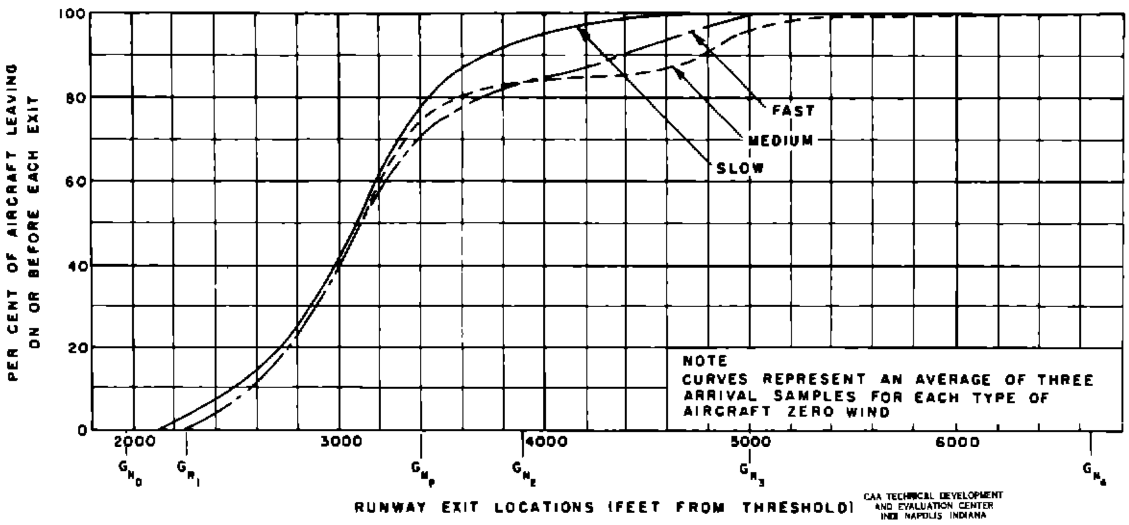


**Fig 5 Cumulative Distributions of the Use of Runway 36 Exits at Washington National Airport**

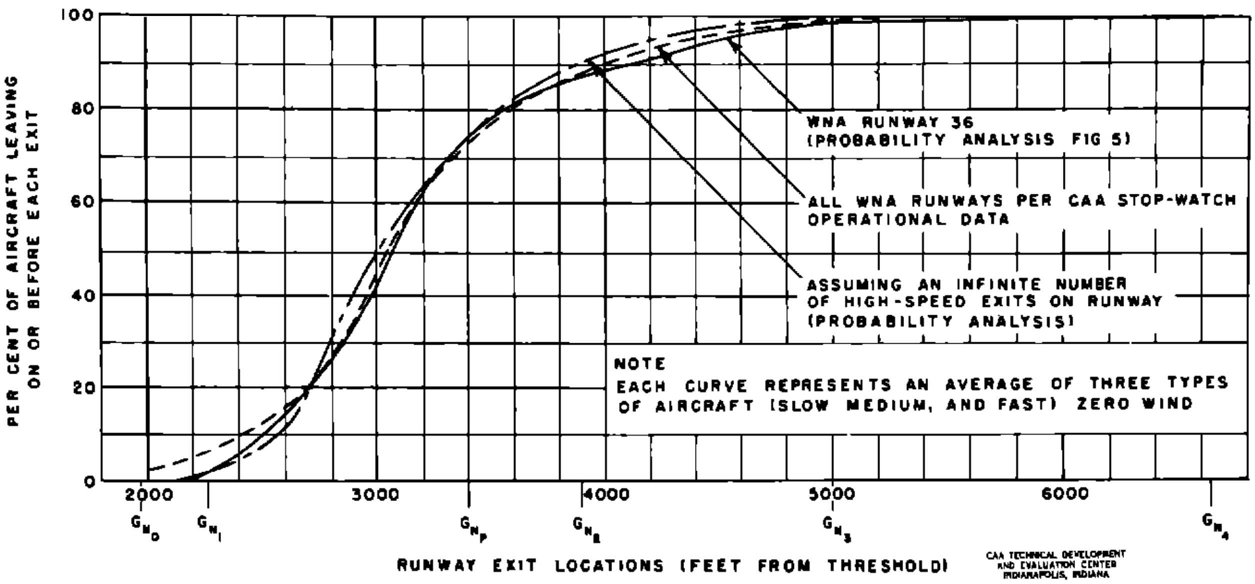


**Fig 6 Comparative Cumulative Distributions of the Use of Runway Exits**

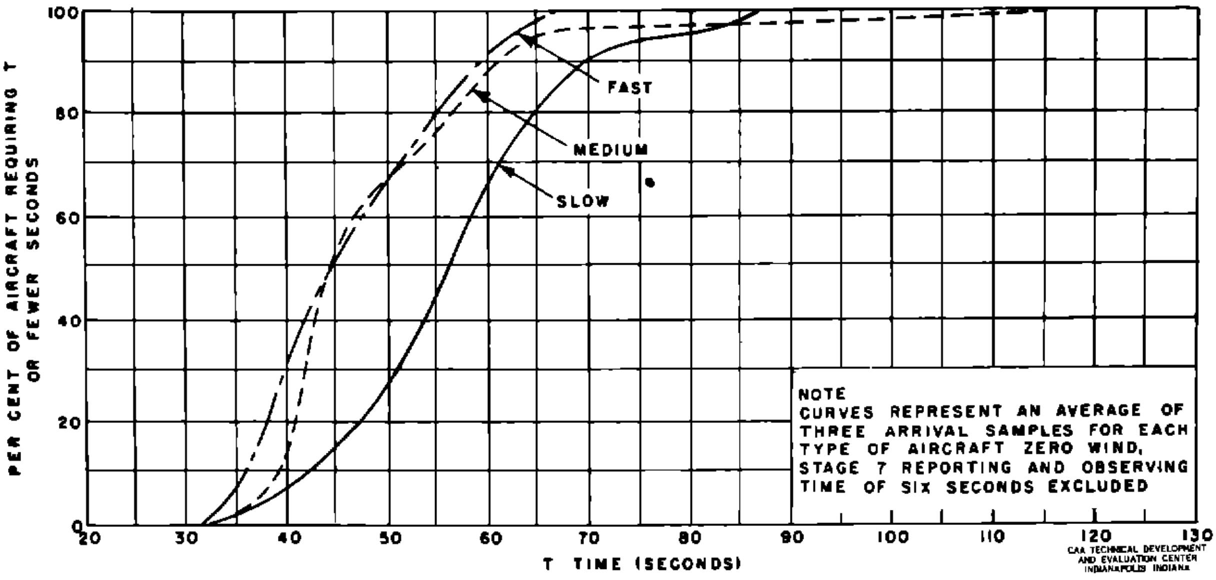


Fig 7 Cumulative Distributions of Time Required by Various-Speed Aircraft From Wave-Off Point to Exit From Runway 36 at Washington National Airport NOTE. Additional Exit Assumed at 3400 Feet From Runway Threshold

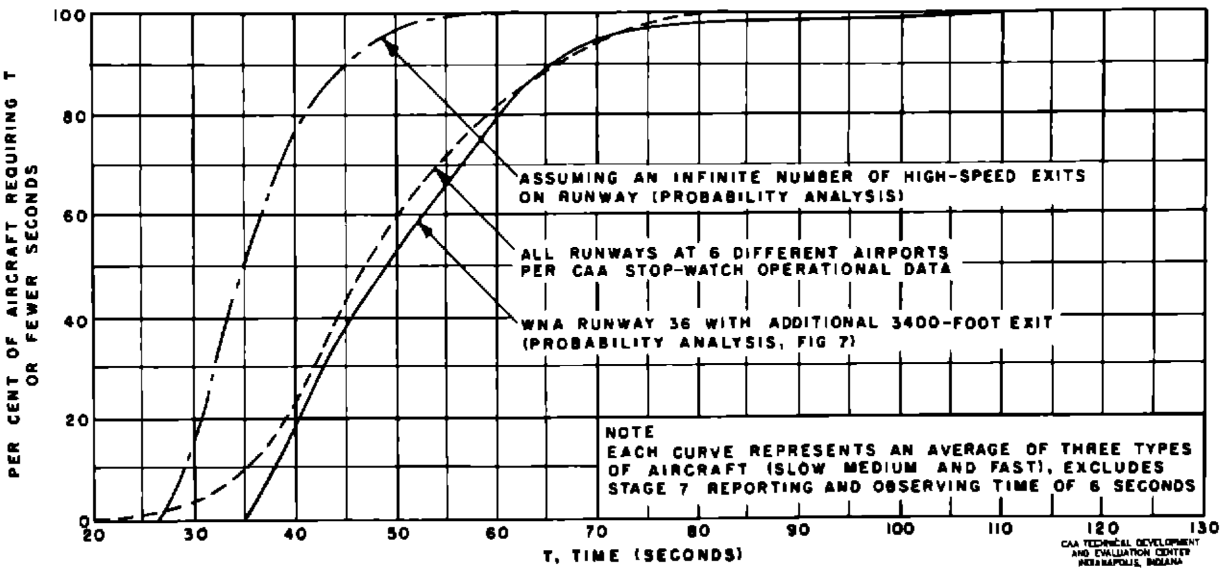


Fig. 8 Comparative Cumulative Distributions of Average Time Required From Wave-Off Point to Runway Exit

## TABLE XVII

### SUMMARY OF PROBABLE WAVE-OFFS*

| Sequence | Optimum Outer-Marker Minimum Separation (seconds) | Probability of Wave-Offs on Glide Slope (per cent) | Probability of Wave-Offs Due to Runway-Occupancy Rule (per cent) |
|---|---|---|---|
| SS | 122 | 0 18 | 0 29 |
| SM | 130 | 0 14 | 0 61 |
| SF | 131 | 0 10 | 0 65 |
| MS | 94 | 0 14 | 0 13 |
| MM | 104 | 0 11 | 0 20 |
| MF | 108 | 0 08 | 0 22 |
| FS | 83 | 0 11 | 0 04 |
| FM | 92 | 0 08 | 0 09 |
| FF | 97 | 0 07 | 0 10 |
| Per Cent Total Probability | | 1 01 | 2 33 |

*Test Conditions  Theoretically infinite sample of arrivals, zero wind, all WNA landings, optimum outer-marker separations, and 3400-foot exit assumed on WNA runway 36

## TABLE XVIII

### SUMMARY OF THE OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS FOR ZERO AND 20-MPH HEADWIND

| Sequence | 0 Wind | | 20-MPH Wind | | Sequence | 0 Wind | | 20-MPH Wind | |
|---|---|---|---|---|---|---|---|---|---|
| | $G_1$ Distance Separation (miles) | $G_1$ Time Separation (seconds) | $G_1$ Distance Separation (miles) | $G_1$ Time Separation (seconds) | | $G_1$ Distance Separation (miles) | $G_1$ Time Separation (seconds) | $G_1$ Distance Separation (miles) | $G_1$ Time Separation (seconds) |
| SF | 5 66 | 131 | 6 37 | 163 | $F_M M_M$ | 3 0 | 77 | 3 0 | 90 |
| MF | 4 50 | 108 | 4 84 | 134 | $FM_M$ | 3 0 | 77 | 3 0 | 90 |
| SM | 5 10 | 130 | 5 70 | 165 | $F_M M$ | 3 0 | 77 | 3 0 | 90 |
| FM | 3 56 | 92 | 3 75 | 113 | | | | | |
| FS | 2 76 | 83 | 2 72 | 97 | $F_M S_M$ | 3 0 | 90 | 3 0 | 108 |
| MS | 3 12 | 94 | 3 13 | 113 | $FS_M$ | 3 0 | 90 | 3 0 | 108 |
| FF | 4 04 | 97 | 4 25 | 118 | $F_M S$ | 3 0 | 90 | 3 0 | 108 |
| MM | 4 03 | 104 | 4 28 | 128 | | | | | |
| SS | 4 06 | 122 | 4 30 | 155 | $M_M S_M$ | 3 0 | 90 | 3 0 | 108 |
| | | | | | $MS_M$ | 3 0 | 90 | 3 0 | 108 |
| $S_M F_M$ | 4 33 | 104 | 4 57 | 127 | $M_M S$ | 3 0 | 90 | 3 0 | 108 |
| $SF_M$ | 3 0 | 72 | 3 0 | 83 | | | | | |
| $S_M F$ | 3 0 | 72 | 3 0 | 83 | $F_M F_M$ | 3 0 | 72 | 3 0 | 83 |
| | | | | | $FF_M$ | 3 0 | 72 | 3 0 | 83 |
| $M_M F_M$ | 3 27 | 81 | 3 42 | 95 | $F_M F$ | 3 0 | 72 | 3 0 | 83 |
| $MF_M$ | 3 0 | 72 | 3 0 | 83 | | | | | |
| $M_M F$ | 3 0 | 72 | 3 0 | 83 | $M_M M_M$ | 3 0 | 77 | 3 0 | 90 |
| | | | | | $MM_M$ | 3 0 | 77 | 3 0 | 90 |
| $S_M M_M$ | 3 89 | 100 | 4 06 | 122 | $M_M M$ | 3 0 | 77 | 3 0 | 90 |
| $SM_M$ | 3 0 | 77 | 3 0 | 90 | | | | | |
| $S_M M$ | 3 0 | 77 | 3 0 | 90 | $S_M S_M$ | 3 0 | 90 | 3 0 | 108 |
| | | | | | $SS_M$ | 3 0 | 90 | 3 0 | 108 |
| | | | | | $S_M S$ | 3 0 | 90 | 3 0 | 108 |

Note  SF means slow WNA arrival followed by a fast WNA arrival  $S_M F_M$ – slow military arrival followed by a fast military arrival  $SF_M$ – slow WNA arrival followed by a fast military arrival  $S_M F$ – slow military arrival followed by a fast WNA arrival  etc
The weighted acceptance rate for the zero-wind condition = 36 1 per hour with an average interval of 1 minute 40 seconds  for a 20-mph headwind, 29 8 per hour with an average interval of 2 minutes

TABLE XIX

SUMMARY OF PROBABLE WAVE-OFFS FOR 2 1/2-HOUR TRAFFIC SAMPLES

| Sample Number | Wind (mph) | Arrivals Only | | Arrivals and Departures | |
|---|---|---|---|---|---|
| | | Number of Glide-Slope Wave-Offs | Number of Runway-Occupancy Wave-Offs | Number of Glide-Slope Wave-Offs | Number of Runway-Occupancy Wave-Offs |
| 1 | 0 | 0 | 0 | 0 | 0 |
| | 20 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 0 | 1 |
| | 20 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 |
| | 20 | 0 | 0 | 0 | 0 |

Test Conditions Optimum outer-marker minimum separations and 3400-foot exit assumed on WNA Runway 36 Each arrival sample consisted of a total of 66 aircraft, each departure sample consisted of a total of 63 aircraft

TABLE XX

SUMMARY OF ARRIVAL DELAYS FOR IDEAL ANALYSIS* AND WITH OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS

| Period of Operations (hour) | Total Number of Arrivals | Sample Number | 0 Wind | | | 20-MPH Wind | | |
|---|---|---|---|---|---|---|---|---|
| | | | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 1 | 3.05 | 91.4 | 8.77 | 6.39 | 94.3 | 15.93 |
| | | 2 | 2.82 | 91.4 | 6.27 | 6.07 | 97.1 | 11.62 |
| | | 3 | 3.19 | 91.4 | 8.77 | 6.01 | 91.4 | 17.38 |
| | | Average | 3.02 | 91.4 | | 6.16 | 94.3 | |
| 1 to 2 1/2 | 47 | 1 | 2.47 | 80.9 | 8.77 | 7.16 | 95.7 | 15.93 |
| | | 2 | 2.23 | 80.9 | 6.27 | 5.65 | 97.9 | 11.62 |
| | | 3 | 4.02 | 89.4 | 10.65 | 8.91 | 93.6 | 22.05 |
| | | Average | 2.91 | 83.7 | | 7.24 | 95.7 | |
| 1/2 to 3 | 66 | 1 | 1.94 | 74.2 | 8.77 | 5.74 | 86.4 | 15.93 |
| | | 2 | 1.91 | 74.2 | 6.27 | 4.94 | 92.4 | 11.62 |
| | | 3 | 2.95 | 71.2 | 10.65 | 6.75 | 87.9 | 22.05 |
| | | Average | 2.27 | 73.2 | | 6.48 | 88.9 | |

*Samples of Arrivals Only

TABLE XXI

SUMMARY OF DELAYS USING ARRIVALS PLUS DEPARTURES FOR IDEAL ANALYSIS UNDER CONDITIONS OF OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS AND ZERO WIND

| Period of Operations (hour) | Total Arrivals | WNA Departures | Sample Number | Arrival Delays | | | Departure Delays | | | Operations Delays | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 20 | 1 | 4 18 | 94 3 | 9 85 | 4 50 | 90 0 | 10 30 | 4 3 | 92 7 | 10 3 |
| | | | 2 | 4 46 | 94 3 | 10 38 | 5 13 | 90 0 | 9 17 | 4 7 | 92 7 | 10 4 |
| | | | 3 | 3 93 | 91 4 | 11 47 | 3 24 | 85 0 | 9 18 | 3 7 | 89 1 | 11 5 |
| | | | Average | 4 19 | 93 3 | | 4 29 | 88 3 | | 4 2 | 91 5 | |
| 1 to 2 1/2 | 47 | 33 | 1 | 4 61 | 95 7 | 9 98 | 5 78 | 93 9 | 10 32 | 5 1 | 95 0 | 10 3 |
| | | | 2 | 4 00 | 95 7 | 10 38 | 5 74 | 93 9 | 11 92 | 4 7 | 95 0 | 11 9 |
| | | | 3 | 5 85 | 93 6 | 15 43 | 7 47 | 90 9 | 16 33 | 6 5 | 92 5 | 16 3 |
| | | | Average | 4 82 | 95 0 | | 6 33 | 92 9 | | 5 4 | 94 2 | |
| 1/2 to 3 | 66 | 51 | 1 | 3 61 | 84 8 | 9 98 | 4 57 | 84 3 | 10.32 | 4 0 | 84 6 | 10 3 |
| | | | 2 | 3 38 | 89 4 | 10 38 | 4 67 | 92 2 | 11 92 | 3 9 | 90 6 | 11 9 |
| | | | 3 | 4 25 | 75 8 | 15 43 | 5.81 | 86 3 | 16 33 | 4 9 | 80 4 | 16 3 |
| | | | Average | 3 75 | 83 3 | | 5 02 | 87 6 | | 4 3 | 85 2 | |

## DISCUSSION OF THE RESULTS[15]

### Ideal Analysis With Zero- And 20-Mph Headwind

Highlights of the ideal analysis of the three traffic samples of arrivals only and the three samples of arrivals plus departures are shown in Tables XX, XXI, and XXII A delay is defined as any additional time required to meet the specified outer-marker or runway separations beyond the time normally required with no other traffic involved An operation is defined as either an arrival or a departure Table XX lists the ideal-analysis delays for the samples of arrivals only under the conditions of both zero wind and 20-mph headwind Tables XXI and XXII list the ideal delays for the samples of arrivals plus departures for the zero-wind condition and the 20-mph wind, respectively

Note the large variations between samples when like conditions are compared, note also that sample No 3 had the highest delays in practically every period except in a few cases during the hour 1 to 2 When this occurred, the delays backed up appreciably and consistently into the next half-hour period where the traffic input was less This is evidence of the caution that must be exercised in making comparisons when using only one random-traffic sample

It is also seen that the delays for the condition of a 20-mph headwind are about double the corresponding delays for the zero-wind condition The maximum theoretical acceptance rates are 29 8 per hour and 36 1 per hour for 20-mph wind and for zero wind, respectively, a difference of about 20 per cent The 22- and 25-minute maximum delays incurred during the 20-mph headwind conditions are of special interest, since it is expected that in actual practice these delays will be at least twice again as large This further bears out the importance of keeping the acceptance rates as high as possible and the work load as low as possible Related to the acceptance rate, of course, is the controllers' work load and proficiency Uncertainties, strain, and such conditions result in conservatism, thus decreasing the operational acceptance rate and backing up delays

### Graphical Analysis of Washington National Airport Phases 2, 6, and 7 at Zero Wind

The three Washington National Airport twin-stack phases 2, 6, and 7 described in Appendix A were graphically analyzed for the three traffic samples of arrivals only and for the three traffic samples of arrivals plus departures Because of a shortage of time, only the zero-wind condition was investigated The pertinent results are tabulated as absolute and system delays on Tables XXIII through XXVIII Comparisons of the absolute delays of the three phases are

[15]The average delay per aircraft throughout this report is calculated on the basis of the average for all aircraft, including those not delayed

TABLE XXII

SUMMARY OF DELAYS USING ARRIVALS PLUS DEPARTURES FOR IDEAL ANALYSIS
UNDER CONDITIONS OF OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS AND 20-MPH WIND

| Period of Operations (hour) | Total Arrivals | WNA Departures | Sample Number | Arrival Delays | | | Departure Delays | | | Operations Delays | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Amount Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 20 | 1 | 6 68 | 94 3 | 15 93 | 4 90 | 95 0 | 13 93 | 6 0 | 94 6 | 15 9 |
| | | | 2 | 8 86 | 97 1 | 17 52 | 7 33 | 95 0 | 15 98 | 8 3 | 96 3 | 17 5 |
| | | | 3 | 6 52 | 94 3 | 18 32 | 3 06 | 90 0 | 10 08 | 5 3 | 92 7 | 18 3 |
| | | | Average | 7 35 | 95 2 | | 5 10 | 93 3 | | 6 5 | 94 5 | |
| 1 to 2 1/2 | 47 | 33 | 1 | 8 37 | 95 7 | 16 95 | 8 03 | 97 0 | 18 92 | 8 2 | 96 2 | 18 9 |
| | | | 2 | 10 07 | 97 9 | 17 52 | 10 92 | 97 0 | 18 58 | 10 4 | 97 5 | 18 6 |
| | | | 3 | 9 94 | 95 7 | 25 25 | 9 86 | 93 9 | 25 13 | 9 9 | 95 0 | 25 3 |
| | | | Average | 9 46 | 96 4 | | 9 60 | 96 0 | | 9 5 | 96 2 | |
| 1/2 to 3 | 66 | 51 | 1 | 7 25 | 92 4 | 16 95 | 7 98 | 94 1 | 18 92 | 7 6 | 93 1 | 18 9 |
| | | | 2 | 9 33 | 97 0 | 17 52 | 11 06 | 98 0 | 18 58 | 10 1 | 97 4 | 18 6 |
| | | | 3 | 8 24 | 90 9 | 25 25 | 9 56 | 94 1 | 25 13 | 8 8 | 92 3 | 25 3 |
| | | | Average | 8 27 | 93 4 | | 9 53 | 95 4 | | 8 8 | 94 3 | |

TABLE XXIII

SUMMARY OF ABSOLUTE DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7
USING ARRIVALS ONLY UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS*

| Period of Operations (hour) | Total Number of Arrivals | Sample Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Average Delay per Aircraft (minutes) | Number Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 1 | 6 52 | 94 3 | 15 68 | 5 71 | 94 3 | 16 55 | 7 68 | 94 3 | 17 25 |
| | | 2 | 4 53 | 91 4 | 10 78 | 5 96 | 94 3 | 12 13 | 4 31 | 88 6 | 10 98 |
| | | 3 | 4 05 | 82 9 | 11 90 | 4 54 | 88 6 | 14 57 | 4 76 | 85 7 | 15 08 |
| 1 to 2 1/2 | 47 | 1 | 7 18 | 95 7 | 15 68 | 6 06 | 95 7 | 16 55 | 8 52 | 95 7 | 20 25 |
| | | 2 | 4 22 | 93 6 | 10 78 | 5 75 | 95 7 | 12 13 | 4 22 | 89.4 | 10 98 |
| | | 3 | 5 67 | 87 2 | 15 67 | 6 47 | 91 5 | 17 17 | 6 90 | 89 4 | 18.67 |
| 1/2 to 3 | 66 | 1 | 5 54 | 89 4 | 15 68 | 4 77 | 89 4 | 16 55 | 6 72 | 89 4 | 20 25 |
| | | 2 | 3 39 | 86 4 | 10 78 | 4.81 | 90 9 | 12 13 | 3 42 | 83 3 | 10 98 |
| | | 3 | 4 23 | 77 3 | 15 67 | 4 84 | 83 3 | 17 17 | 5 18 | 78 8 | 18 67 |

*Absolute delays are total delays

illustrated in Figs 9 through 12 An absolute delay is the total delay, it represents the total time in excess of that for the shortest route with no other traffic System delay is defined as the delay attributable to the system and is the absolute delay minus the ideal delay, in other words, system delay is the delay due to the entire system of traffic, routes, rules, configuration, and so forth, in excess of the ideal delay

Table XXIII lists the absolute delays of the phases for the three different traffic samples of arrivals only In Table XXIV, the three samples are averaged and the phases are compared on the basis of absolute delays and system delays Figs 9 and 10 show comparisons of the absolute average and maximum delays for the average of the three traffic samples of arrivals only Fig 10 is presented in the form of a time series of average delays for arrivals in each successive 15-minute period Phase 2 appears to be the most efficient on the basis of average delay per arrival as examples, when comparing absolute delays, phase 2 is more efficient than phase 7 by about 14 per cent whereas when comparing system delays, phase 2 is more efficient than phase 7 by about 29 per cent

When the average delays of Table XXIII are compared with the corresponding ideal delays of Table XX, it is seen that the magnitudes of the delays differ markedly between samples However, there is no correlation between the ideal and the graphical insofar as the order of ranking is concerned, in the ideal the order is 3 > 2 > 1, whereas in the graphical it was usually 1 > 3 > 2

TABLE XXIV

SUMMARY OF ABSOLUTE AND SYSTEM ARRIVAL DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7 USING SAMPLES OF ARRIVALS ONLY AND UNDER CONDITONS OF ZERO WIND AND OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Phase Number | Absolute Delays: Average Delay per Aircraft * (minutes) | Absolute Delays: Number of Aircraft Delayed* (per cent) | Absolute Delays: Maximum Delay (minutes) | System Delays: Average Delay per Aircraft * (minutes) | System Delays: Number of Aircraft Delayed* (per cent) | System Delays: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 2 | 5.03 | 89.5 | 15.68 | 2.01 | - 1.9 | 6.91 |
| | | 6 | 5.40 | 92.4 | 16.55 | 2.38 | 1.0 | 7.78 |
| | | 7 | 5.58 | 89.5 | 17.25 | 2.56 | - 1.9 | 8.48 |
| 1 to 2 1/2 | 47 | 2 | 5.69 | 92.2 | 15.68 | 2.78 | 8.5 | 5.03 |
| | | 6 | 6.09 | 94.3 | 17.17 | 3.18 | 10.6 | 6.52 |
| | | 7 | 6.55 | 91.5 | 20.25 | 3.64 | 7.8 | 9.60 |
| 1/2 to 3 | 66 | 2 | 4.39 | 84.4 | 15.68 | 2.12 | 11.7 | 5.03 |
| | | 6 | 4.81 | 87.9 | 17.17 | 2.54 | 15.2 | 6.52 |
| | | 7 | 5.11 | 83.8 | 20.25 | 2.84 | 11.1 | 9.60 |

*Average of 3 samples.
NOTE· Absolute delays = total delay. System delay = absolute minus ideal delay.

TABLE XXV

SUMMARY OF ABSOLUTE ARRIVAL DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7 USING SAMPLES OF ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Sample Number | Phase 2: Average Delay per Aircraft (minutes) | Phase 2: Number of Aircraft Delayed (per cent) | Phase 2: Maximum Delay (minutes) | Phase 6: Average Delay per Aircraft (minutes) | Phase 6: Number of Aircraft Delayed (per cent) | Phase 6: Maximum Delay (minutes) | Phase 7: Average Delay per Aircraft (minutes) | Phase 7: Number of Aircraft Delayed (per cent) | Phase 7: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 1 | 6 52 | 94 3 | 15 68 | 5 71 | 94 3 | 16 55 | 7 68 | 94.3 | 17 25 |
| | | 2 | 4 53 | 91 4 | 10 78 | 5 96 | 94 3 | 12 13 | 4 31 | 88 6 | 10 98 |
| | | 3 | 4.05 | 82 9 | 11 90 | 4 54 | 88 6 | 14 57 | 4 76 | 85 7 | 15 08 |
| | | Average | 5 03 | 89 5 | | 5 40 | 92 4 | | 5.58 | 89 5 | |
| 1 to 2 1/2 | 47 | 1 | 7 18 | 95 7 | 15 68 | 6 06 | 95 7 | 16 55 | 8 52 | 95 7 | 20 25 |
| | | 2 | 4 22 | 93 6 | 10 78 | 5 75 | 95 7 | 12 13 | 4 22 | 89 4 | 10 98 |
| | | 3 | 5 67 | 87 2 | 15 67 | 6 47 | 91 5 | 17 17 | 6 90 | 89 4 | 18 67 |
| | | Average | 5 69 | 92 2 | | 6 09 | 94 3 | | 6 55 | 91 5 | |
| 1/2 to 3 | 66 | 1 | 5 54 | 89 4 | 15 68 | 4 77 | 89 4 | 16 55 | 6 72 | 89 4 | 20.25 |
| | | 2 | 3 39 | 86 4 | 10 78 | 4 81 | 90 9 | 12 13 | 3 42 | 83 3 | 10 98 |
| | | 3 | 4 23 | 77 3 | 15.67 | 4 84 | 83 3 | 17.17 | 5.18 | 78.8 | 18 67 |
| | | Average | 4 39 | 84 4 | | 4 81 | 87 9 | | 5 11 | 83 8 | |

TABLE XXVI

SUMMARY OF ABSOLUTE DEPARTURE DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7
USING SAMPLES OF ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Departures | Sample Number | Phase 2 Average Delay per Aircraft (minutes) | Phase 2 Number of Aircraft Delayed (per cent) | Phase 2 Maximum Delay (minutes) | Phase 6 Average Delay per Aircraft (minutes) | Phase 6 Number of Aircraft Delayed (per cent) | Phase 6 Maximum Delay (minutes) | Phase 7 Average Delay per Aircraft (minutes) | Phase 7 Number of Aircraft Delayed (per cent) | Phase 7 Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 20 | 1 | 1 60 | 70 0 | 8 47 | 1 63 | 60.0 | 7 80 | 1 65 | 80 0 | 7 58 |
| | | 2 | 2 97 | 80.0 | 8.92 | 1.99 | 85 0 | 4.88 | 3 73 | 80 0 | 9 35 |
| | | 3 | 1 64 | 85.0 | 4 77 | 2 05 | 80 0 | 5 35 | 1.45 | 65.0 | 6 32 |
| | | Average | 2 07 | 78 3 | | 1 89 | 75 0 | | 2 28 | 75 0 | |
| 1 to 2 1/2 | 33 | 1 | 2 96 | 81 8 | 8 70 | 3 02 | 75 8 | 7 80 | 2 50 | 84.8 | 7 58 |
| | | 2 | 3.57 | 84 9 | 10 03 | 2.43 | 87 9 | 4 88 | 4.32 | 87 9 | 9.35 |
| | | 3 | 5 34 | 90 9 | 14 97 | 3 50 | 87 9 | 10 35 | 2.57 | 75 8 | 9.98 |
| | | Average | 3 96 | 85 9 | | 2 98 | 83 9 | | 3 13 | 82.8 | |
| 1/2 to 3 | 51 | 1 | 2 41 | 78.4 | 8.70 | 2 63 | 76.5 | 7 80 | 2.05 | 82 4 | 7.58 |
| | | 2 | 3 10 | 82 4 | 10.03 | 2 80 | 88 2 | 10 35 | 3.69 | 82 4 | 9.35 |
| | | 3 | 4.55 | 90.2 | 14 97 | 3 07 | 86 3 | 10.35 | 2 56 | 78.4 | 9 98 |
| | | Average | 3.35 | 83 7 | | 2.83 | 83 7 | | 2.77 | 81.1 | |

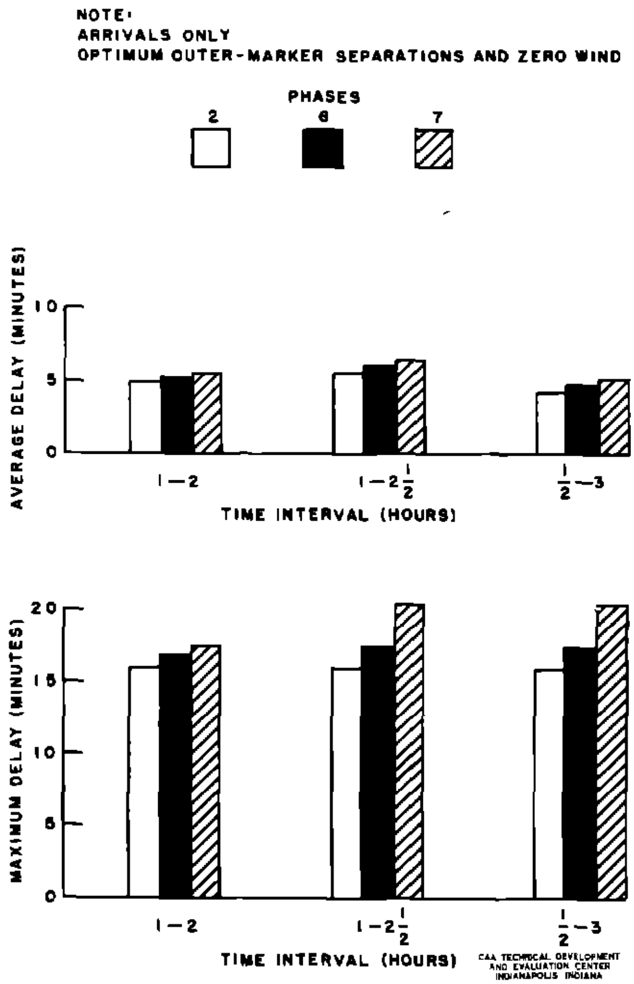


Fig 9 Average and Maximum Absolute Delays per Arrival (Graphical Analysis)

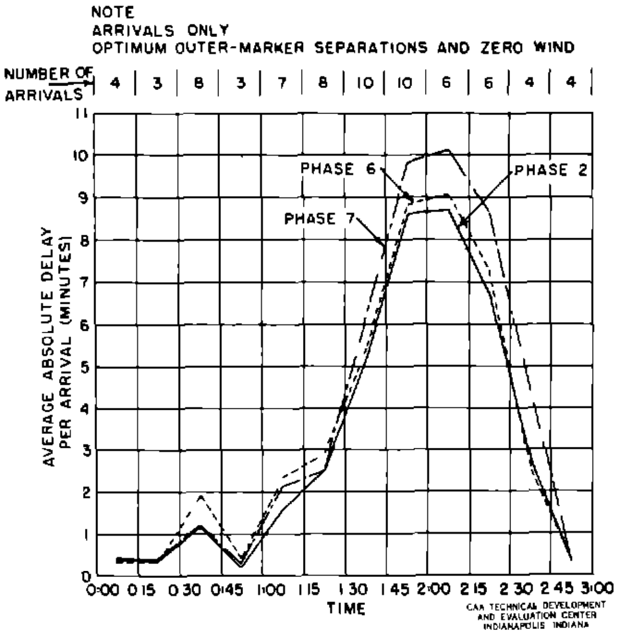


Fig 10 Average Absolute Delays Per Arrival (Graphical Analysis)

Figs 11 and 12 show the comparisons between phases of the absolute delays per operation for the average of the three samples of arrivals plus departures Tables XXV, XXVI, and XXVII list for each sample and for the average of the three samples the delays of the arrivals, the delays of the departures, and the weighted averages of the arrivals and departures (operations) for the samples of arrivals plus departures Table XXVIII lists the absolute and system delays for the averages of the three traffic samples by operations, it shows little choice between phases

Arrival absolute delays on Table XXV (samples of arrivals plus departures) are shown to be identical to the arrival absolute delays on Tables XXIII and XXIV This is because, in the graphical analysis, perfect knowledge and perfect execution, including the probable aircraft performance on the glide slope and on the runway, are assumed Therefore, in conformance with the departure and arrival separations defined in the previous section of this report, arrivals were accepted at the outer marker just as in the case of arrivals only and, when necessary, departures were held on the gound until a sufficiently long gap of time appeared between arrivals, then the departures were interspersed to suit

The resulting departure delays are relatively small, as seen in Table XXVI This insertion technique therefore offers attractive possibilities from the standpoint of over-all safety, economy, and efficiency If, as in the present operational practice, arrival separations were increased to allow more frequent interspersion of departures on single runways, the departure delays would decrease However, the over-all delays would back up and tend to pyramid because the acceptance rate would essentially be decreased Furthermore, delays in the air cost much more in decreased safety and economy than delays on the ground There are several possible methods of achieving in practice this technique of interspersing departures The simplest is to cut down the spreads of aircraft performance, perhaps by some form of speed control such as an automatic or semiautomatic approach coupler Another method could be by use of a type of rate-of-closure, speed-indicating, and approach-sequencing PAR radar

Comparison of Tables XXV, XXVI, XXVII, and XXVIII (graphical results) with Table XXI (ideal results) shows that the departure delays in the graphical analysis are much less than those in the ideal analysis Accordingly, the delays per operation are less graphically than ideally, as shown in Figs 21 through 23 This condition results from the fact that the ideal analysis as described in Appendix C explicitly follows the priorities and separations, based on average aircraft performance and discussed in the previous section, arrivals or departures are delayed accordingly, therefore As discussed previously, the principle of perfect knowledge and perfect execution in the graphical analysis permits enough flexibility to intersperse these

TABLE XXVII

SUMMARY OF ABSOLUTE OPERATIONS DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7
USING SAMPLES OF ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Operations* | Sample Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 55 | 1 | 4.73 | 85.5 | 15.68 | 4.22 | 81.8 | 16.55 | 5.49 | 89.1 | 17.25 |
| | | 2 | 3.96 | 87.3 | 10.78 | 4.52 | 90.9 | 12.13 | 4.10 | 85.5 | 10.98 |
| | | 3 | 3.17 | 83.6 | 11.90 | 3.64 | 85.5 | 14.57 | 3.56 | 78.2 | 15.08 |
| | | Average | 3.95 | 85.5 | | 4.13 | 86.1 | | 4.38 | 84.3 | |
| 1 to 2 1/2 | 80 | 1 | 5.44 | 90.0 | 15.68 | 4.88 | 87.5 | 16.55 | 6.04 | 91.3 | 20.25 |
| | | 2 | 3.95 | 90.0 | 10.78 | 4.38 | 92.5 | 12.13 | 4.26 | 88.8 | 10.98 |
| | | 3 | 5.54 | 88.8 | 15.67 | 5.24 | 90.0 | 17.17 | 5.11 | 83.8 | 18.67 |
| | | Average | 4.98 | 89.6 | | 4.81 | 90.0 | | 5.14 | 88.0 | |
| 1/2 to 3 | 117 | 1 | 4.17 | 84.6 | 15.68 | 3.83 | 83.8 | 16.55 | 4.68 | 86.3 | 20.25 |
| | | 2 | 3.26 | 84.6 | 10.78 | 3.93 | 89.7 | 12.13 | 3.54 | 82.9 | 10.98 |
| | | 3 | 4.37 | 82.9 | 15.67 | 4.07 | 84.6 | 17.17 | 4.04 | 78.6 | 18.67 |
| | | Average | 3.93 | 84.0 | | 3.94 | 86.0 | | 4.09 | 82.6 | |

*Operations = arrivals and departures averaged

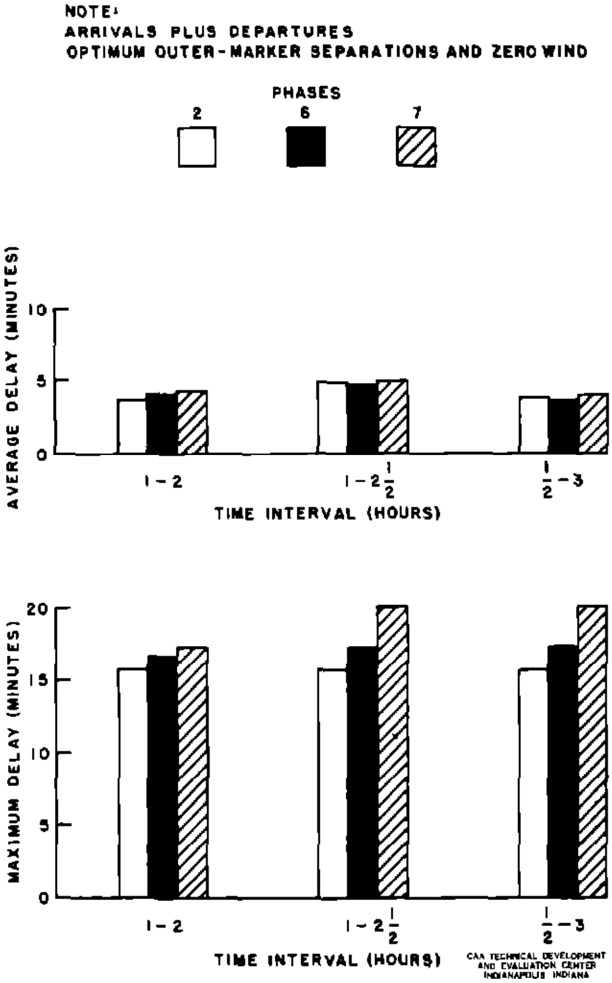


Fig 11 Average and Maximum Absolute Delays Per Operation (Graphical Analysis)

TABLE XXVIII

SUMMARY OF ABSOLUTE AND SYSTEM OPERATIONS DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2, 6, AND 7 USING SAMPLES OF ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Operations | Phase Number | Absolute Delays: Average Delay per Aircraft* (minutes) | Absolute Delays: Number of Aircraft Delayed* (per cent) | Absolute Delays: Maximum Delay (minutes) | System Delays: Average Delay per Aircraft* (minutes) | System Delays: Number of Aircraft Delayed* (per cent) | System Delays: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 55 | 2 | 3.95 | 85.5 | 15.68 | -0.25 | - 6.0 | 4.18 |
| | | 6 | 4.13 | 86.1 | 16.55 | -0.07 | - 5.4 | 5.05 |
| | | 7 | 4.38 | 84.3 | 17.25 | 0.18 | - 7.2 | 5.75 |
| 1 to 2 1/2 | 80 | 2 | 4.98 | 89.6 | 15.68 | -0.42 | - 4.6 | - 0.62 |
| | | 6 | 4.81 | 90.0 | 17.17 | -0.59 | - 4 2 | 0.80 |
| | | 7 | 5.14 | 88.0 | 20.25 | -0.26 | - 6.2 | 3.95 |
| 1/2 to 3 | 117 | 2 | 3.93 | 84.0 | 15.68 | -0.36 | - 1.2 | -0.62 |
| | | 6 | 3.94 | 86.0 | 17.17 | -0.36 | 0.8 | 0.80 |
| | | 7 | 4.09 | 82.6 | 20.25 | -0.21 | - 2.6 | 3.95 |

*Average of 3 samples

departures more efficiently without being penalized by a separation large enough to take care of the worst case, as in the ideal To a limited degree, this flexibility is also found in actual practice

It must be remembered that the ideal-analysis technique is meant to be merely a convenient and simple mathematical tool for exploring the theoretical effects of randomness, the construction of typical peak-period traffic samples, various traffic rates, separation rules, and other such factors The only ideal criterion is that random arrivals and departures are somehow delayed an amount just sufficient to meet the outer-marker and runway minima and to be consistent with the specified priority rules In the graphical analysis, the steps required to meet these rules are followed realistically, just as they might occur in actual practice or in simulation airways are followed, descent rules and distances to descend are computed, altitude and distance separations are observed, finite stacking times and times to complete 360° turns are accounted for where required, limits of turning and of vectoring are established, and so forth

Again upon reference to Tables XXIII, XXV, XXVI, and XXVII, the differences in delays between traffic samples will be noted even though these samples are identical in construction and differ only in the internal randomness in the sequencing of the exponential time intervals, of the aircraft types, and of the entry points Several glaring examples are evident In Table XXIII (arrivals only), the average absolute delay per arrival for sample No 2 in phase 2 for the period 1 to 2 1/2 hours is 4 22 minutes The corresponding delay for sample No 1 in phase 7 is 8 52 minutes This would mean that phase 2 is better than phase 7 by more than two to one On the other hand, comparison of the 4 23-minute average delay of sample No 2 for phase 7 with the 7 18-minute average delay of sample No 1 of phase 2 shows that phase 7 is now the most efficient by about 70 per cent As a matter of fact, the averages for the three traffic samples for the period of 1 to 2 1/2 hours show an absolute delay of 6 55 minutes per arrival in phase 7 and 5 69 minutes for phase 2, a difference of only 15 per cent, a percentage which is statistically insignificant Comparisons of phases even by like samples also show such inconsistencies, although to a lesser degree This fact further emphasizes the caution that must be exercised in making comparative evaluations with single, though relatively large, random samples

In comparison of the delays of operations (arrivals plus departures) in Table XXVIII with the corresponding ideal delays on Table XXI , it is again noted that there is no correlation in

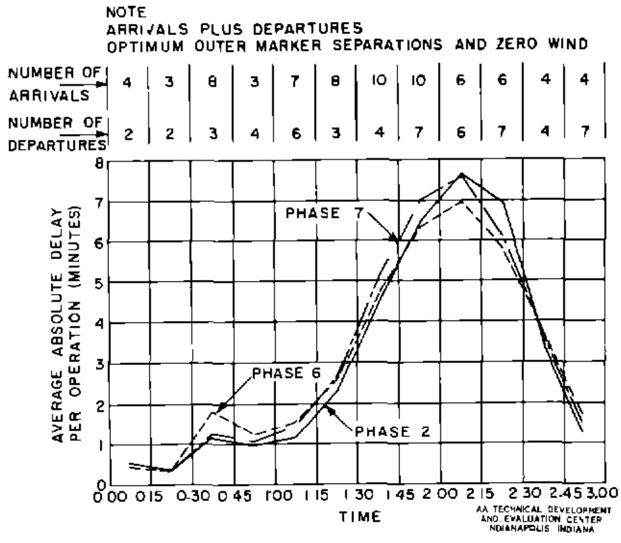


Fig 12 Average Absolute Delays (Graphical Analysis)

order of rank between samples In some cases the average delays follow 1 > 2 > 3, then 3 > 2 > 1, and so on in both the ideal and graphical analyses and with no consistent agreement

Dynamic-Simulator Results for Washington National Airport Phases 2, 6, and 7 With Zero Wind

A Delays.

Each traffic sample was run three times in the dynamic simulator, making a total of nine runs per phase Twenty-seven runs were made using the three samples of arrivals only, and twenty-seven were run using the three samples of arrivals plus departures

Tabulations and illustrations of the more pertinent results are given in Tables XXIX through XXXIV and in Figs 13 through 23 Table XXIX lists, for the samples of arrivals only, the absolute delays on each individual run and the averages of the three runs per sample according to the particular phase The variations between repeat runs and samples are again evidenced, thus re-emphasizing the danger of assessing results on the basis of single runs or on the basis of averages of single like or unlike random samples or both

Table XXX summarizes the data of Table XXIX by averaging the results of all runs and samples per phase and by then comparing the three phases through the listing of the absolute delays, the system delays, and the differences between dynamic-simulator and graphical-simulator delays Casual observation of the data indicates that there are significant differences in the magnitudes of the average delays for the three phases However, on an absolute-delay basis these differences are less than 8 per cent This amount is insignificant since it is probably less than can be attributed to chance when the variable contributions of the humans in the system and the effects of the random, though relatively large, traffic samples are considered Further comparison of the phases on the basis of system delays shows phase 2 to be most efficient by about 13 per cent Further checking with the comparable graphical results shows reasonably good agreement However, whether these differences are significant or not remains questionable at this time

In Table XXX, the differences between the dynamic-simulator and the graphical results can be considered to be criteria or indices of merit in assessing the work load and the ability of the controllers and pilots in actually handling traffic in each particular phase or method of controlling traffic This means that the larger the differences are, the more difficult the traffic is to handle, since in the graphical analysis perfect knowledge, perfect execution, and unlimited time to make the best decision in each instance dictate that the graphical delays are the lowest possible that are consistent with the particular rules, samples, and conditions being used It would be premature in this preliminary work to attempt to calibrate these criteria for comparative-evaluation purposes However, for reference purposes it is noted that by comparing the dynamic graphical simulator differences in average delays per arrival for the period 1/2 to 3 hours, for

TABLE XXIX

SUMMARY OF ABSOLUTE ARRIVAL DELAYS FOR INDIVIDUAL RUNS AND AVERAGES OF RUNS ON DYNAMIC SIMULATOR UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Sample Number | Run Number | Phase 2 Average Delay per Aircraft (minutes) | Phase 2 Number of Aircraft Delayed (per cent) | Phase 2 Maximum Delay (minutes) | Phase 6 Average Delay per Aircraft (minutes) | Phase 6 Number of Aircraft Delayed (per cent) | Phase 6 Maximum Delay (minutes) | Phase 7 Average Delay per Aircraft (minutes) | Phase 7 Number of Aircraft Delayed (per cent) | Phase 7 Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 1 | 1 | 8 68 | 94 3 | 21 2 | 8 47 | 94 3 | 20 7 | 7.59 | 100 | 20 5 |
| | | | 2 | 6 62 | 97 1 | 23 0 | 7.13 | 97 1 | 17 2 | 8 47 | 97 1 | 22 1 |
| | | | 3 | 6 88 | 97 1 | 18.3 | 8.85 | 100 | 19.1 | 10 20 | 94.3 | 23.8 |
| | | | Average | 7 39 | 96 2 | | 8 15 | 97.1 | | 8 75 | 97 1 | |
| | | 2 | 4 | 7 86 | 97 1 | 17.9 | 7 80 | 100 | 15 8 | 4.79 | 94.3 | 12 9 |
| | | | 5 | 5 32 | 100 | 13.6 | 5 93 | 100 | 15.0 | 5 66 | 97 1 | 15.0 |
| | | | 6 | 7 53 | 100 | 17 1 | 9 10 | 100 | 20.7 | 10.33 | 100 | 24 2 |
| | | | Average | 6.90 | 99 0 | | 7.61 | 100 | | 6 93 | 97.1 | |
| | | 3 | 7 | 6.62 | 97 1 | 22.0 | 6.54 | 100 | 16 3 | 6 58 | 97 1 | 16.8 |
| | | | 8 | 6 35 | 97 1 | 17 5 | 6.66 | 100 | 18 5 | 6.54 | 100 | 16 7 |
| | | | 9 | 6.30 | 100 | 16.3 | 7.34 | 97 1 | 20.3 | 5 31 | 97 1 | 15 3 |
| | | | Average | 6.42 | 98 1 | | 6 85 | 99.0 | | 6.14 | 98 1 | |
| 1 to 2 1/2 | 47 | 1 | 1 | 9 77 | 95 7 | 21.9 | 9 41 | 95.7 | 20 7 | 8 29 | 100 | 20 5 |
| | | | 2 | 6 85 | 97 9 | 23 0 | 7.19 | 97 9 | 17 2 | 9 07 | 97 9 | 22 1 |
| | | | 3 | 6 49 | 97 9 | 18 3 | 8 67 | 100 | 19 1 | 11.18 | 95 7 | 23 8 |
| | | | Average | 7 70 | 97 2 | | 8 42 | 97 9 | | 9 51 | 97.9 | |
| | | 2 | 4 | 8 12 | 97 9 | 17 9 | 7 52 | 100 | 15 8 | 4 52 | 93.6 | 12.9 |
| | | | 5 | 4.53 | 97 9 | 13 6 | 5 61 | 100 | 15 0 | 5 45 | 97 9 | 15 0 |
| | | | 6 | 8 00 | 100 | 17 9 | 9 41 | 100 | 22 9 | 10 72 | 100 | 24 2 |
| | | | Average | 6 88 | 98 6 | | 7 51 | 100 | | 6 90 | 97 2 | |
| | | 3 | 7 | 9 29 | 97 9 | 24 0 | 7 72 | 100 | 18 8 | 8 20 | 97 9 | 16 8 |
| | | | 8 | 7 95 | 97 9 | 19 1 | 8 65 | 100 | 20 0 | 8 28 | 100 | 19 1 |
| | | | 9 | 8 34 | 100 | 18 4 | 9 82 | 97 9 | 22 4 | 6 29 | 97 9 | 15 3 |
| | | | Average | 8 53 | 98 6 | | 8 73 | 99 3 | | 7 59 | 98.6 | |
| 1/2 to 3 | 66 | 1 | 1 | 7 61 | 92 4 | 21 9 | 7 90 | 93 9 | 20 7 | 7 06 | 98 5 | 20 5 |
| | | | 2 | 5 57 | 95 5 | 23 0 | 6 02 | 97 0 | 17 2 | 7 48 | 93 9 | 22 1 |
| | | | 3 | 5 27 | 95 5 | 18 3 | 7 08 | 97 0 | 19 1 | 9 31 | 93 9 | 23 8 |
| | | | Average | 6 15 | 94 5 | | 7 00 | 96 0 | | 7 95 | 95.4 | |
| | | 2 | 4 | 7 00 | 97 0 | 17 9 | 6 22 | 98 5 | 15 8 | 3 82 | 86 4 | 12 9 |
| | | | 5 | 3 76 | 92 4 | 13 6 | 4.69 | 95 5 | 15 0 | 4.40 | 92 4 | 15 0 |
| | | | 6 | 6 78 | 97 0 | 17 9 | 7 86 | 98 5 | 22 9 | 8 89 | 97 0 | 24 2 |
| | | | Average | 5.85 | 95 5 | | 6.26 | 97 5 | | 5 70 | 91 9 | |
| | | 3 | 7 | 7 75 | 97 0 | 24 0 | 6 02 | 97 0 | 18 8 | 6 24 | 97 0 | 16 8 |
| | | | 8 | 6 13 | 92 4 | 19 1 | 6 74 | 93 9 | 20 0 | 6 29 | 95 5 | 19.1 |
| | | | 9 | 6 45 | 97 0 | 18 4 | 7 70 | 97 0 | 22.4 | 4 92 | 98 5 | 15.3 |
| | | | Average | 6 78 | 95 5 | | 6 82 | 96.0 | | 5 82 | 97 0 | |

NOTE Samples of arrivals only

example, phase 7 was easier to handle than phase 2 by $\frac{1\ 87}{1\ 38} = 1\ 35$, or 35 per cent On the other hand, comparison of the absolute average delays shown on Table XXX for the same period shows phase 2 to be more efficient than phase 7 on an over-all-delay basis by $\frac{6\ 49}{6\ 26} = 1\ 035$, or 3 1/2 per cent Further comparison of system (absolute minus ideal) delays shows phase 2 to be more efficient than phase 7 by $\frac{4\ 22}{3\ 99} = 1\ 06$, or 6 per cent Comparisons of the ratios of the average delays of all the dynamic-simulator results with the graphical results for the average of all periods and all phases show that the dynamic simulator approached about 75 per cent of the degree of perfection of the graphical, phases 2 and 6 rated 72 per cent, and phase 7 rated best, 79 per cent

Certainly much more experimental data must be obtained before any simulation, analytical and statistical tools can be properly calibrated with a reasonable degree of validity Meanwhile,

TABLE XXX

SUMMARY OF ARRIVAL DELAYS FOR DYNAMIC-SIMULATOR RUNS UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations | Number of Arrivals | Phase Number | Absolute Delays | | | System Delays | | | Difference Between Dynamic and Graphical Delays | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (hour) | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 2 | 6 90 | 97 8 | 23 0 | 3 88 | 6 4 | 14 2 | 1 87 | 8 3 | 7 3 |
| | | 6 | 7 54 | 98 7 | 20 7 | 4 52 | 7 3 | 11 9 | 2 14 | 6 3 | 4 1 |
| | | 7 | 7 27 | 97 4 | 24 2 | 4 25 | 6 0 | 15 4 | 1 69 | 7 9 | 6 9 |
| 1 to 2 1/2 | 47 | 2 | 7 70 | 98 3 | 24 0 | 4 79 | 14 6 | 13.3 | 2 01 | 6 1 | 8 3 |
| | | 6 | 8 22 | 99 1 | 22 9 | 5 31 | 15 4 | 12 2 | 2 13 | 4 8 | 5 7 |
| | | 7 | 8 00 | 97 9 | 24 2 | 5 09 | 14 2 | 13 5 | 1 45 | 6 4 | 3 9 |
| 1/2 to 3 | 66 | 2 | 6 26 | 95 2 | 24 0 | 3 99 | 22 0 | 13 3 | 1 87 | 10 8 | 8 3 |
| | | 6 | 6 69 | 96 5 | 22 9 | 4 42 | 23 3 | 12 2 | 1 88 | 8 6 | 5 7 |
| | | 7 | 6 49 | 94 8 | 24 2 | 4 22 | 21 6 | 13 5 | 1 38 | 11 0 | 3 9 |

NOTE Samples of arrivals only
The system delay is the absolute delay minus the ideal delay It is the entire system of traffic, rules, human factors, layout, and so forth in excess of that required for the shortest route with no traffic

results must be interpreted cautiously There are many more conditions and ranges of variables to be investigaged Hasty misuse and misinterpretation of preliminary data can result in erroneous conclusions

Tables XXXI and XXXII list for the samples of arrivals plus departures the arrival-and-departure absolute delays for each individual run and the averages of the runs according to the particular phase In Table XXXIII, the data of Tables XXXI and XXXII are summarized by averaging the results of all samples and runs according to the different phases, these data are presented in the form of absolute and system delays for the arrivals and departures separately The fact that the departure-system delays are negative is attributable to the fact that the ideal analysis followed explicit and inflexible rules, as discussed previously

The same differences between individual runs, like and unlike samples, and other variations discussed in the foregoing for the samples of arrivals only also exist in these arrival-plus-departure data and will not be discussed further However, when corresponding graphical results are compared with the dynamic-simulator results, it is noted that the arrival delays went up appreciably in the dynamic-simulator runs where arrival delays were held constant by using the departure-interspersion technique in the graphical analysis At the same time, the dynamic-simulator departure delays were usually less than those in the graphical analysis This difference resulted from the fact that TDEC controllers used the usual degree of conservatism in providing larger arrival separations than those used for arrivals only Such conservatism is typical of present-day, single-runway practice where large variations in probable performance must be taken into account if wave-offs are to be minimized However, it decreases the acceptance rate and causes the arrival delays to increase more than the decrease in departure delays This condition is undesirable

A more meaningful comparison of the results for the samples of arrivals plus departures is shown in Table XXXIV in the form of delays per operation It is seen that where a little choice between phases was implied for the case of arrivals only, there was even less choice on the basis of operations in the samples of arrivals plus departures Even the differences between the graphical and dynamic-simulator results remain fairly constant

The over-all ratio of dynamic to graphical average delays per operation for all periods showed the dynamic simulator approached the degree of perfection of the graphical by about 66 per cent, phase 2 rated 65 per cent, phase 6 rated 63 per cent, and phase 7 rated best at 69 per cent

Further illustrations of the dynamic-simulator over-all results and comparisons with graphical and ideal data are shown in Figs 13 through 23 Figs 13 and 14 are bar graphs of the comparison between the three phases of the dynamic-simulator absolute average and maximum delays averaged out for all runs and samples Figs 15 through 23 show the comparisons of the average absolute delays between phases, between corresponding graphical, dynamic, and

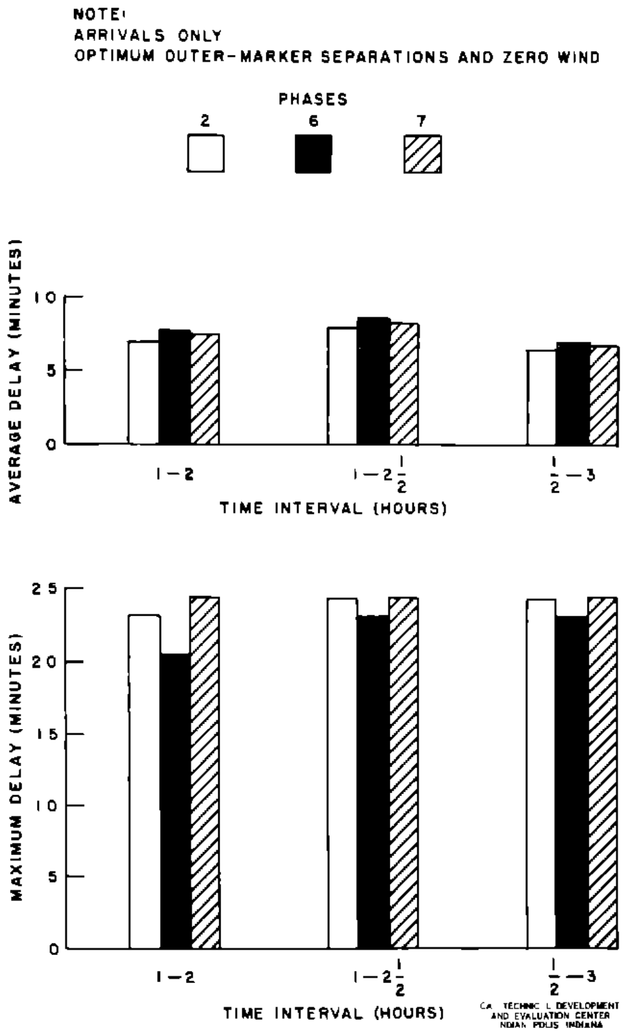


Fig 13 Average and Maximum Absolute Delays Per Arrival (TDEC Dynamic Simulator)

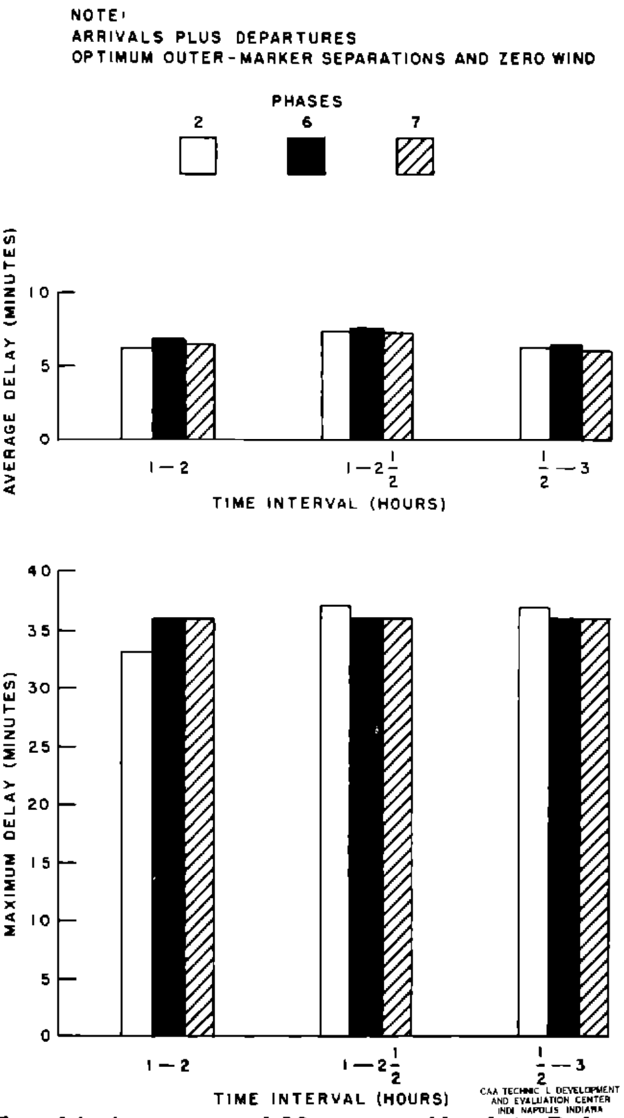


Fig 14 Average and Maximum Absolute Delays Per Operation (TDEC Dynamic Simulator)

ideal delays, and so forth, all in the form of time series of average delays per arrival or per operation in each successive 15-minute period The agreement between the graphical and the dynamic-simulator results, the differences, and the index of merit discussed previously should all be noted These time-series presentations show how the delays in the system build up and back up with the particular time and traffic rates They also show that appreciable differences exist between phases for short saturated periods of 15 or 30 minutes, even though the delay data averaged out for periods of one or more hours show relatively little difference Whether or not these 15- or 30-minute periods are of any significance is beyond the scope of this work However, the delays occurring during these short periods of rather infrequent occurrences are somewhat similar to those which the Bell Telephone Laboratories classify as "grade-of-service Are short periods, or infrequent occurrences, or both, the conditions for which the system should be designed? If so, what grade of service is acceptable for other conditions or periods? The answers to such questions are quite controversial and should be judged at much higher levels

B Communications

Pertinent data on communications densities per channel, average communications time per aircraft, average message length, and average number of messages per aircraft for the

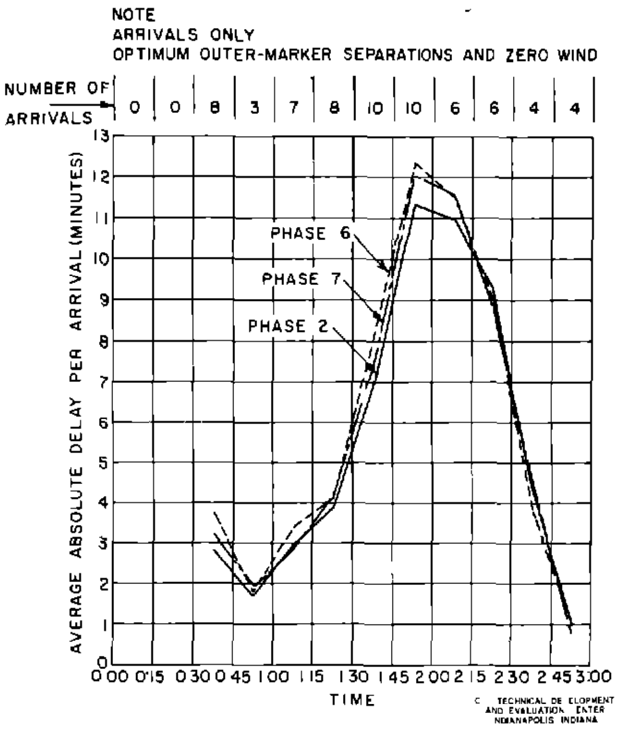


Fig 15 Average Absolute Delays Per Arrival (TDEC Dynamic Simulator)

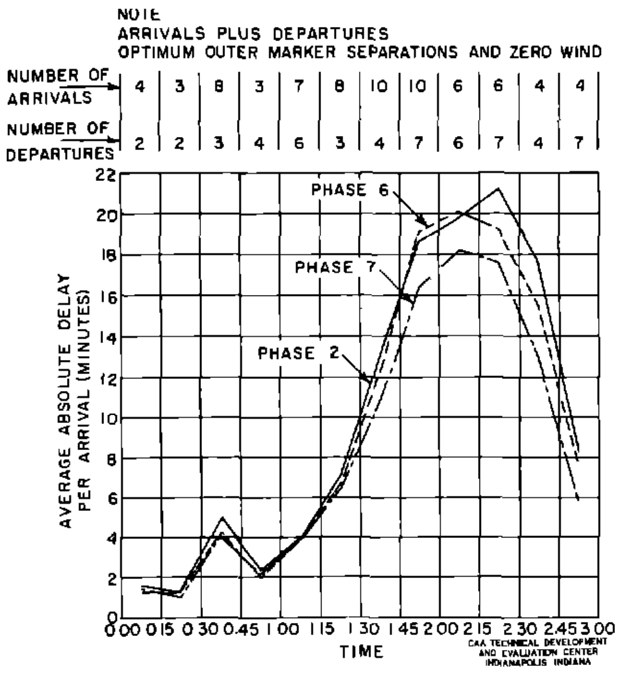


Fig 16 Average Absolute Delays Per Arrival (TDEC Dynamic Simulator)

various phases and channels are given in Tables XXXV and XXXVI and in Figs 24 through 28 Table XXXV and Figs 24 and 25 are for the samples of arrivals only Table XXXVI and Figs 26, 27, and 28 are for the samples of arrivals plus departures Fig 28 is presented as the combined density of the east and west approach-control sectors (channels 1 and 3) in the form of the time series discussed previously, the build-up of communication densities per phase with time and traffic rates can be followed and further correlated with the time series of delays per phase shown in Figs 16 and 17

Four communication channels were simulated, east-sector approach control, west-sector approach control, airport ground control, and a channel for center-to-tower transition In addition, in place of the usual flight-progress boards and strips, a two-digit limited-data-transfer device was used between the center and the tower and between east and west approach-control sectors in the tower

As in the case of delays, the communications data show that there is little or no difference between phases The small differences that do occur are no greater than should be expected by chance

Examination of the data reveals the following interesting facts The air-borne personnel talk about 70 to 80 per cent as much as those at the ground station There is a difference between samples in the amount of communications sample 2 carries far less communications than the other two samples in the west sector and far more than the other two in the east sector when both air and ground during all phases and runs are considered There is an apparent difference between phases in ground communications, with phase 7 having the most live time in the west sector This was caused by several irregular circumstances During all three runs of sample No 1 during phase 7, departure control was handled on the same channel as the west sector, and during run 18 of phase 7, the air traffic control channel broke down and was combined with this same ground channel in the west sector With these irregularities accounted for, there was no significant difference between phases

Further examination of the data shows an apparent difference in the amount of talking, that is, there appears to have been less talking when both arrivals and departures were handled than there was when only arrivals were involved This was due to the fact that during the runs involving only arrivals, there were more airplane consoles available than during the runs involving both arrivals and departures, therefore it was possible to start the arrival aircraft further out

TABLE XXXI

SUMMARY OF ABSOLUTE ARRIVAL DELAYS FOR INDIVIDUAL RUNS AND AVERAGES OF RUNS ON DYNAMIC SIMULATOR USING ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Sample Number | Run Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 1 | 10 | 12 4 | 94 3 | 24 6 | 12 1 | 97 1 | 30 1 | 15 3 | 100 | 35 8 |
| | | | 11 | 10 9 | 97 1 | 27 1 | 12 0 | 94 3 | 29 8 | 11 8 | 91 4 | 32 4 |
| | | | 12 | 11 3 | 91 4 | 33 1 | 13 2 | 97 1 | 31 3 | 10 6 | 100 | 23.3 |
| | | | Average | 11 5 | 94 3 | | 12 4 | 96 2 | | 12 6 | 97 1 | |
| | | 2 | 13 | * | * | * | 12 7 | 100 | 22 2 | 10 6 | 97 1 | 22 8 |
| | | | 14 | * | * | * | 11 8 | 100 | 35 8 | 13 4 | 100 | 29 5 |
| | | | 15 | 9 8 | 100 | 20 4 | 9 7 | 97 1 | 22 9 | 8 0 | 100 | 20 2 |
| | | | Average | 9 8 | 100 | | 11 4 | 99 0 | | 10 7 | 99 0 | |
| | | 3 | 16 | 6 5 | 100 | 21 3 | 8 8 | 100 | 20 7 | 7 5 | 100 | 20 0 |
| | | | 17 | 9 5 | 100 | 30 9 | 10 3 | 100 | 25 5 | 6 0 | 97 1 | 17 1 |
| | | | 18 | 8 7 | 100 | 26 1 | 8 7 | 100 | 20 6 | 7.9 | 97 1 | 20 8 |
| | | | Average | 8 2 | 100 | | 9 3 | 100 | | 7 1 | 98 1 | |
| 1 to 2 1/2 | 47 | 1 | 10 | 13 8 | 95 7 | 24 6 | 14 3 | 97 9 | 30 1 | 18 3 | 100 | 35 8 |
| | | | 11 | 13 1 | 97 9 | 27 1 | 13 5 | 95 7 | 29 8 | 13 9 | 93 6 | 32 4 |
| | | | 12 | 13 4 | 93 6 | 33 1 | 14 9 | 97 9 | 31 3 | 11 5 | 100 | 23 3 |
| | | | Average | 13 4 | 95 7 | | 14 2 | 97 2 | | 14 6 | 97 9 | |
| | | 2 | 13 | * | * | * | 13 5 | 100 | 22 6 | 12 4 | 97 9 | 22 8 |
| | | | 14 | * | * | * | 14 0 | 100 | 35 8 | 15 5 | 100 | 32 8 |
| | | | 15 | 10 8 | 100 | 20 4 | 11 7 | 97 9 | 35 2 | 8 2 | 100 | 20 2 |
| | | | Average | 10 8 | 100 | | 13 1 | 99 3 | | 12 1 | 99 3 | |
| | | 3 | 16 | 9 1 | 100 | 22 9 | 11 5 | 100 | 28 0 | 9 7 | 100 | 21 7 |
| | | | 17 | 14 1 | 100 | 37 4 | 13 8 | 100 | 29 1 | 8 1 | 97 9 | 19 5 |
| | | | 18 | 11 4 | 100 | 26 3 | 11 7 | 100 | 30 1 | 11 0 | 97 9 | 24 1 |
| | | | Average | 11 5 | 100 | | 12 3 | 100 | | 9 6 | 93 6 | |
| 1/2 to 3 | 66 | 1 | 10 | 11 4 | 95 5 | 24 6 | 12 2 | 97 0 | 30 1 | 15 6 | 100 | 35 8 |
| | | | 11 | 11 7 | 98 5 | 27 1 | 11 1 | 95 4 | 29 8 | 12 0 | 95 4 | 32 4 |
| | | | 12 | 11 8 | 95 5 | 33 1 | 12 6 | 97 0 | 31 3 | 9 4 | 97 0 | 23 3 |
| | | | Average | 11 6 | 96 5 | | 12 0 | 96 8 | | 12 3 | 97 5 | |
| | | 2 | 13 | * | * | * | 11 9 | 100 | 22 6 | 11 4 | 98 5 | 22 8 |
| | | | 14 | * | * | * | 12 9 | 100 | 35 8 | 14 2 | 100 | 35 7 |
| | | | 15 | 10 6 | 100 | 20 6 | 11 5 | 98 5 | 35 2 | 7 3 | 97 | 20 2 |
| | | | Average | 10 6 | 100 | | 12 1 | 99 5 | | 11 0 | 98 5 | |
| | | 3 | 16 | 7 2 | 100 | 22 9 | 9 7 | 100 | 28 0 | 7 6 | 100 | 21 7 |
| | | | 17 | 12 5 | 100 | 37 4 | 11 2 | 100 | 29 1 | 6 8 | 97 0 | 19 5 |
| | | | 18 | 9 5 | 98 5 | 26 3 | 9 5 | 100 | 30 1 | 9 2 | 98 5 | 24 1 |
| | | | Average | 9 6 | 99 5 | | 10 1 | 100 | | 7 7 | 98 5 | |

*Runs 13 and 14 of phase 2 were not included because they were run under adverse conditions

in the problem and thus have them under actual simulated control for a longer time Consequently this added to the total amount of communications

In summary, over-all examination of the communications data shows that use of the limited-data-transfer device between the center and the tower and between sector controllers in the tower, plus some form of sector-control radar-vectoring procedures in the terminal area, results in simple communications which can be handled for a good number of years to come with low density and work load on only a few channels and with present equipment The implication

TABLE XXXII

SUMMARY OF ABSOLUTE DEPARTURE DELAYS FOR INDIVIDUAL RUNS AND AVERAGES OF RUNS ON DYNAMIC SIMULATOR USING ARRIVALS PLUS DEPARTURES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Departures | Sample Number | Run Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 20 | 1 | 10 | 1 00 | 85 0 | 5 4 | 1 80 | 95 0 | 8 3 | 1 14 | 75 0 | 3 2 |
| | | | 11 | 1 10 | 85 0 | 3 5 | 0 77 | 95 0 | 3 1 | 1 50 | 80 0 | 4.5 |
| | | | 12 | 2 0 | 90 0 | 8 7 | 0 79 | 55 0 | 3 6 | 1 60 | 90 0 | 9 2 |
| | | | Average | 1 4 | 86 7 | | 1 1 | 81 7 | | 1 4 | 81 7 | |
| | | 2 | 13 | * | * | * | 1 1 | 75 0 | 4 2 | 1 70 | 92 0 | 5 9 |
| | | | 14 | * | * | * | 0 79 | 75 0 | 2 6 | 1 60 | 95 0 | 4 9 |
| | | | 15 | 2 20 | 85 0 | 5 3 | 0 72 | 75 0 | 2 8 | 2 00 | 95 0 | 6.1 |
| | | | Average | 2 20 | 85 0 | | 0 9 | 75 0 | | 1 8 | 94 0 | |
| | | 3 | 16 | 0 78 | 80 0 | 2 4 | 0 80 | 95 0 | 3 2 | 0 89 | 85 0 | 2 4 |
| | | | 17 | 1 90 | 100 | 5 8 | 0 36 | 70 0 | 1 5 | 1 00 | 95 0 | 3 7 |
| | | | 18 | 1 04 | 90 0 | 3 6 | 0 60 | 65 0 | 2 6 | 0 97 | 90 0 | 2 4 |
| | | | Average | 1 2 | 90 0 | | 0 6 | 76 7 | | 1 0 | 90 0 | |
| 1 to 2 1/2 | 33 | 1 | 10 | 1 70 | 91 0 | 5 4 | 1 5 | 97 0 | 8 3 | 1.11 | 78 8 | 3 2 |
| | | | 11 | 1 30 | 90 9 | 4 1 | 1 03 | 97 0 | 3 1 | 1 80 | 84 8 | 5 1 |
| | | | 12 | 3 0 | 94 0 | 8 7 | 0 83 | 66 7 | 3 6 | 3 50 | 93.9 | 9 2 |
| | | | Average | 2 0 | 92 0 | | 1 1 | 86 9 | | 2 1 | 85.8 | |
| | | 2 | 13 | * | * | * | 1 30 | 78 8 | 5 2 | 2 30 | 93 0 | 7 8 |
| | | | 14 | * | * | * | 0 94 | 78 8 | 3 1 | 1 40 | 78 8 | 4 9 |
| | | | 15 | 2 10 | 91 0 | 6 1 | 0 72 | 72 7 | 2 9 | 1 90 | 94 0 | 6 1 |
| | | | Average | 2 1 | 91 0 | | 1 0 | 76 8 | | 1 9 | 88 6 | |
| | | 3 | 16 | 1 10 | 84 8 | 3 0 | 1 30 | 97 0 | 3 7 | 1 50 | 87 9 | 5 6 |
| | | | 17 | 2 30 | 100 | 8 1 | 0 57 | 78 8 | 2 2 | 1 60 | 90 9 | 6 6 |
| | | | 18 | 1 35 | 90 9 | 5 0 | 0 91 | 72 7 | 3 2 | 1 10 | 90 9 | 3 1 |
| | | | Average | 1 6 | 91 9 | | 0 9 | 82 8 | | 1 4 | 89 9 | |
| 1/2 to 3 | 51 | 1 | 10 | 1 40 | 86.3 | 5 4 | 1 3 | 90 2 | 8 3 | 0 95 | 78 4 | 3 2 |
| | | | 11 | 1 10 | 86 3 | 4 1 | 0 96 | 98 0 | 3 1 | 1 30 | 72 5 | 5 1 |
| | | | 12 | 2 10 | 86 3 | 8 7 | 0 64 | 58 6 | 3 6 | 2 50 | 92 2 | 9 2 |
| | | | Average | 1 5 | 86 3 | | 1 0 | 82 3 | | 1 6 | 81 0 | |
| | | 2 | 13 | * | * | * | 1 2 | 73 5 | 5 2 | 2 1 | 92 0 | 7 8 |
| | | | 14 | * | * | * | 0 84 | 72 5 | 4 2 | 1 3 | 80 4 | 4 9 |
| | | | 15 | 1 90 | 90 2 | 6 1 | 0 79 | 74 5 | 3.8 | 1 7 | 96 0 | 6.1 |
| | | | Average | 1 9 | 90 2 | | 0 9 | 73 5 | | 1 7 | 89.5 | |
| | | 3 | 16 | 1 00 | 82 3 | 4 5 | 1 30 | 96 1 | 4 0 | 1 30 | 90 2 | 5 6 |
| | | | 17 | 2 10 | 98 0 | 8 1 | 0 85 | 80 4 | 5 1 | 1 40 | 92 2 | 6 6 |
| | | | 18 | 1 13 | 88 2 | 5 0 | 1 10 | 74 5 | 4 4 | 1 30 | 92 2 | 4 6 |
| | | | Average | 1 4 | 89 5 | | 1 1 | 83 7 | | 1 3 | 91 5 | |

*Runs 13 and 14 of Phase 2 were not included because they were run under adverse conditions

is apparent The effect of simplifying procedures (assuming no attendant decrease in safety) can often alleviate and sometimes eliminate many barriers, some of which are usually inherent because of unorganized attempts to alleviate some other deficiency In the studies described in this report, there was little flow control exercised or necessary in feeding aircraft into the terminal area The simple, straightforward, direct-control procedures allowed the random high traffic rates employed to be absorbed in the terminal area with a relatively low work load and with a minimum of delays

TABLE XXXIII

SUMMARY OF ABSOLUTE AND SYSTEM ARRIVAL AND DEPARTURE DELAYS FOR DYNAMIC-SIMULATOR RUNS UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Number of Departures | Phase Number | Absolute Delays | | | | | | System Delays | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Arrivals | | | Departures | | | Arrivals | | | Departures | | |
| | | | | Average Delay per Aircraft* (minutes) | Number of Aircraft Delayed* (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft* (minutes) | Number of Aircraft Delayed* (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft* (minutes) | Number of Aircraft Delayed* (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft* (minutes) | Number of Aircraft Delayed* (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 20 | 2 | 9.8 | 98.1 | 33.1 | 1.4 | 87.2 | 8.7 | 5.6 | 4.8 | 21.6 | -2.9 | -1.1 | -1.0 |
| | | | 6 | 11.0 | 98.4 | 35.8 | 0.9 | 77.8 | 8.3 | 6.8 | 5.1 | 24.3 | -3.4 | -10.5 | -2.0 |
| | | | 7 | 10.1 | 98.1 | 35.8 | 1.4 | 88.6 | 9.2 | 5.9 | 4.8 | 24.3 | -2.3 | +0.3 | -1.1 |
| 1 to 2 1/2 | 47 | 33 | 2 | 12.2 | 98.6 | 37.4 | 1.8 | 98.3 | 8.7 | 7.4 | 3.6 | 22.0 | -4.5 | +5.6 | -7.6 |
| | | | 6 | 13.2 | 98.8 | 35.8 | 1.0 | 82.2 | 8.3 | 8.4 | 3.8 | 20.4 | -5.3 | -10.5 | -8.0 |
| | | | 7 | 12.1 | 98.6 | 35.8 | 1.8 | 88.1 | 9.2 | 7.3 | 3.6 | 20.4 | -4.5 | -4.6 | -7.1 |
| 1/2 to 3 | 66 | 51 | 2 | 10.7 | 98.7 | 37.4 | 1.5 | 88.7 | 8.7 | 6.9 | 15.4 | 22.0 | -3.5 | +1.1 | -7.6 |
| | | | 6 | 11.4 | 98.8 | 35.8 | 1.0 | 79.8 | 8.3 | 7.6 | 15.5 | 20.4 | -4.0 | -7.8 | -8.0 |
| | | | 7 | 10.3 | 98.2 | 35.8 | 1.5 | 87.5 | 9.2 | 6.5 | 14.9 | 20.4 | -3.5 | -0.[illegible] | -7.1 |

*Averages of all runs and samples except runs 13 and 14 of Phase 2, which are not included.

## IDEAL ANALYSIS OF USE OF 3-MILE SEPARATION

Without a fine degree of speed control, use of the three-mile uniform separations from the outer marker to the runway yielded an abnormally high percentage of probable wave-offs For purposes of reference and for setting up the proper order, sequence, and outer-marker arrival times in the wave-off analysis it was necessary to analyze the 3-mile rule ideally At the time this was done, the entire 3-hour samples of traffic were used, none of the probable wave-offs were reintroduced The minimum separations for the zero-wind condition were given in Table XI, the minimum separations during the 20-mph headwind are shown in Table XXXVII

Use of the 3-mile separation rule yields a theoretical maximum acceptance rate of 41 3 aircraft per hour in zero wind and 35 0 aircraft per hour in a 20-mph headwind, if it is assumed that there are no wave-offs A summary of the arrival delays using the three 3-hour samples of arrivals only and samples of arrivals plus departures is shown in Tables XXXVIII and XXXIX Both the zero-wind and 20-mph-headwind conditions are included, and no wave-offs were reintroduced Previously described rules for the intermixing of departures were used All military operations were presumed to land or to take off at Bolling or at Anacostia Again it should be noted that the arrival delays for the 20-mph-headwind condition are more than double those of the zero-wind condition Further comparisons of the samples of arrivals only with the samples of arrivals plus departures show that single-runway interspersion of departures increases the delay of the arrivals by about another 50 to 60 per cent

## GRAPHICAL ANALYSIS OF MODIFIED PHASE-2 PROCEDURES

Phases 2, 6, and 7, are essentially moving-block systems where aircraft are "vectored" (controlled by radar) when necessary all the way from the rim of the 40-mile diameter to the inner twin stacks and to the airport Although moving-block systems produce smaller delays than other systems, at least on an analytical basis, they can impose severe work loads on the humans in the system when some practical type of computing and when flight-path planning devices are not available In addition, when the performance of both controllers and pilots is not up to the usual high standards, the number of communications, repeats, and other factors might

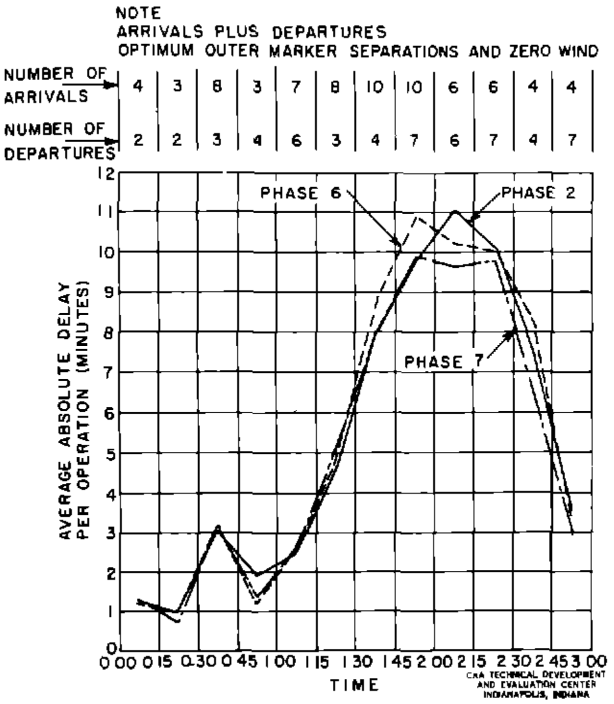


Fig 17 Average Absolute Delays Per Operation (TDEC Dynamic Simulator)

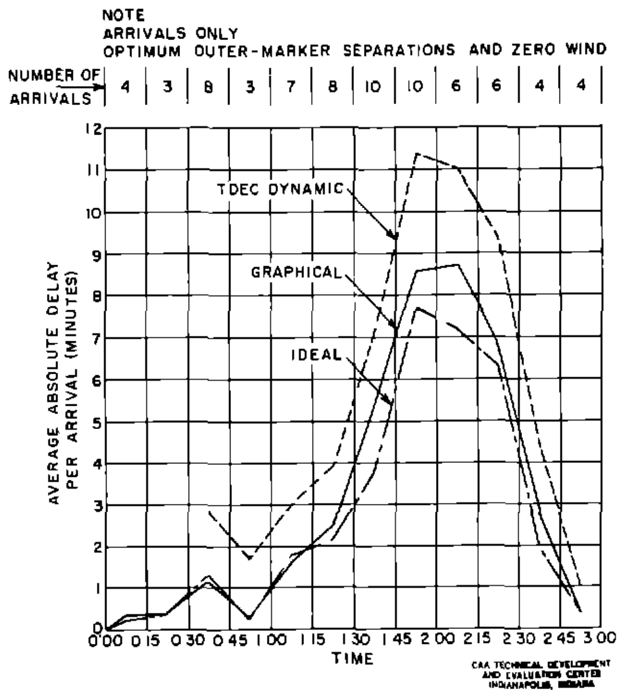


Fig 18 Average Absolute Delays Per Arrival, Phase 2 (Ideal, Graphical, and TDEC Dynamic Simulator)

TABLE XXXIV

SUMMARY OF OPERATIONS DELAYS FOR DYNAMIC SIMULATOR UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operation | Number of Arrivals | Number of Departures | Phase Number | Absolute Delays: Average Delay per Aircraft* (minutes) | Absolute Delays: Number of Aircraft Delayed* (per cent) | Absolute Delays: Maximum Delay (minutes) | System Delay: Average Delay per Aircraft* (minutes) | System Delay: Number of Aircraft Delayed* (per cent) | System Delay: Maximum Delay (minutes) | Difference Between Graphical and Dynamic Delays: Average Delay per Aircraft* (minutes) | Difference Between Graphical and Dynamic Delays: Number of Aircraft Delayed* (per cent) | Difference Between Graphical and Dynamic Delays: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 20 | 2 | 6 3 | 93 6 | 33 1 | 2 1 | 2 3 | 21 6 | 2 3 | 8 1 | 17 4 |
| | | | 6 | 6 8 | 90 0 | 35 8 | 2 6 | -1 3 | 24 3 | 2 7 | 3 9 | 19 2 |
| | | | 7 | 6 5 | 94 3 | 35 8 | 2 3 | 3 0 | 24 3 | 2 1 | 10 0 | 18 5 |
| 1 to 2 1/2 | 47 | 33 | 2 | 7 3 | 98 5 | 37 4 | 1 5 | 4 4 | 21 1 | 2 3 | 8 9 | 21 7 |
| | | | 6 | 7 4 | 91 0 | 35 8 | 1.6 | -3 1 | 19 5 | 2 6 | 1 0 | 18 6 |
| | | | 7 | 7 2 | 93 6 | 35 8 | 1 4 | -0 5 | 19 5 | 2 1 | 5 6 | 15 5 |
| 1/2 to 3 | 66 | 51 | 2 | 6 2 | 93 8 | 37 4 | 1 5 | 8 4 | 21 1 | 2 3 | 9 8 | 21 7 |
| | | | 6 | 6 3 | 89 7 | 35 8 | 1 6 | 4 3 | 19 5 | 2 4 | 3 7 | 18 6 |
| | | | 7 | 6 0 | 93 0 | 35 8 | 1 3 | 7 6 | 19 5 | 1 9 | 10 4 | 15 5 |

*Average of all runs and samples except runs 13 and 14 of Phase 2

TABLE XXXV

COMPARISON OF ARRIVAL COMMUNICATIONS DATA FOR DYNAMIC-SIMULATOR RUNS UNDER CONDITIONS OF ZERO WIND FOR OPERATIONS DURING HOURS 1/2 TO 3

| Sample Number | Phase Number | Tower and Air Total: Channel 1, West Sector: Density of Live Time (per cent) | Channel 1: Average Message Length (seconds) | Channel 1: Average Communications Time per Aircraft (seconds) | Tower and Air Total: Channel 3, East Sector: Density of Live Time (per cent) | Channel 3: Average Message Length (seconds) | Channel 3: Average Communications Time per Aircraft (seconds) | Center and Tower Total: Channel 6, Center-to-Tower Transition: Density of Live Time (per cent) | Channel 6: Average Message Length (seconds) | Channel 6: Average Communications Time per Aircraft (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 29 0 | 3 9 | 97 3 | 35.0 | 3 6 | 79 7 | 12 0 | 2 8 | 16 6 |
| | 6 | 29 0 | 3 [illegible] | 84 7 | 41.[illegible] | 3 1 | 91 8 | 12 0 | 2 7 | 16 4 |
| | 7 | 23 0 | 3 3 | 82 1 | 35 0 | 3 6 | 83 2 | 13 0 | 2 4 | 19 1 |
| 2 | 2 | 23 0 | 3 4 | 69 4 | 37.0 | 3 3 | 86 3 | 12 0 | 2 5 | 15 8 |
| | 6 | 31.0 | 3 2 | 103 3 | 34 0 | 2 8 | 85.0 | 16.0 | 2 3 | 22 1 |
| | 7 | 24.0 | 3 2 | 73 3 | 34 0 | 3 3 | 80 8 | 18 0 | 3 1 | 24.2 |
| 3 | 2 | 29 0 | 3 0 | 88 1 | 31 0 | 2 7 | 77 2 | 12 0 | 2 3 | 15 7 |
| | 6 | 29 0 | 3 1 | 89 4 | 35 0 | 3 1 | 84 9 | 13 0 | 3.1 | 17 8 |
| | 7 | 25 0 | 3 3 | 76 9 | 31.0 | 2 9 | 77 9 | 15 0 | 2.7 | 20 8 |
| Average | 2 | 27 0 | 3.4 | 84 9 | 34 0 | 3 2 | 81 1 | 12 0 | 2 5 | 16 1 |
| | 6 | 30 0 | 3 1 | 92 5 | 37 0 | 3 0 | 87 2 | 14 0 | 2 7 | 18 8 |
| | 7 | 24 0 | 3 3 | 77 5 | 33 0 | 3 3 | 80 6 | 15 0 | 2 7 | 21.4 |

All values are for an average of 3 runs per sample

Breakdown of tower-and-air data not available  Runs used samples of arrivals only

affect the over-all results by offsetting the benefits derived from the most efficient systems In order to reach some compromise, the relative merits of a system with both fixed and moving blocks were investigated graphically It was believed that such a system would reduce the work load and thus maintain top efficiency without additional personnel and unproven equipment, at the same time maintaining or bettering safety standards

In this fixed-moving-block system, it is assumed that the portion of the terminal area up to and including the twin feeder stacks and holding patterns would be operated somewhat as a fixed-block system The portion between the twin stacks, the outer marker, and the airport would operate as a moving-block system and would use the optimum and minimum radar separations described previously

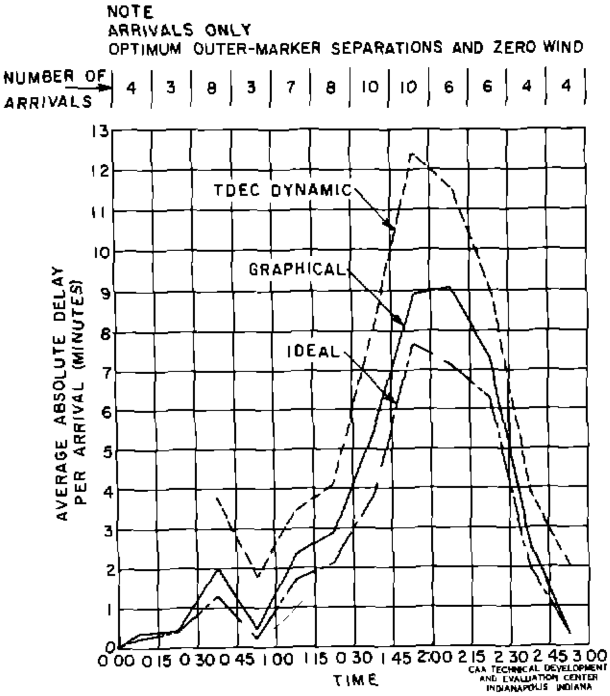


Fig 19 Average Absolute Delays Per Arrival, Phase 6 (Ideal, Graphical, and TDEC Dynamic Simulator)

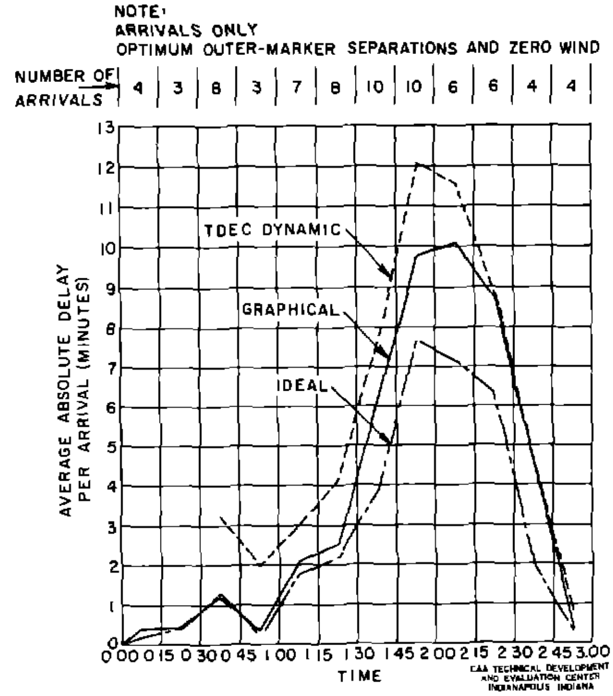


Fig 20 Average Absolute Delays Per Arrival, Phase 7 (Ideal, Graphical, and TDEC Dynamic Simulator)

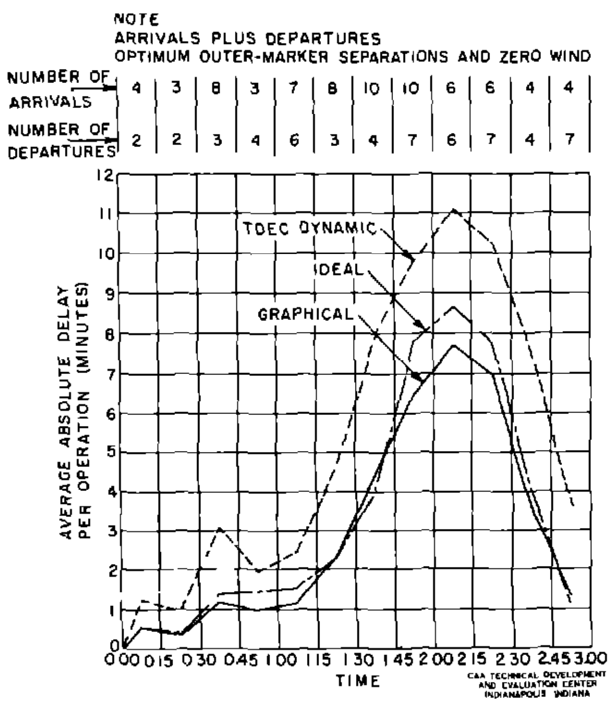


Fig 21 Average Absolute Delays Per Operation Phase 2 (Ideal, Graphical, and TDEC Dynamic Simulator)

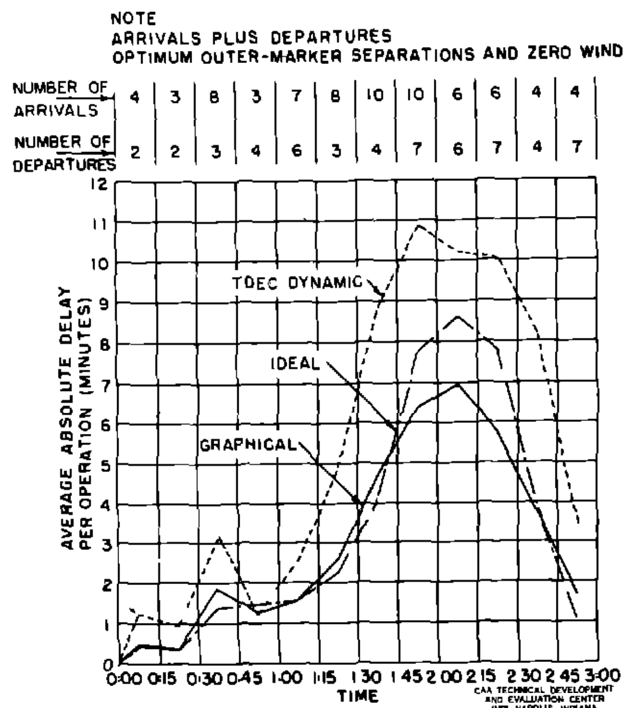


Fig 22 Average Absolute Delays Per Operation Phase 6 (Ideal, Graphical, and TDEC Dynamic Simulator)

TABLE XXXVI

COMPARISON OF COMMUNICATIONS DATA FOR DYNAMIC-SIMULATOR RUNS USING ARRIVALS PLUS DEPARTURES AT ZERO WIND

| Period of Operation (hour) | Channel Number | Sector | Phase Number | Sample Number | Tower to Air: Density Live Time (per cent) | Tower to Air: Average Length of Message (seconds) | Tower to Air: Average Communication Time per Aircraft (seconds) | Air to Tower: Density Live Time (per cent) | Air to Tower: Average Length of Message (seconds) | Air to Tower: Average Communication Time per Aircraft (seconds) | Tower and Air Total: Density Live Time (per cent) | Tower and Air Total: Average Length of Message (seconds) | Tower and Air Total: Average Communication Time per Aircraft (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 1 | West | 2 | 1 | 13 | | | 10 | | | 23 | | |
| | | | | 2 | 11 | | | 8 | | | 19 | | |
| | | | | 3 | 16 | | | 12 | | | 28 | | |
| | | | | Average | 13 | | | 10 | | | 23 | | |
| | | | 6 | 1 | 18 | | | 12 | | | 30 | | |
| | | | | 2 | 10 | | | 7 | | | 17 | | |
| | | | | 3 | 14 | | | 10 | | | 24 | | |
| | | | | Average | 14 | | | 9 | | | 23 | | |
| | | | 7 | 1 | 23 | | | 14 | | | 37 | | |
| | | | | 2 | 10 | | | 8 | | | 18 | | |
| | | | | 3 | 20 | | | 12 | | | 32 | | |
| | | | | Average | 18 | | | 11 | | | 29 | | |
| 1 to 2 | 3 | East | 2 | 1 | 15 | | | 12 | | | 27 | | |
| | | | | 2 | 20 | | | 16 | | | 36 | | |
| | | | | 3 | 19 | | | 14 | | | 33 | | |
| | | | | Average | 18 | | | 14 | | | 32 | | |
| | | | 6 | 1 | 16 | | | 11 | | | 27 | | |
| | | | | 2 | 24 | | | 18 | | | 42 | | |
| | | | | 3 | 18 | | | 13 | | | 31 | | |
| | | | | Average | 19 | | | 14 | | | 33 | | |
| | | | 7 | 1 | 13 | | | 12 | | | 25 | | |
| | | | | 2 | 21 | | | 16 | | | 37 | | |
| | | | | 3 | 16 | | | 12 | | | 28 | | |
| | | | | Average | 18 | | | 13 | | | 30 | | |
| 1 to 2 1/2 | 1 | West | 2 | 1 | 13 | | | 11 | | | 24 | | |
| | | | | 2 | 13 | | | 10 | | | 23 | | |
| | | | | 3 | 18 | | | 13 | | | 31 | | |
| | | | | Average | 15 | | | 11 | | | 26 | | |
| | | | 6 | 1 | 16 | | | 11 | | | 27 | | |
| | | | | 2 | 13 | | | 10 | | | 23 | | |
| | | | | 3 | 15 | | | 10 | | | 25 | | |
| | | | | Average | 15 | | | 10 | | | 25 | | |
| | | | 7 | 1 | 25 | | | 15 | | | 40 | | |
| | | | | 2 | 12 | | | 9 | | | 21 | | |
| | | | | 3 | 20 | | | 12 | | | 32 | | |
| | | | | Average | 19 | | | 12 | | | 31 | | |
| | 3 | East | 2 | 1 | 16 | | | 13 | | | 29 | | |
| | | | | 2 | 19 | | | 15 | | | 34 | | |
| | | | | 3 | 18 | | | 14 | | | 32 | | |
| | | | | Average | 18 | | | 14 | | | 32 | | |
| | | | 6 | 1 | 18 | | | 13 | | | 31 | | |
| | | | | 2 | 22 | | | 16 | | | 38 | | |
| | | | | 3 | 17 | | | 12 | | | 29 | | |
| | | | | Average | 19 | | | 14 | | | 33 | | |
| | | | 7 | 1 | 15 | | | 13 | | | 28 | | |
| | | | | 2 | 19 | | | 15 | | | 34 | | |
| | | | | 3 | 15 | | | 12 | | | 27 | | |
| | | | | Average | 16 | | | 13 | | | 29 | | |

NOTE This table uses an average of three runs per sample, nine runs per phase

TABLE XXXVI (Continued)

COMPARISON OF COMMUNICATIONS DATA FOR DYNAMIC-SIMULATOR RUNS USING ARRIVALS PLUS DEPARTURES AT ZERO WIND

| Period of Operation | Channel Number | Sector | Phase Number | Sample Number | Tower to Air | | | Air to Tower | | | Tower and Air Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Density Live Time | Average Length of Message | Average Communication Time per Aircraft | Density Live Time | Average Length of Message | Average Communication Time per Aircraft | Density Live Time | Average Length of Message | Average Communication Time per Aircraft |
| (hour) | | | | | (per cent) | (seconds) | (seconds) | (per cent) | (seconds) | (seconds) | (per cent) | (seconds) | (seconds) |
| 1/2 to 3 | 1 | West | 2 | 1 | 12 | 3.1 | 46.2 | 10 | 2.5 | 38.2 | 22 | 2.8 | 84.4 |
| | | | | 2 | 13 | 3.4 | 50.3 | 10 | 2.5 | 39.3 | 23 | 3.0 | 89.6 |
| | | | | 3 | 15 | 3.4 | 54.4 | 11 | 2.5 | 39.8 | 26 | 3.0 | 94.3 |
| | | | | Average | 13 | 3.3 | 50.3 | 10 | 2.5 | 39.1 | 23 | 2.9 | 89.4 |
| | | | 6 | 1 | 15 | 3.7 | 54.9 | 9 | 2.2 | 34.1 | 24 | 3.0 | 89.0 |
| | | | | 2 | 13 | 3.5 | 50.0 | 10 | 2.4 | 36.5 | 23 | 3.0 | 86.3 |
| | | | | 3 | 13 | 3.5 | 46.4 | 9 | 2.3 | 31.7 | 22 | 2.9 | 78.0 |
| | | | | Average | 14 | 3.6 | 50.4 | 9 | 2.3 | 34.1 | 23 | 3.0 | 84.4 |
| | | | 7 | 1 | 21 | 4.0 | 75.2 | 14 | 2.4 | 48.4 | 35 | 3.2 | 123.6* |
| | | | | 2 | 12 | 3.5 | 45.6 | 9 | 2.5 | 33.4 | 21 | 3.0 | 79.0 |
| | | | | 3 | 14 | 3.5 | 53.2 | 10 | 2.4 | 36.3 | 24 | 3.0 | 89.5 |
| | | | | Average | 16 | 3.7 | 58.0 | 11 | 2.4 | 39.4 | 27 | 3.1 | 97.4 |
| | 3 | East | 2 | 1 | 15 | 3.2 | 41.0 | 13 | 2.5 | 35.1 | 28 | 2.8 | 76.0 |
| | | | | 2 | 17 | 3.3 | 47.6 | 13 | 2.4 | 36.5 | 30 | 2.8 | 84.1 |
| | | | | 3 | 19 | 3.4 | 51.9 | 13 | 2.3 | 36.1 | 32 | 2.9 | 87.1 |
| | | | | Average | 17 | 3.3 | 46.5 | 13 | 2.4 | 35.9 | 30 | 2.8 | 82.4 |
| | | | 6 | 1 | 18 | 3.4 | 50.0 | 13 | 2.2 | 35.6 | 31 | 2.8 | 85.4 |
| | | | | 2 | 19 | 3.5 | 53.7 | 13 | 2.2 | 36.0 | 32 | 2.9 | 89.6 |
| | | | | 3 | 17 | 3.3 | 46.2 | 13 | 2.4 | 34.6 | 30 | 2.9 | 80.8 |
| | | | | Average | 18 | 3.4 | 50.0 | 13 | 2.3 | 35.4 | 31 | 2.9 | 85.3 |
| | | | 7 | 1 | 15 | 2.8 | 39.7 | 12 | 2.1 | 32.6 | 27 | 2.5 | 72.1 |
| | | | | 2 | 16 | 3.4 | 45.5 | 12 | 2.3 | 31.7 | 28 | 2.8 | 77.1 |
| | | | | 3 | 15 | 3.1 | 41.3 | 12 | 2.3 | 31.5 | 27 | 2.7 | 72.8 |
| | | | | Average | 15 | 3.1 | 42.1 | 12 | 2.2 | 31.9 | 27 | 2.7 | 74.0 |
| | 5 | Gnd Control | 2 | 1 | | | | | | | 18 | 3.4 | 36.1 |
| | | | | 2 | | | | | | | 14 | 3.4 | 27.4 |
| | | | | 3 | | | | | | | 15 | 3.6 | 25.6 |
| | | | | Average | | | | | | | 16 | 3.5 | 29.7 |
| | | | 6 | 1 | | | | | | | 19 | 3.4 | 38.9 |
| | | | | 2 | | | | | | | 19 | 2.9 | 33.2 |
| | | | | 3 | | | | | | | 15 | 3.1 | 29.7 |
| | | | | Average | | | | | | | 18 | 3.1 | 33.9 |
| | | | 7 | 1 | | | | | | | ** | ** | ** |
| | | | | 2 | | | | | | | 15 | 3.1 | 30.6 |
| | | | | 3 | | | | | | | 14 | 3.2 | 16.5 |
| | | | | Average | | | | | | | 15 | 3.2 | 23.5 |
| | 6 | Ctr to Twr | 2 | 1 | | | | | | | 8 | 2.8 | 12.7 |
| | | | | 2 | | | | | | | 8 | 2.7 | 13.8 |
| | | | | 3 | | | | | | | 9 | 2.7 | 16.6 |
| | | | | Average | | | | | | | 8 | 2.7 | 14.4 |
| | | | 6 | 1 | | | | | | | 9 | 3.0 | 14.2 |
| | | | | 2 | | | | | | | 8 | 2.9 | 16.5 |
| | | | | 3 | | | | | | | 8 | 2.8 | 12.4 |
| | | | | Average | | | | | | | 8 | 2.9 | 14.4 |
| | | | 7 | 1 | | | | | | | 9 | 2.7 | 14.5 |
| | | | | 2 | | | | | | | 10 | 2.7 | 16.2 |
| | | | | 3 | | | | | | | 8 | 2.4 | 21.1 |
| | | | | Average | | | | | | | 9 | 2.6 | 17.3 |

* Channels 1 and 5 combined.

**Not available.

TABLE XXXVII

OUTER-MARKER MINIMUM SEPARATIONS USING 3-MILE UNIFORM RULE WITH 20-MPH HEADWIND

| Sequence | Time Separation (seconds) | Distance Separation (miles) |
|---|---|---|
| FF | 83 | 3 0 |
| MM | 90 | 3 0 |
| SS | 108 | 3 0 |
| MF | 95 | 3 4 |
| SM | 122 | 4 1 |
| SF | 127 | 4 6 |
| FM | 90 | 3 0 |
| FS | 108 | 3 0 |
| MS | 108 | 3 0 |
| Average | | 3 3 |

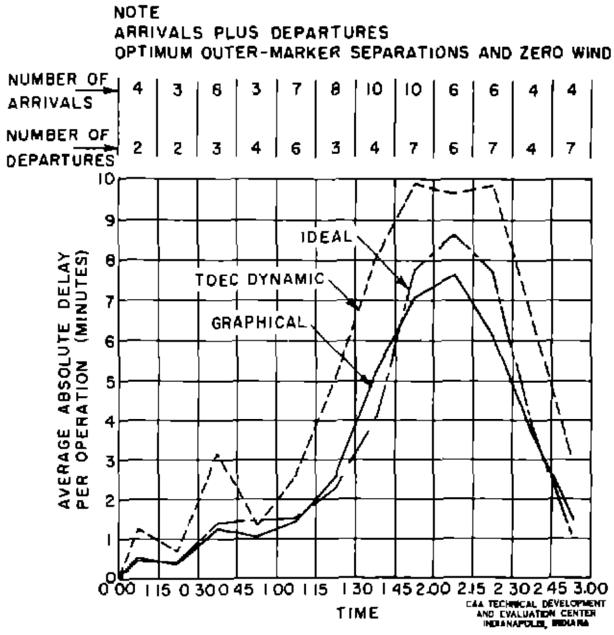


Fig 23 Average Absolute Delays Per Operation Phase 7 (Ideal, Graphical, and TDEC Dynamic Simulator)

Where holding fixes lie relatively close to the minimum path of aircraft entering a system from any direction, minimum delays will occur Therefore, no excessive detours and the consequent cumulative backing up of delays to aircraft from opposite directions will result when it is necessary to route traffic to the twin stacks as clearance limits for possible holding Since the A and B twin stacks of phase 2 lie closer to the minimum paths than those of the other two phases, it was selected as the best configuration for the partial-fixed-block and partial-moving-block procedures See Fig 33 in Appendix A Furthermore, it was felt that symmetrically located stacks simplified handling procedures Also, the less the distance to be vectored, the less the variability Although the distance from the A and B stacks to the outer marker is relatively small, it was felt that there was still a sufficient degree of flexibility to put the random arrivals of a fixed-block system into a sequence, even during peak congestion periods

Table XL summarizes the pertinent delayresults of the graphical analysis For purposes of identification, the fixed-moving-block system is called phase 2 (a). Only the zero-wind condition was analyzed, and the related results of the original moving-block graphical analysis of phase 2 are repeated for purposes of convenient comparison Figs 29 and 30 show the time-series comparisons for the samples of arrivals only and for the samples of arrivals plus departures Optimum outerm-marker minimum separations were employed

The results show that from the standpoint of delays to arrivals only, phase 2 is more efficient than phase 2 (a) by about 30 per cent, on the basis of delays per operation, phase 2 is better by only 8 per cent Again, the caution that must be exercised in judging the merits of a system by using only one traffic sample, even though it is a relatively large one, should be borne in mind For example, comparison of the average delays per operation for the period 1 to 2 1/2 hours shows 5 5 minutes for phase 2 when sample No 3 is used and 5 2 minutes for phase 2 (a) when sample No 2 is used This comparison indicates that phase 2 (a) is superior to phase 2 by 6 per cent, contrary to the over-all comparison which averaged out all samples and periods

When it is considered that the delay per operation provides a more realistic criterion for comparing single-runway (or possibly intersecting-runway) operation at Washington National Airport, the 8-per cent penalty of phase 2 (a) appears to be negligible in view of its potential simplicity of operation The over-all efficiency with live controllers and pilots may more than offset this 8 per cent, which after all is indicative only of the relative merits of the phases on an analytical and not on an over-all-system basis Further study of some practical aspects of the use of a moving-block system between the inner twin stacks and the outer marker reveal that:

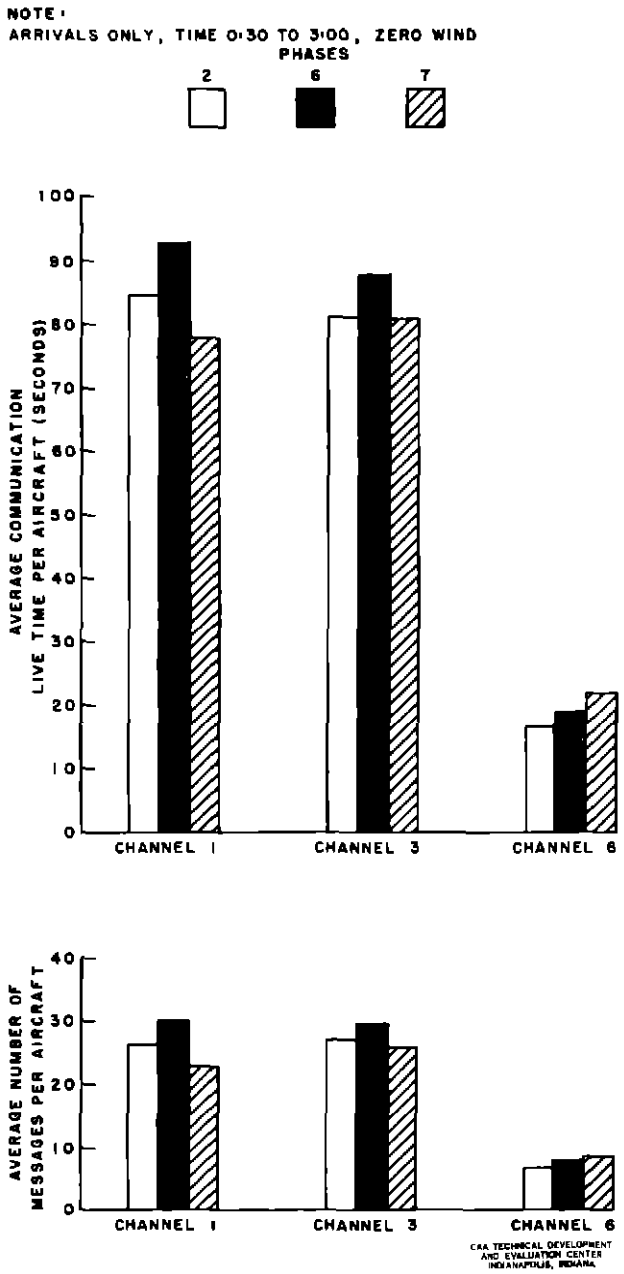


Fig 24 Average Communication Live Time and Number of Messages Per Aircraft (TDEC Dynamic Simulator)

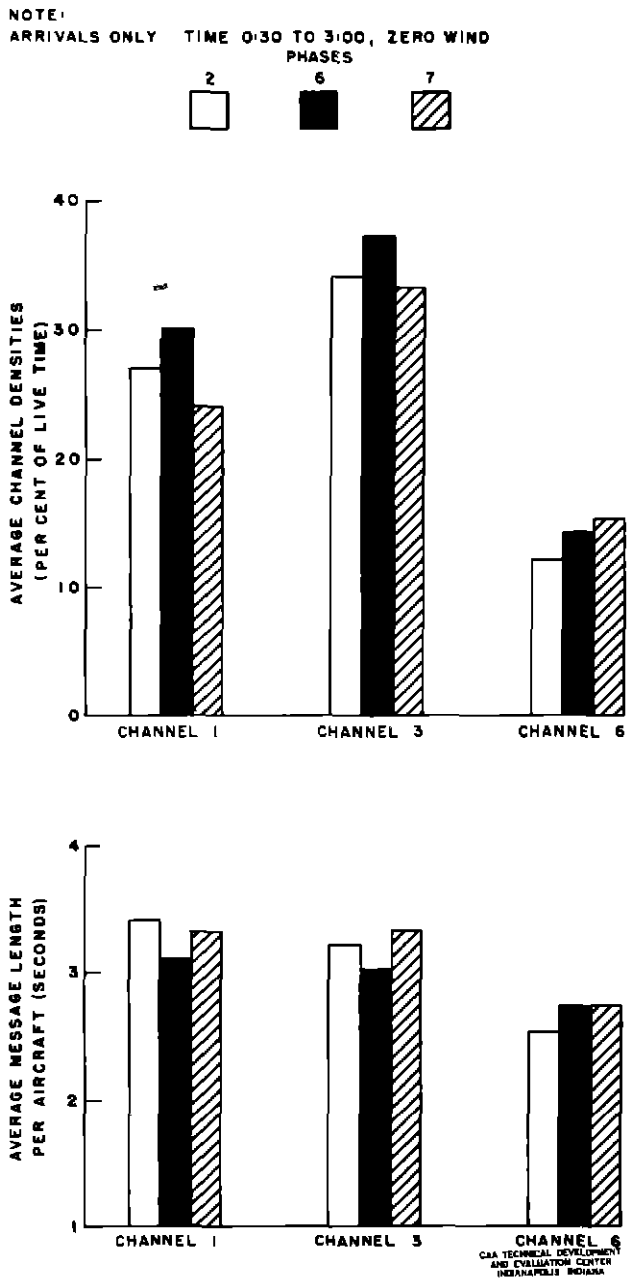


Fig 25 Average Channel Densities and Message Length Per Aircraft, Arrivals Only (TDEC Dynamic Simulator)

a Separation between aircraft can be effected by using graduated series of fixed tracks between the feeder stacks and the outer marker This device is called a multitrack system By means of a simple computing device, the controller can compute gate times at the outer marker and can select the particular approach track for each aircraft to enable it to arrive over the approach gate with the proper separation from other aircraft The fixed and relatively short and simple approach tracks make it possible for controllers and aircraft to achieve this gate time within a small tolerance, the controller need only learn from the computer which fixed track is to be followed He would then simply transmit these heading instructions to the aircraft from a radarscope overlay without the usual mental calculations and resulting conservatism

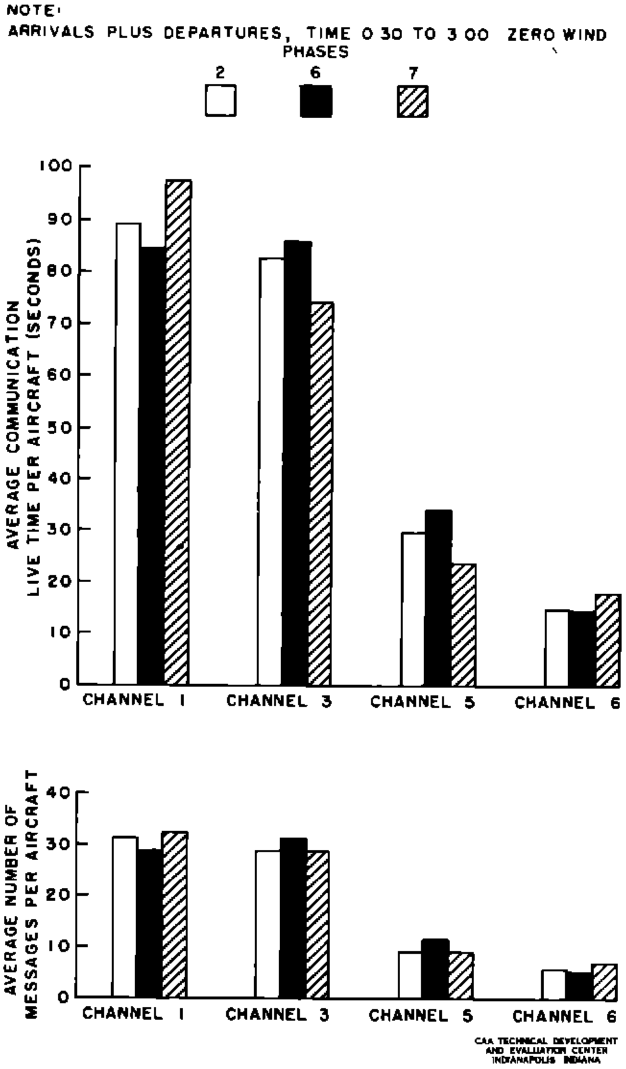


Fig 26 Average Communication Live Time and Number of Messages Per Aircraft, Arrivals Only (TDEC Dynamic Simulator)

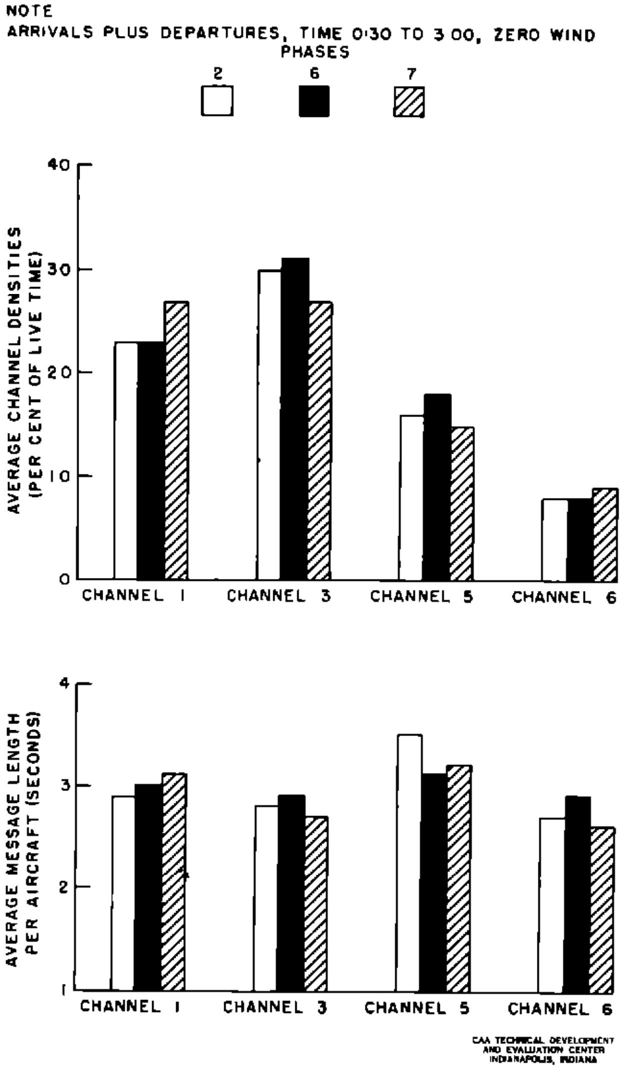


Fig 27 Average Channel Densities and Message Lengths Per Aircraft, Arrivals Plus Departures (TDEC Dynamic Simulator)

b Airborne pictorial displays showing the various approach tracks could further reduce the over-all work load and the amount of air/ground communications required The controller, having determined the proper track from the computer, would assign the track to be followed The pilots could then navigate their own way along the assigned tracks In this way, the controller would function mainly as a monitor and would stand ready to override the system at any time if necessary Since the lowest altitude is 2500 feet at the holding fixes and 1500 feet at the outer marker, an aircraft with unsafe separation can always be turned back to 1500 feet at one of the holding fixes

Preliminary tests of a system similar to that of phase 2 (a) have been conducted at TDEC, and the results were quite satisfactory TDEC personnel have also integrated into the system an apparently smooth and efficient method of combining jet-type with conventional propeller-type aircraft The details and results are published elsewhere [16]

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[16] Anderson and Vickers, op cit

## STATISTICAL AND THEORETICAL ASPECTS

### Significance of the Delay Parameters, Traffic Samples, and Delay Theory

The preceding data show that the number and the magnitude of the variations between the average delays per aircraft for the various traffic samples indicate an acceptably good representation of the random variations anticipated in day-to-day air traffic The backing up of delays from the peak hour 1 to 2 to the next half-hour period for certain samples and conditions should also be considered, along with the fact that little or no correlation exists between the average delay per aircraft and the maximum delay or the percentage of aircraft delayed Even in the ideal analysis, almost all of the aircraft operations are delayed because the traffic-loading rates are high, in cases of high traffic rates, the use of the percentage of aircraft delayed therefore becomes meaningless for indicating trends The maximum delays depend more upon the positioning of large time intervals within the random samples, and although they are of operational interest they cannot be used as a meaningful basis for comparative-evaluation purposes

The results of the ideal analysis show that for the samples of arrivals only the average delays for the 20-mph-headwind condition (maximum acceptance rate = 29 8 per hour) are more than double those for the zero-wind condition (maximum acceptance rate = 36 1 per hour) For the samples of arrivals plus departures, the corresponding delays are nearly double For the traffic samples, rules, and procedures outlined in this report it can be expected that in actual operation the delays will be twice again as large

It was previously stated that different systems of air traffic control do not always react proportionally to different random samples of traffic Thus, it is risky to use one representative random-traffic sample to determine the relative merits of any given air traffic control system The question arises whether the three random-traffic samples previously outlined were sufficient to ensure that they would yield an acceptable degree of statistical stability A plot of average delays versus loading (the arrival rate divided by the acceptance rate) for each particular sample showed great variation between samples and showed dispersal within samples However, a similar plot averaging the delays of the arrivals of the peak hour 1 to 2 for the three

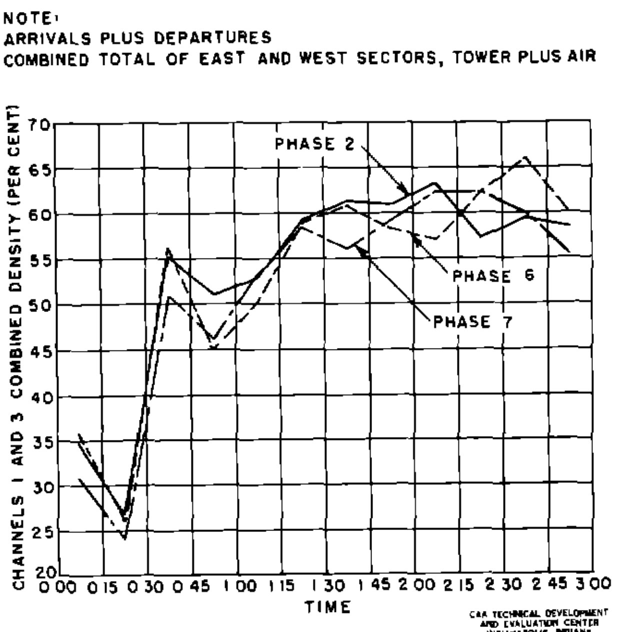


Fig 28 Average Combined Channel Densities, Arrivals Plus Departures (TDEC Dynamic Simulator)

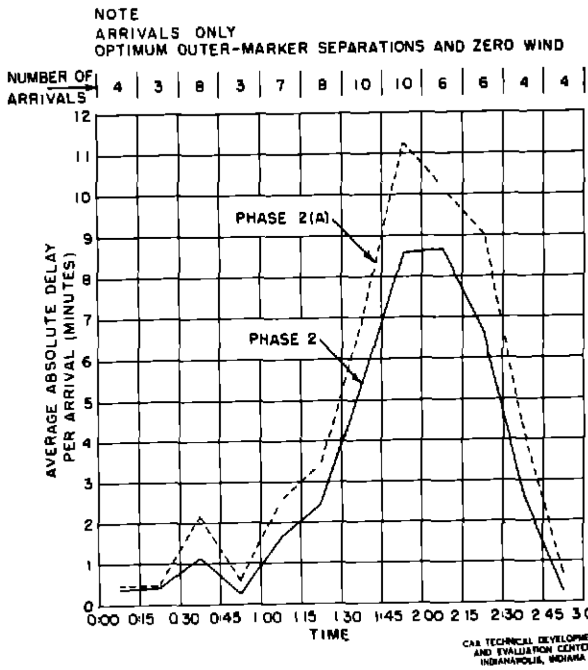


Fig 29 Average Absolute Delay Per Arrival, Phases 2 and 2 (a), Arrivals Only (Graphical Analysis)

TABLE XXXVIII

SUMMARY OF ARRIVAL DELAYS FOR IDEAL ANALYSIS USING ARRIVAL TRAFFIC ONLY UNDER CONDITIONS OF 3-MILE UNIFORM SEPARATION AT ZERO- AND 20-MPH WIND

| Period of Operations (hour) | Number of Arrivals | Sample Number | Zero Wind: Average Delay per Aircraft (minutes) | Zero Wind: Number of Aircraft Delayed (per cent) | Zero Wind: Maximum Delay (minutes) | 20-MPH Wind: Average Delay per Aircraft (minutes) | 20-MPH Wind: Number of Aircraft Delayed (per cent) | 20-MPH Wind: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 1 | 2.16 | 82.9 | 6.60 | 4.14 | 88.6 | 11.48 |
| | | 2 | 1.54 | 80.0 | 4.42 | 2.98 | 91.4 | 6 57 |
| | | 3 | 2.04 | 85.7 | 6.58 | 3.60 | 88.6 | 10.20 |
| | | Average | 1 91 | 82.9 | 5.87 | 3.64 | 89.5 | 9.42 |
| 1/2 to 2 1/2 | 58 | 1 | 1.51 | 65.5 | 6.60 | 3.29 | 84.5 | 11.48 |
| | | 2 | 1.13 | 70.7 | 4.42 | 2.19 | 82.8 | 6.57 |
| | | 3 | 1.69 | 69.0 | 6.58 | 3.69 | 82.8 | 11.05 |
| | | Average | 1.44 | 68.4 | 5.87 | 3.06 | 83.4 | 9.70 |
| 0 to 3 | 73 | 1 | 1.30 | 61.6 | 6.60 | 2.74 | 75.3 | 11.48 |
| | | 2 | 0.93 | 60.3 | 4.42 | 1.77 | 69.9 | 6.57 |
| | | 3 | 1.41 | 60.3 | 6.58 | 3.02 | 71.2 | 11.05 |
| | | Average | 1.21 | 60.7 | 5.87 | 2.51 | 72.1 | 9.70 |

NOTE The arrival delays for the 20-mph condition are about double those for the zero-wind condition even though the theoretical acceptance rates of 41.3 per hour for zero wind and 35 per hour for 20-mph headwind were not appreciably lowered.

samples of arrivals only or of arrivals plus departures for the two wind conditions and for both the 3-mile-uniform and the optimum-minimum separations at the outer marker produces a smooth curve, as shown in Fig 31 Thus, not only are the three traffic samples sufficient to represent day-to-day variations but they are also sufficient to reduce the influence of randomness on the validity of the subsequent evaluations The sharp increase in slope with loading in Fig 31 is also worthy of being noticed At this one-hour peak arrival rate of 35 aircraft per hour, increasing the loading from 80 to 100 per cent doubled the delays

As a measure of the effect of using operational vectoring procedures with live controllers and pilots, the average of the results for zero-wind phases 2, 6, and 7 (7 24 minutes, more than double again that of the ideal) on the TDEC dynamic simulator is also plotted in Fig 31 Also shown are the corresponding graphical-analysis delays for the average (5 3 minutes) of all samples and all phases Until further runs planned for future programs are made for the conditions of higher and lower acceptance rates, the trend and the calibration factor cannot be determined conclusively

The correlation coefficient between corresponding graphical and dynamic-simulator average delays for each 15-minute period in any phasefor an average of three samples is 0 98 This means that the observed data confirm the validity of the following linear relationships This high correlation holds for both the delays per arrival in the samples of arrivals only and the delays per operation in the samples of arrivals plus departures

For Arrivals Only
Dynamic-Simulator Average Delays = 1 12 + 1 11 x graphical
For Arrivals Plus Departures
Dynamic-Simulator Average Delays = 0 88 + 1 42 x graphical

TABLE XXXIX

SUMMARY OF ARRIVAL DELAYS FOR IDEAL ANALYSIS USING 3-MILE UNIFORM-SEPARATION RULE UNDER CONDITIONS OF ZERO- AND 20-MPH WIND WITH ARRIVAL-PLUS-DEPARTURE TRAFFIC

| Period of Operations (hour) | Number of Arrivals | Number of Departures | Sample Number | Zero Wind: Average Delay per Aircraft (minutes) | Zero Wind: Number of Aircraft Delayed (per cent) | Zero Wind: Maximum Delay (minutes) | 20-MPH Wind: Average Delay per Aircraft (minutes) | 20-MPH Wind: Number of Aircraft Delayed (per cent) | 20-MPH Wind: Maximum Delay (minutes) |
|---|---|---|---|---|---|---|---|---|---|
| 1 to 2 | 35 | 25 | 1 | 2.46 | 85.7 | 6.82 | 5.11 | 91.4 | 12.18 |
| | | | 2 | 2.57 | 91.4 | 6.17 | 4.20 | 94.3 | 9.37 |
| | | | 3 | 2.70 | 88.6 | 8.60 | 4.67 | 91.4 | 14.72 |
| | | | Average | 2.58 | 88.6 | 7.20 | 4.66 | 92.4 | 12.09 |
| 1/2 to 2 1/2 | 58 | 50 | 1 | 2.34 | 81.0 | 6.82 | 5.97 | 89.7 | 16.52 |
| | | | 2 | 1.82 | 82.8 | 6.17 | 3.75 | 94.8 | 9.37 |
| | | | 3 | 3.14 | 75.9 | 10.40 | 6.06 | 87.9 | 21.08 |
| | | | Average | 2.43 | 79.9 | 7.80 | 5.26 | 90.8 | 15.66 |
| 0 to 3 | 73 | 68 | 1 | 1.98 | 74.0 | 6.82 | 5.43 | 86.3 | 16.52 |
| | | | 2 | 1.48 | 71.2 | 6.17 | 3.15 | 86.3 | 9.37 |
| | | | 3 | 2.56 | 65.8 | 10.40 | 5.38 | 83.6 | 21.08 |
| | | | Average | 2.01 | 70.3 | 7.80 | 4.65 | 85.4 | 15.66 |

The foregoing empirical relationships yield an accurate estimate for any loading except extremely low ones, which are unimportant

When the average delays for 15-minute periods are being predicted, the standard error in estimating dynamic-simulator results from graphical results is only 43 seconds for the samples of arrivals only, for the samples of arrivals plus departures, the standard error or deviation is 61 seconds When estimated on an hourly basis, the results are even better

When peak arrival rates persist for long periods such as five hours or more, the system will start to break down This is evident from delay theory,[17, 18] as shown in Fig 32 In delay theory, it is assumed that traffic samples are infinite and have Poisson-distributed average arrival rates The system theoretically starts to saturate at a loading of about 90 per cent or more Certainly, in operational practice this saturation will occur at a much lower loading Again, determination of the calibration factors awaits further testing on the dynamic and graphical simulators No cross plotting of the ideal-analysis of Fig 31 and of the corresponding graphical- and dynamic-simulator results is made with the delay-theory data of Fig 32, because they are not comparable The results of the simulation work described in this report are for finite and more realistic transient traffic samples of relatively short duration and with the usual building up to a peak and a subsequent dropping off While traffic is building up, the system is just starting to approach some degree of stability with delays for this short period distributed exponentially as expected However, in the latter part of the runs, the traffic begins to saturate the system, levels off, and then drops off to almost nothing Since this behavior is typical of present and possibly of future peak-traffic rates, the system will never be in a steady state This means that delay theory cannot be used without some empirical modification Study of the frequency distribution of the simulation-delay results shows that these delays do not follow the Poisson law Further examination of these distributions points up why the delays do not follow the theoretical delay curves, the delays come from at least two different populations

[17] Bowen and Pearcey, op cit

[18] T Pearcey, "Delays in the Landing of Air Traffic," Journal of the Royal Aeronautical Society, December 1948

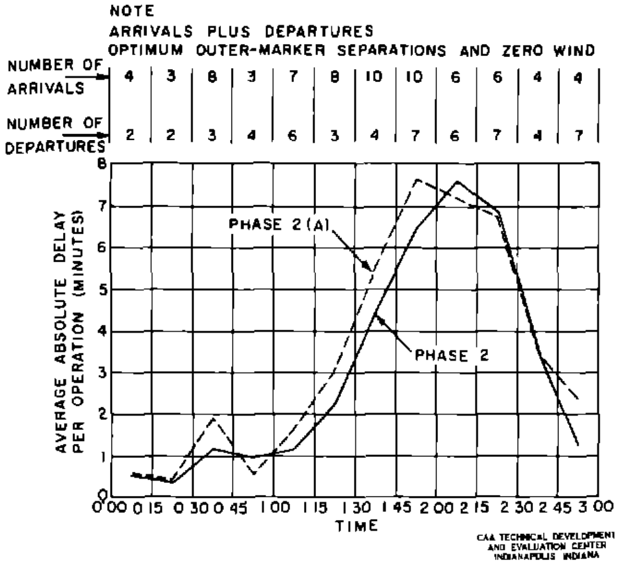


Fig 30 Average Absolute Delay Per Operation Phases 2 and 2 (a), Arrivals Plus Departures (Graphical Analysis)

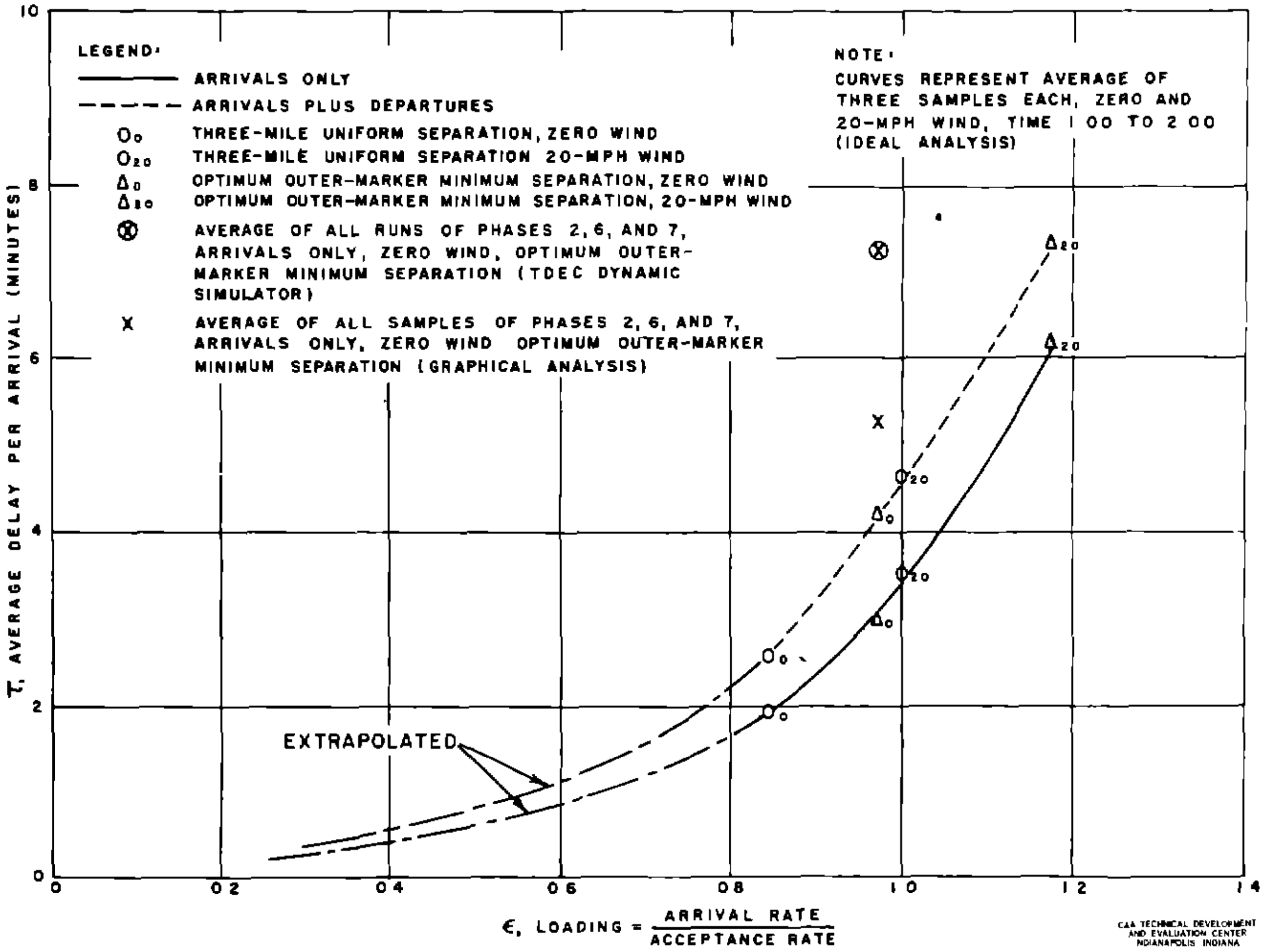


Fig 31 Average Delay Per Arrival as a Function of Loading

Intervals Between Successive Operations

Data on the average intervals between successive operations were compiled from the dynamic-simulator runs Only a one-hour period in which there was always an availability of aircraft was used For the samples of arrivals only, the average interval between successive approaches on the dynamic simulator was 1 minute 53 seconds for phase 2, 1 minute 56 seconds for phase 6, and 2 minutes 1 second for phase 7 Corresponding graphical-simulator data showed no significant difference between phases and averaged about 1 minute 45 seconds

For samples of arrivals plus departures in the dynamic simulator, 52 operations per hour were handled for the average of all phase 2 runs, 51 3 per hour for phase 6 runs, and 50 per hour for phase 7 runs Corresponding graphical results again showed no appreciable difference between phases and averaged about 56 operations per hour on the single runway

In the dynamic-simulator runs with arrival and departure aircraft intermixed on the single runway No 36, the average time for two successive landings was 128 seconds When a take-off was interspersed between arrivals, the average interval between the two approach aircraft was 144 seconds The average time between successive take-offs was 65 seconds On the basis of these figures, a take-off adds only 16 seconds if inserted between two landings but adds 65 seconds if one take-off follows another Therefore, it can be concluded that when a backlog of arrivals and departures exists, by far the most efficient handling is to alternate landings with take-offs rather than to handle a few landings and then a few take-offs

Conduct of the Dynamic-Simulator Experiments

In order to uncover possible clues about variations between repeat runs, an examination of aircraft separations was made Table XVIII listed the minimum time separations at the outer marker for the various arrival sequences of S, M, and F aircraft as based on average approach speeds of 120, 130, and 150 mph, respectively Data on the outer-marker arrival times were checked for simulator time intervals smaller than these assigned minima. Such intervals were defined as TILTAM's, or Time Intervals Less Than Assigned Minima Only those of 15 seconds or more and of 25 seconds or more were tabulated as being significant Fifteen seconds represents approximately one-half mile and 25 seconds slightly less than one mile of separation at the average approach speeds given

TABLE XL

COMPARISON OF ABSOLUTE ARRIVAL DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2 AND 2(A) USING ARRIVAL-PLUS-DEPARTURE TRAFFIC UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Arrivals | Sample Number | Phase 2 | | | Phase 2(A) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 35 | 1 | 6.52 | 94.3 | 15.68 | 6.78 | 94.3 | 15.85 |
| | | 2 | 4.53 | 91.4 | 10.78 | 7.27 | 97.1 | 14.67 |
| | | 3 | 4.05 | 82.9 | 11.90 | 5.87 | 91.4 | 15.13 |
| | | Average | 5.03 | 89.5 | | 6.64 | 94.3 | |
| 1 to 2 1/2 | 47 | 1 | 7.18 | 95.7 | 15.68 | 7.39 | 95.7 | 15.85 |
| | | 2 | 4.22 | 93.6 | 10.78 | 7.23 | 97.9 | 14.67 |
| | | 3 | 5.67 | 87.2 | 15.67 | 7.46 | 83.6 | 16.75 |
| | | Average | 5.69 | 92.2 | | 7.36 | 95.7 | |
| 1/2 to 3 | 66 | 1 | 5.54 | 89.4 | 15.68 | 5.89 | 87.9 | 15.85 |
| | | 2 | 3.39 | 86.4 | 10.78 | 5.92 | 92.4 | 14.67 |
| | | 3 | 4.23 | 77.3 | 15.67 | 5.81 | 86.4 | 16.75 |
| | | Average | 4.39 | 84.4 | | 5.87 | 88.9 | |

TABLE XLI

COMPARISON OF ABSOLUTE DEPARTURE DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2 AND 2(A) USING ARRIVAL-PLUS-DEPARTURE TRAFFIC UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Departures | Sample Number | Phase 2 | | | Phase 2(A) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Average Delay per Aircraft (minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) | Average Delay per Aircraft (Minutes) | Number of Aircraft Delayed (per cent) | Maximum Delay (minutes) |
| 1 to 2 | 20 | 1 | 1.60 | 70.0 | 8.47 | 2.01 | 70.0 | 8.67 |
| | | 2 | 2.97 | 80.0 | 8.92 | 1.78 | 85.0 | 5.92 |
| | | 3 | 1.64 | 85.0 | 4.77 | 1.43 | 80.0 | 3.53 |
| | | Average | 2.07 | 78.3 | | 1.74 | 78.3 | |
| 1 to 2 1/2 | 33 | 1 | 2.96 | 81.8 | 8.70 | 3.25 | 81.8 | 8.88 |
| | | 2 | 3.57 | 84.9 | 10.03 | 2.41 | 87.9 | 7.63 |
| | | 3 | 5.34 | 90.9 | 14.97 | 3.07 | 87.9 | 12.45 |
| | | Average | 3.96 | 85.9 | | 2.91 | 85.9 | |
| 1/2 to 3 | 51 | 1 | 2.41 | 78.4 | 8.70 | 2.32 | 74.5 | 8.88 |
| | | 2 | 3.10 | 82.4 | 10.03 | 2.23 | 86.3 | 7.63 |
| | | 3 | 4.55 | 90.2 | 14.97 | 2.78 | 80.4 | 12.45 |
| | | Average | 3.35 | 83.7 | | 2.44 | 80.4 | |

The results are shown in Tables XLIII and XLIV for the 2 1/2-hour samples of arrivals only and for samples of arrivals plus departures The corresponding average delays per aircraft for the period of hours 1/2 to 3 are shown for comparison, It is seen that the number of TILTAM's during the runs involving both arrivals and departures were much less than those for the samples of arrivals only This was due to learning, to better discipline, and to the larger arrival separations employed by TDEC controllers in interspersing departures However, no significant relationship exists between the number of TILTAM's and the average delays Furthermore, the number and magnitude of the TILTAM's had little effect on the over-all results

Since the controllers were rotated from run to run, an examination was made of the delays of those aircraft handled by each controller, but no statistical relationship between delays and controllers was found The effect of rotating the console operators was examined, again with negligible effect on the over-all results

Relationship Between Average Delay and Communication Density in Dynamic-Simulator Runs

An analysis of variance was performed on the delays of arrival aircraft By this method the variation caused by any of the significant variables such as controllers, phases, and traffic samples is isolated and can be compared with the random residual error The results show that the variations in delays between repeat runs and between traffic samples overwhelm any effects of changing the phases It is concluded, therefore, that the changes in samples and the particular moods of the controllers (as during repeat runs)affected the delays more than the location of the twin stacks or the procedures associated with each sample In fact, the over-all differences between phases are no more than should be expected by chance

However, TDEC controllers had often remarked that there were significant differences in their work load for the various phases Since these differences might show up in the communications data, the communications densities for the peak hour were compared No consistent relationships between delays and communications load were found A comparison between the average delay per arrival and the densities of communications per phase for the average of all runs of the samples of arrivals plus departures is shown in Table XLV as an example

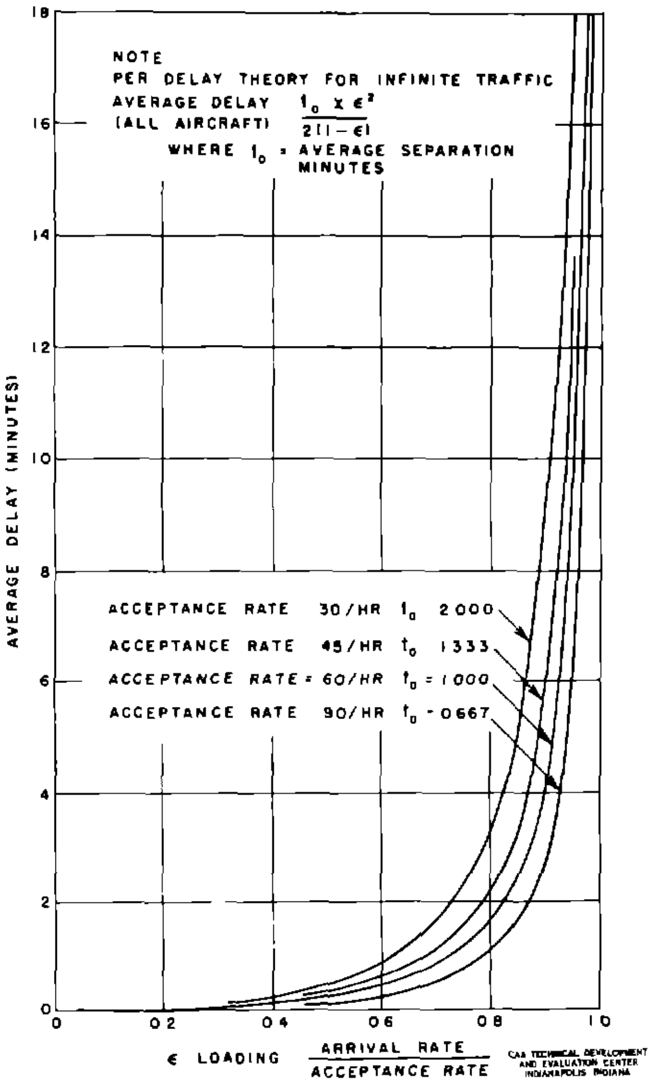


Fig 32 Theoretical Average Delay as a Function of Loading

General Impressions and Conclusions

Air traffic control simulation programs can be set up for either one or both of two basic reasons (a) for comparing different methods of control and the effectiveness of new equipment, techniques, and the like, or (b) for making estimates of what a given method or piece of equipment will do in actual operational practice

In either case, some sort of validation is necessary Without proper validation, the results may be meaningless The TDEC dynamic simulator and the FIL graphical simulator are very useful for making comparisons, but more intensive programs and comparisons using actual operation are necessary in order for the results to be more reliable Comparisons of the average delays for all runs, samples, phases, and periods show that the dynamic-simulator results for the samples of arrivals only approached those of the graphical by about 75 per cent, for the samples of arrivals plus departures this ratio was about 66 per cent, on the basis of average delays per operation

Two types of traffic samples should be used in the dynamic simulator The first has a short, saturated period, and the second is a longer, more realistic sample with a build-up, a peak, and a leveling-off period The type of sample depends on the simulation objective For approximative comparison purposes, the short, heavily loaded sample should suffice For

TABLE XLII

COMPARISON OF ABSOLUTE OPERATIONS DELAYS FOR GRAPHICAL ANALYSIS OF PHASES 2 AND 2(A) USING ARRIVAL-PLUS-DEPARTURE TRAFFIC UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER SEPARATIONS

| Period of Operations (hour) | Number of Operations | Sample Number | Phase 2 Average Delay per Aircraft (minutes) | Phase 2 Number of Aircraft Delayed (per cent) | Phase 2(A) Average Delay per Aircraft (minutes) | Phase 2(A) Number of Aircraft Delayed (per cent) |
|---|---|---|---|---|---|---|
| 1 to 2 | 55 | 1 | 4.7 | 85.5 | 5.0 | 85.5 |
| | | 2 | 4.0 | 87.3 | 5.3 | 92.7 |
| | | 3 | 3.2 | 83.6 | 4.3 | 87.3 |
| | | Average | 4 0 | 85.5 | 4.9 | 88.5 |
| 1 to 2 1/2 | 80 | 1 | 5.4 | 90.0 | 5.7 | 90.0 |
| | | 2 | 4.0 | 90.0 | 5.2 | 93.8 |
| | | 3 | 5.5 | 88.8 | 5.6 | 91.2 |
| | | Average | 5.0 | 89.6 | 5.5 | 91.7 |
| 1/2 to 3 | 117 | 1 | 4.2 | 84.6 | 4.3 | 82.1 |
| | | 2 | 3.3 | 84.6 | 4.3 | 89.7 |
| | | 3 | 4.4 | 82.9 | 4.5 | 83.8 |
| | | Average | 4.0 | 84.0 | 4.4 | 85.2 |

estimates of reality (especially in terminal-area systems using radar-vectoring), the longer, more realistic samples should be used  This longer sample should include a quick build-up of traffic, followed by an hour or so of operations at the maximum rate anticipated for the future, as was done in the experiments described in this report  However, the results of the dynamic-simulator runs show that the total lengths of the traffic samples can be cut to two hours without any sacrifice in statistical significance

The present method of using three similar, but random, samples with three runs per sample seems adequate  It permits the measurement by statistical tools not only of the differences between methods of control, but also of the effects of day-to-day variations in traffic (samples) and of different controllers and pilots, or of differing moods of the controllers and pilots (runs)

The main criteria for determining differences between traffic systems, equipment, and other variants are

(a) The average delay and distribution of delays, for significant periods
(b) The time under control per aircraft
(c) The communication density or control density (communication live time per aircraft divided by time under control)
(d) Number of controllers and controller work load

Delays for the period 1 to 2 1/2 hours are greater than for the period 1 to 2 hours, although the arrival rate is about 31 per hour for the period 1 to 2 1/2 hours and about 35 per hour for the hour 1 to 2  This difference in delays is due to the peak hourly traffic backing up into the next half hour where the arrival rate is appreciably less than the maximum theoretical acceptance rate of 36 aircraft per hour  However, in comparing delays between samples, phases, and runs, it is noted that the average delays and variations between runs are just about the same comparatively, so that either length of period is adequate for evaluation purposes

The airborne traffic talks about 70 to 80 per cent as much as the ground  Because this figure is almost the same as most communications data obtained from nonradar operations, it appears that radar control should not change the communication picture as drastically as some private line (ATCSS) exponents believe  In the future, however, the content of simulator communications should be examined for realism

TABLE XLIII

ABSOLUTE DELAYS VERSUS TILTAMS* FOR DYNAMIC SIMULATION
USING ARRIVAL SAMPLES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS
FOR OPERATION DURING HOURS 1/2 TO 3

| Sample Number | Run Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Average Delay per Arrival (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More | Average Delay per Arrival (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More | Average Delay per Arrival (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More |
| 1 | 1 | 7 6 | 13 | 7 | 7 9 | 9 | 7 | 7 1 | 9 | 6 |
| | 2 | 5 6 | 9 | 7 | 6 0 | 10 | 7 | 7 5 | 8 | 6 |
| | 3 | 5 3 | 16 | 10 | 7 1 | 10 | 8 | 9 3 | 8 | 6 |
| 2 | 4 | 7 0 | 9 | 7 | 6 2 | 8 | 2 | 3 8 | 11 | 5 |
| | 5 | 3 8 | 10 | 7 | 4 7 | 11 | 5 | 4 4 | 13 | 9 |
| | 6 | 6 8 | 5 | 4 | 7 9 | 14 | 9 | 8 9 | 13 | 6 |
| 3 | 7 | 7 8 | 9 | 3 | 6 0 | 8 | 3 | 6 2 | 12 | 10 |
| | 8 | 6 1 | 9 | 6 | 6 7 | 6 | 2 | 6 3 | 10 | 5 |
| | 9 | 6 5 | 2 | 1 | 7 7 | 5 | 3 | 4 9 | 13 | 5 |

*A Tiltam is defined as the time interval less than the assigned minimum

TABLE XLIV

ABSOLUTE DELAYS VERSUS TILTAMS FOR DYNAMIC SIMULATION
USING ARRIVAL-PLUS-DEPARTURE SAMPLES UNDER CONDITIONS OF ZERO WIND AND OPTIMUM OUTER-MARKER MINIMUM SEPARATIONS
FOR OPERATION DURING HOURS 1/2 TO 3

| Sample Number | Run Number | Phase 2 | | | Phase 6 | | | Phase 7 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Average Delay per Aircraft (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More | Average Delay per Aircraft (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More | Average Delay per Aircraft (minutes) | Number of Tiltams 15 Seconds or More | Number of Tiltams 25 Seconds or More |
| 1 | 10 | 11 4 | 2 | 1 | 12 2 | 4 | 3 | 15 6 | 2 | 0 |
| | 11 | 11 7 | 5 | 2 | 11 1 | 6 | 4 | 12 0 | 3 | 1 |
| | 12 | 11 8 | 5 | 1 | 12 6 | 6 | 5 | 9.4 | 5 | 3 |
| 2 | 13 | -- | 2 | 0 | 11 9 | 2 | 1 | 11 4 | 7 | 5 |
| | 14 | -- | 2 | 0 | 12 9 | 1 | 1 | 14 2 | 3 | 1 |
| | 15 | 10 6 | 5 | 1 | 11 5 | 6 | 2 | 7 3 | 12 | 7 |
| 3 | 16 | 7 2 | 4 | 2 | 9 7 | 0 | 0 | 7 6 | 6 | 2 |
| | 17 | 12 5 | 1 | 0 | 11 2 | 3 | 2 | 6 2 | 10 | 2 |
| | 18 | 9 5 | 4 | 2 | 9 5 | 6 | 3 | 9 2 | 2 | 0 |

NOTE No relationship exists between Tiltams and delays except that two cases of average delays over 14 minutes had less than 4 Tiltams and two cases of more than 8 Tiltams had delays of less than 8 minutes

## CONCLUSIONS AND RECOMMENDATIONS

### Review of the Results

With prolonged peak traffic and present semiarbitary safety rules, use of the CAA uniform-radar-separation rule of three miles will result in an abnormally high percentage of probable wave-offs both on the glide slope and on runway No 36 at Washington National Airport unless some form of speed control is used Use of the optimum minimum separations averaging about four miles at the outer marker, described previously in this report, will reduce the probability of a glide-slope wave-off to less than 1 per cent However, even with these optimum separations, the present layout of instrument runway No 36 is such that the number of wave-offs due to the runway-occupancy rule will still be too high at approximately 16 per cent An additional high-speed exit located at 3400 feet from the runway threshold is recommended This exit could serve both directions of this 6800-foot runway and would reduce the probable number of runway wave-offs to 2 per cent

The implications are evident Large random spreads of aircraft performance in the air and on the ground contribute significantly to the large minimum separations required of a safe traffic control system The use of some form or degree of speed control, the use of zero readers, or the use of some type of display or computer aids and monitors will reduce these spreads It is also possible that semiautomatic or fully automatic pilots and approach couplers might reduce these spreads to almost nothing Then traffic controllers could reduce their guesswork and conservatism in properly handling traffic in heavy IFR weather and could accordingly increase the acceptance rate The manner in which the magnitude of delays is affected by a small change in the acceptance rate during peak loading should be recalled However, a further analysis of the runway problem would be necessary to effect these larger acceptance rates The increased input rate from the glide slope to the runway would then require an even more judicious location and spacing of runway exits

When a backlog of arrivals and departures exists, the most efficient handling on a single runway is the alternation of landings with take-offs rather than the handling of first a few landings and then a few take-offs

Delays and communications loads for the three Washington National Airport phases 2, 6, and 7 were relatively low While some runs differed widely from others, the averages for the three runs and the three samples were stable Furthermore, there was little choice between phases except during small saturated periods where phase 6 was slightly less efficient than the other two It is concluded that any reasonable type of twin-stack terminal-area vector control similar to the phase 2, phase 6, or phase 7 configurations can handle peak hours of traffic averaging about 50 operations per hour on a single runway for several years to come, if the radar is always reliable This statement implies that little flow control is necessary, most rearrangement into sequence can be accomplished in the terminal area A configuration similar to phase 2, with feeder fixes located close to the minimum flight paths and with a combination of fixed blocks up to and including the feeder fixes and moving blocks thereafter, shows promise for reducing the work load

Development of Mathematical Techniques

Because these simulation processes are slow and laborious, it is important that the traffic designs are planned to produce the maximum of information from each run At the same time, the statistical analysis of each run and of the variations between runs should be as thorough as possible and should use the most powerful techniques available If air-traffic engineering is to become or is to approach a science, attempts should be made to set up mathematical descriptions or analogues of the interactions of the many variables involved Although completely rational formulae do not seem to be immediately forthcoming, the development of semiempirical relationships would be valuable, short extrapolations beyond the few quantitative values thus far determined by simulation could be made with the use of well-validated calibration factors

The development of mathematical formulae to describe air-traffic flow is not easy Literature on the subject includes the works of Bell, Bowen, Pearcey, Palm, Crommelin, Pollaczek, Erlang, Fry, and Riordan Unfortunately, the treatises on the subject are too idealized, and extensions of these studies are required to comprehend the many situations and the short, finite, peak periods of mixed traffic peculiar to air-traffic flow and control In the development of these mathematical formulae, close checks should be made so that theory will not stray too far from realism Moreover, checks should be made against actual flight results in order to validate both simulation and theory Certainly the problems are challenging ones for which there is immediate need for solution

Future Simulation Activities

Properly used, simulation is a safe and useful substitute for conducting experiments in air traffic control, which experiments involve controlled flights of aircraft and involve the operation of equipment which may or may not already exist It has been shown that analytical and simplified simulation techniques such as the FIL graphical simulation are extremely useful and are inexpensive means of evaluating and screening on a preliminary basis the many situations, procedures, ranges of variables, and other factors to be explored

The preliminary investigations to date demonstrate that the joint TDEC-FIL simulation activities yield a proper perspective in the assessment of the relative merits of proposed systems of traffic control This work was of a preliminary nature, however; and in it a firm foundation was laid for further and more conclusive evaluations of many other fundamental systems and procedures Although the correlations between the ideal, graphical-, and dynamic-simulator results are consistently good, the calibration factor for extending these results to other situations and procedures is not considered conclusive enough as yet It is therefore recommended that subsequent programs be undertaken to evaluate the effects of

1 The introduction of jet aircraft
2 The introduction of slower aircraft, to be designated VS for very slow
3 The introduction of helicopters
4 The use of outer-marker separations smaller than the presently used optimum and with some degree of speed control
5 Higher traffic rates of longer duration
6 Changes in the descent rules of 500 fpm and 1000 fpm
7 Downwind approaches
8 Conditions of headwind
9 Terminal-area en route and departure control
10 Airport-surface control
11 Combination fixed- and moving-block systems
12 Airport shutdown and gradual decrease or increase in acceptance rate with weather
13 Use of intersecting runways for landings and take-offs

The assumed aircraft performances and random distributions used in this analysis were based on data available at the time of writing Some of these data were extensive and others were limited for these particular purposes, because a wide variety of conditions were lumped together Also, data are meager on the actual behavior of aircraft during periods of IFR in complex situations and when under radar-vectoring control It is strongly urged that a program be undertaken for obtaining these operational data at an airport such as Washington National where certain radar-control procedures are in actual operational use The validity of the results of the analyses is no better than the initial assumptions These data are vital, therefore, prior to any large-scale expansion of these analytical and simulation activities

Certain long-range fundamental investigations should be undertaken using a more flexible type of dynamic simulator to evaluate the contribution to the system of various situations, techniques, and devices such as radar traffic displays, clutter on radar scopes, its occurrence, degree, and other conditions, DME, transponders, all equipped or partially equipped, colors for identification, data-transfer equipment, direct-view storage-display tubes, bright-tube displays, personnel requirements in towers and centers, pictorial computers, communications techniques, and computers for controllers

The foregoing is a partial list of the many situations, techniques, and variables to be explored in any logical assessment and planning of things to come It is evident that they fall into two general categories (1) procedures and systems of the present and the near future, some with local or limited application and others with more general application, and (2) certain fundamental investigations of techniques and equipment applicable, for the most part, to a common system five to ten years hence

The task of carrying out the two proposed types of simulation programs, plus certain other local simulation evaluations for CAA Office of Federal Airways , is a rather imposing one which cannot be undertaken with the present dynamic simulator at TDEC First, the present dynamic simulator should be modified and supplemented to

1 Provide at least twelve consoles for terminal-area problems,
2 Provide at least twenty-four consoles for en route problems,
3 Increase the accuracies of the computing devices,
4 Provide for turns other than standard-rate turns,
5 Provide means for degrading the scope to simulate clutter, precipitation, and other interferences,
6 Provide means for pilots to determine their position other than by viewing the screen,
7 Provide random generating devices to automatically feed representative normal distributions of speed, rates of descent, and other variables into the computers,
8 Provide means for simulating the airport proper

Second, steps should be taken to study and to prepare specifications for the design and procurement of another simulator to evaluate the more fundamental aspects of future air-traffic control In studying and preparing these specifications, consideration should be given to the means for evaluating the many proposed techniques and equipment, which include those outlined in the foregoing, and to consider

1 The capabilities of evaluating traffic congestion, both en route and in the terminal area, and to consider the flexibility required in the types of displays,
2 The ability to evaluate a multiplicity of paths, taking full advantage of the actual paths available, with the aid of a computer type of path selector,
3 Color-TV projection techniques,
4 Design with regard to the statistical parameters and their significance, automatic data recording and processing,
5 Ranges of radar safety beacons at 20, 50, 100 miles, and so forth
6 Beacons which reply only on request instead of having continuous response,
7 Altitude coverage using radars with elevation information, also the value of range and altitude information with or without elevation data,
8 Radar safety beacons with altitude information,
9 Fundamental air-to-ground information and communications such as aural versus visual,
10 Party-line versus private-line communications,
11 Pictorial R-θ computers,
12 Others, as the need arises

# APPENDIX A

## DESCRIPTION OF PHASES 2, 6, AND 7

### General Description and Procedures

Phases 2, 6, and 7 are three twin-stack configurations which had been proposed for the Washington National Airport terminal area They are essentially moving-block systems within a terminal area approximately 40 miles in diameter. Each configuration consists of a two-sector division of control (east and west) with twin inner feeding stacks for holding and feeding inbound aircraft to the outer marker when necessary during heavy-traffic conditions Consistent with the separation rules (essentially 3-mile, or optimum minimum radar separations, or 1000 feet altitude), aircraft are radar-vectored to the outer marker either directly via minimum flight paths, via the prescribed airways, via the inner feeding stacks, or by any combination to suit No two aircraft in the same sector and en route to the inner fixes are permitted to occupy the same altitude at the same time

The three phases differed only in layout of the inner feeding stacks and in their associated procedures The two control sectors are operated independently of each other by a controller until such time as co-ordination is required to arrange arrivals in sequence and to space them to the outer marker This sector division and layout of facilities are shown in Fig 1 and in Figs 33, 34, and 35

It was assumed that all military arrivals would complete their approaches at either Bolling or Anacostia after having passed the Washington National Airport outer marker Arrival routes, altitudes, and holding patterns were arranged to permit use of standard missed-approach procedures and proper, nonconflicting, departure routes and altitudes Minimum entry altitudes were 3500 feet in the east sector (routes A, B, and C) and 3000 feet in the west sector (routes E, F, and G)

Medium and slow aircraft descend at an average rate of 500 fpm and fast aircraft at 1000 fpm Where a fast aircraft is following a medium or a slow one on the same route or at the same holding fix, the fast aircraft descends at 500 fpm Fast aircraft can descent at their 1000-fpm rate at all times between the inner holding fixes and the outer marker All arrival aircraft must be at 1500 feet altitude when they reach the outer marker

### Phase 2 Twin-Stack Configuration

It was assumed that two symmetrically located low-power VOR's were installed in the vicinity of the outer marker, as shown in Fig 33, to be used as final ARTC clearance limits One LVOR was located 4 miles east and 1 1/2 miles south of the outer marker and was designated as Fix A The other LVOR was located 4 miles west and 1 1/2 miles south of the outer marker and was designated as Fix B Arrival aircraft entering on routes A and B could not descend below 3500 feet until they passed Riverdale (RVD) Aircraft entering on route C maintained at least 3500 feet altitude until they passed Andrews Radio (ADW) Aircraft entering

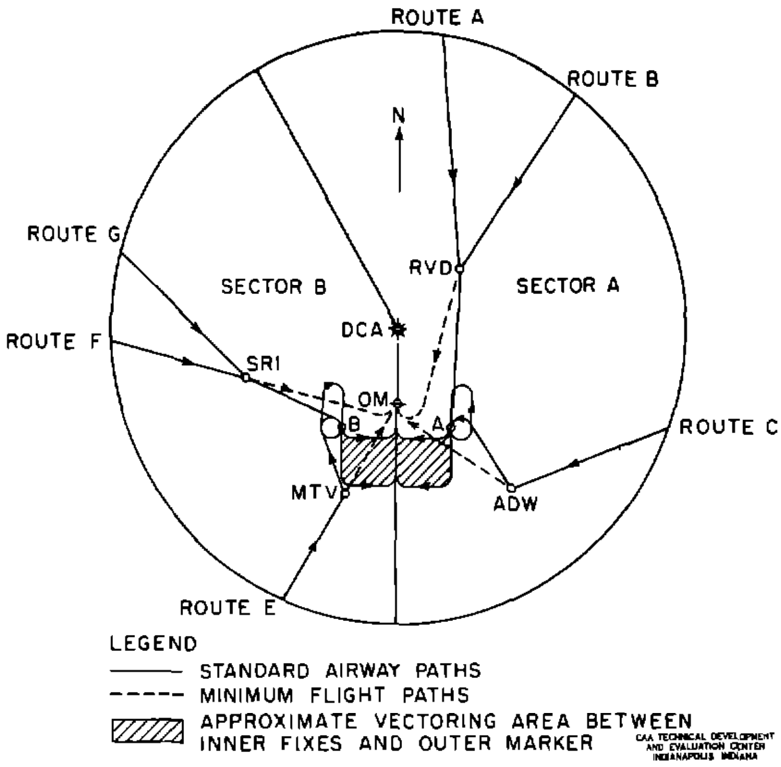


Fig 33 Phase 2 Configuration

on routes F and G maintained at least 3500 feet until they passed Springfield (SRI) Aircraft on route E could descend to 2500 feet before reaching Mount Vernon (MTV)

Minimum altitudes at the A and B twin stacks were 2500 feet Normally, aircraft arriving over Riverdale and Andrews were cleared via direct routes to Fix A, aircraft arriving over Mt Vernon and Springfield were cleared via direct routes to Fix B Occasionally aircraft could be cross-fed from Riverdale direct to Fix B and from Mt Vernon to Fix A, if necessary

Phase 6 Twin-Stack Configuration

It was assumed that the Springfield and Riverdale markers would be used as final clearance limits Location of fixes and normal flight patterns are shown on Fig 34 Aircraft arriving over Andrews followed a direct automatic-direction-finder (ADF) course toward Riverdale until contact was established, at which time they were turned into the down-wind leg of the pattern If radar contact was established before they left the Andrews range, these aircraft were vectored to suit proper separations and required altitude let-downs and were then turned on the base leg Whenever possible, aircraft approaching Mt Vernon from Doncaster were vectored toward the final-approach course on an easterly heading Aircraft arriving over Springfield were vectored on a southeasterly heading prior to being turned on the downwind leg

The minimum altitude for aircraft on routes A and B was 3500 feet until they passed Riverdale; for aircraft on route C, it was 3500 feet until they passed Andrews, and for aircraft on routes F and G, it was 3000 feet until past Springfield Aircraft on route E may descend to 2500 feet before reaching Mt. Vernon Aircraft on routes C or E to Riverdale or Springfield could not

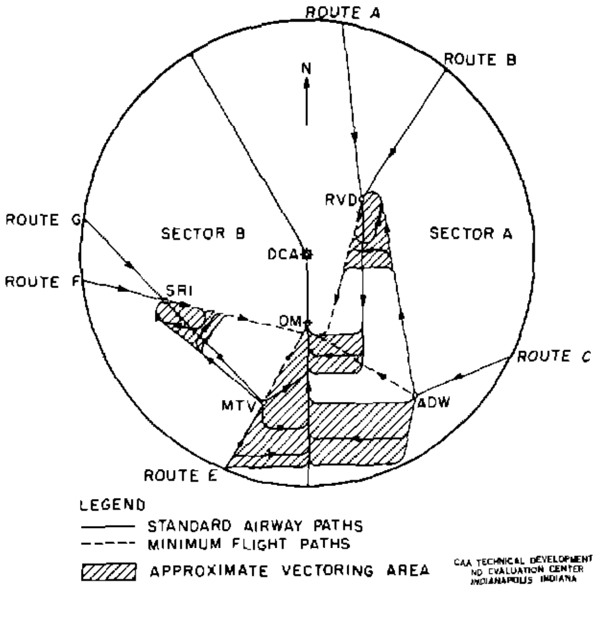


Fig 34 Phase 6 Configuration

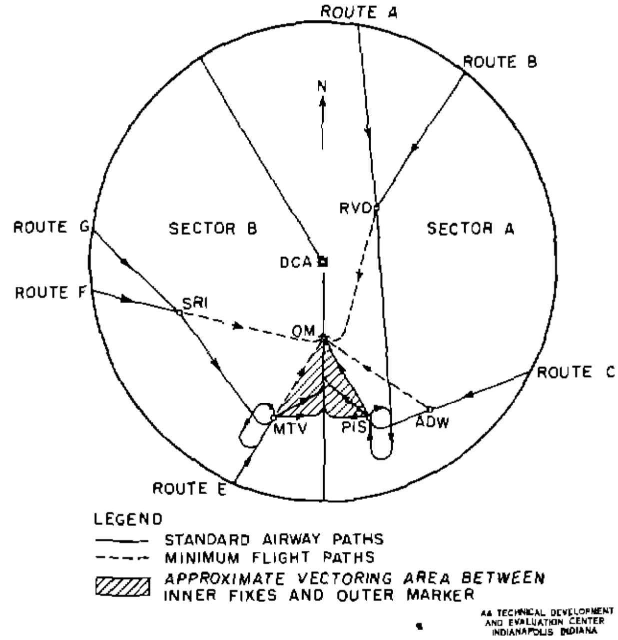


Fig 35 Phase 7 Configuration

descend below the minimum altitudes for these fixes until past them

Phase 7 Twin-Stack Configuration

It was assumed that an LVOR was installed in the vicinity of Piscataway (P I S) as shown in Fig 35 This installation, together with the one at Mt Vernon, formed a symmetrical twin-stack system These two fixes were used as final-clearance limits Aircraft over Riverdale or Andrews normally proceeded to Piscataway on direct ADF courses Aircraft from Springfield went to Mt Vernon on a direct ADF course All rules were similar to those of phase 2, except for the substitution of the phase 7 Mt Vernon and Piscataway inner fixes for the B and A inner fixes of phase 2

## APPENDIX B

### LISTING OF TRAFFIC SAMPLES

Tables XLVI, XLVII, and XLVIII list the three random-arrival samples and Tables XLIX, L, and LI list the three random-departure samples used in these simulation studies Their overall characteristics were given under "Conditions Studied and Methods of Evaluation" of this report Sample No 1 of arrivals was used with sample No 1 of departures, and so on

The routes designated as A, B, C, E, F, and G in the arrival listings were shown in Fig 1 Speed classes are shown as S, slow, similar to DC-3, M, medium, similar to Convair or Martin, and F, fast, similar to DC-6 or Constellation $G_0$ was defined as any point in the terminal area 20 flying miles from the outer marker

TABLE XLV

COMPARISON OF AVERAGE ARRIVAL DELAYS WITH COMMUNICATION DENSITY FOR DYNAMIC SIMULATOR

Conditions of Testing·
Arrivals plus departures, zero wind; hour of operation 1 to 2.

| Sample Number* | Phase Number | Average Absolute Delay Per Arrival (minutes) | Communication Density Channel 3 East Sector (per cent) | Communication Density Channel 1 West Sector (per cent) |
|---|---|---|---|---|
| 1 | 2 | 11.5 | 27 | 23 |
| | 6 | 12.4 | 27 | 30 |
| | 7 | 12.6 | 25 | 37 |
| 2 | 2 | 9.8 | 36 | 19 |
| | 6 | 11.4 | 42 | 17 |
| | 7 | 10.7 | 37 | 18 |
| 3 | 2 | 8.2 | 33 | 28 |
| | 6 | 9.3 | 31 | 24 |
| | 7 | 7.1 | 28 | 32 |
| **Average** | 2 | 9.8 | 32 | 23 |
| | 6 | 11.0 | 33 | 23 |
| | 7 | 10.1 | 30 | 29 |

*The figures for each sample are the average of three runs.

## APPENDIX C

## IDEAL AND GRAPHICAL METHODS OF ANALYSIS*

In the ideal analysis, it is presumed that random traffic can be controlled ideally by effecting specific delays where required These delays are based on perfect knowledge and perfect execution in the handling of arrival and departure traffic while conforming with the prescribed minimum separation and first-come, first-served rules The assumed average-performance data are used throughout In the case of arrival traffic, the first aircraft due to arrive at the outer marker will be the first to land, regardless of entry altitude, entry point, and time of arrival at the boundary of the terminal area The boundary in this investigation is considered to be 20 flying miles from the outer marker and is designated as $G_0$ No speed-ups are used to close gaps in arrival times

An out-of-scale s-T graphical illustration of the method involved in the ideal analysis of a hypothetical sample of arrivals only is shown on Fig 36 The solid s-T lines represent the unaltered, undelayed s-T traverse over the 20 flying miles from $G_0$, entry to the terminal area, to G1, the outer marker The dashed lines represent the delays devised for each case and necessary to meet the prescribed separation minima at $G_1$ for the particular sequences of S, M, or F aircraft on the basis of the first due to arrive at $G_1$ will be first to be brought in for landing It should be noted here that an ideal analysis need not be done graphically Fig 36 is presented for purposes of illustration only As an example, an ideal analysis for a particular random-traffic sample of arrivals only is performed with simple arithematic by

*Detailed descriptions of the methods can be found in Franklin Institute Laboratories Reports Nos F-2164-2 and F-2256

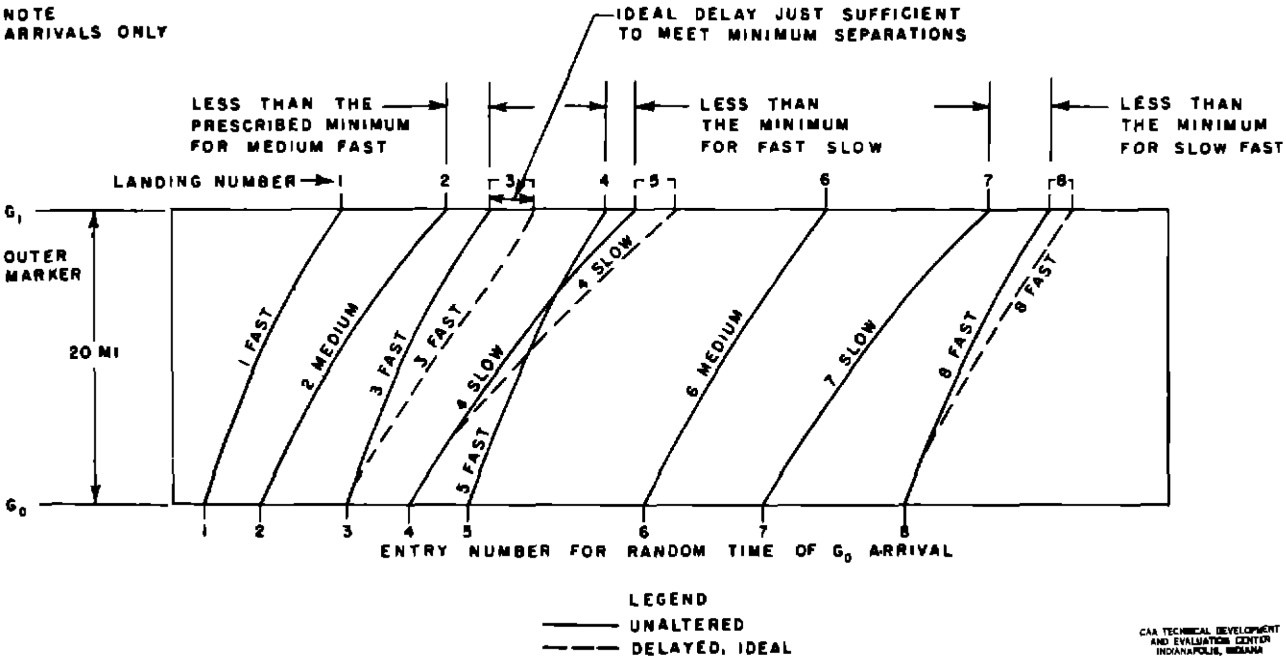


Fig 36 Graphical Illustration of Acceptance Order and Delays at Outer Marker (Arrivals Only)

TABLE XLVI

SAMPLE NUMBER 1 OF ARRIVAL AIRCRAFT

| Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) |
|---|---|---|---|---|
| 0 to 1/2 | 1 | G | S | 230 |
| | 2 | A | M | 260 |
| | 3* | F | S | 570 |
| | 4 | C | S | 960 |
| | 5 | G | F | 1130 |
| | 6 | E | M | 1160 |
| | 7 | A | F | 1790 |
| 1/2 to 1 | 8 | A | F | 2040 |
| | 9 | C | M | 2130 |
| | 10* | A | S | 2140 |
| | 11 | A | S | 2250 |
| | 12 | G | F | 2340 |
| | 13 | C | F | 2470 |
| | 14 | F | M | 2480 |
| | 15 | B | S | 2610 |
| | 16 | B | F | 2860 |
| | 17 | B | M | 3210 |
| | 18 | C | M | 3580 |
| 1 to 1 1/2 | 19 | E | S | 3850 |
| | 20 | B | F | 3940 |
| | 21 | E | M | 3990 |
| | 22 | C | S | 4040 |
| | 23 | B | S | 4370 |
| | 24* | G | S | 4380 |

| Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) |
|---|---|---|---|---|
| 1 to 1 1/2 | 25 | A | F | 4570 |
| | 26 | B | M | 4580 |
| | 27* | E | M | 4590 |
| | 28 | G | F | 4800 |
| | 29 | B | M | 4870 |
| | 30* | E | S | 4880 |
| | 31 | C | S | 4930 |
| | 32 | A | S | 4980 |
| | 33 | A | M | 5390 |
| 1 1/2 to 2 | 34 | E | S | 5420 |
| | 35 | G | S | 5510 |
| | 36 | F | S | 5620 |
| | 37* | G | S | 5670 |
| | 38 | B | F | 5740 |
| | 39 | E | F | 5790 |
| | 40 | G | F | 5840 |
| | 41* | G | S | 5890 |
| | 42 | G | M | 5960 |
| | 43 | B | S | 6070 |
| | 44 | B | S | 6080 |
| | 45 | E | M | 6090 |
| | 46 | A | S | 6160 |
| | 47 | G | S | 6290 |
| | 48* | A | F | 6300 |
| | 49* | A | S | 6750 |

| Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) |
|---|---|---|---|---|
| 1 1/2 to 2 | 50 | C | S | 6760 |
| | 51 | E | S | 7170 |
| | 52* | A | S | 7180 |
| | 53* | C | S | 7190 |
| 2 to 2 1/2 | 54 | B | M | 7220 |
| | 55 | E | S | 7250 |
| | 56* | G | S | 7780 |
| | 57 | A | F | 7870 |
| | 58 | B | S | 7920 |
| | 59 | A | M | 8150 |
| | 60 | G | M | 8300 |
| | 61 | F | F | 8330 |
| | 62 | C | F | 8360 |
| | 63 | F | M | 8550 |
| | 64 | F | S | 8920 |
| | 65* | B | F | 8990 |
| 2 1/2 to 3 | 66 | G | M | 9040 |
| | 67 | B | M | 9070 |
| | 68 | A | M | 9440 |
| | 69 | B | M | 10070 |
| | 70 | B | M | 10360 |
| | 71 | E | F | 10470 |
| | 72 | A | M | 10720 |
| | 73* | A | M | 10790 |

*Military

TABLE XLVII

SAMPLE NUMBER 2 OF ARRIVAL AIRCRAFT

| Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) | Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) | Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 1/2 | 1 | B | F | 90 | 1 to 1 1/2 | 25 | A | M | 4270 | 1 1/2 to 2 | 50 | E | M | 6880 |
| | 2 | G | F | 100 | | 26 | A | F | 4520 | | 51* | A | M | 6910 |
| | 3 | E | S | 190 | | 27 | B | S | 4530 | | 52 | E | S | 6940 |
| | 4 | A | S | 420 | | 28* | E | S | 4740 | | 53* | C | S | 7150 |
| | 5 | B | F | 1090 | | 29 | G | S | 4790 | | | | | |
| | 6 | B | F | 1140 | | 30 | A | M | 5040 | 2 to 2 1/2 | 54 | E | S | 7440 |
| | 7 | A | M | 1790 | | 31 | A | F | 5150 | | 55* | G | S | 7670 |
| | | | | | | 32 | A | F | 5220 | | 56 | F | F | 7860 |
| 1/2 to 1 | 8 | B | M | 1820 | | 33* | B | S | 5390 | | 57* | E | S | 7930 |
| | 9 | F | M | 1910 | | | | | | | 58 | A | S | 8080 |
| | 10 | G | S | 2000 | 1 1/2 to 2 | 34 | A | M | 5460 | | 59 | C | S | 8170 |
| | 11 | G | S | 2010 | | 35 | B | S | 5490 | | 60 | C | M | 8220 |
| | 12 | A | S | 2040 | | 36 | C | S | 5520 | | 61 | G | S | 8350 |
| | 13 | B | S | 2250 | | 37 | C | S | 5630 | | 62 | E | M | 8740 |
| | 14 | G | M | 2360 | | 38 | B | S | 5700 | | 63 | A | M | 8890 |
| | 15 | B | M | 2610 | | 39 | G | F | 5730 | | 64 | E | M | 8960 |
| | 16 | A | F | 2660 | | 40 | A | F | 5900 | | 65 | A | S | 8990 |
| | 17* | C | S | 2670 | | 41 | B | M | 6070 | | | | | |
| | 18* | A | S | 3580 | | 42* | F | S | 6140 | 2 1/2 to 3 | 66 | C | F | 9280 |
| | | | | | | 43 | G | M | 6150 | | 67 | B | F | 9330 |
| 1 to 1 1/2 | 19 | B | M | 3890 | | 44 | C | F | 6360 | | 68 | F | M | 9540 |
| | 20 | B | M | 3940 | | 45 | C | M | 6410 | | 69 | E | F | 9690 |
| | 21 | G | M | 3950 | | 46 | B | M | 6460 | | 70* | E | M | 9760 |
| | 22 | G | F | 3960 | | 47* | G | S | 6490 | | 71* | F | S | 10070 |
| | 23* | G | F | 4070 | | 48 | G | S | 6780 | | 72* | E | F | 10520 |
| | 24 | A | S | 4260 | | 49 | B | M | 6870 | | 73 | E | S | 10790 |

*Military

(1) Noting the times of arrival at $G_0$
(2) Adding the average 20-mile traverse times for the particular aircraft type
(3) Accepting the unaltered order of arrival at $G_1$
(4) Determining what delay times, if any, are necessary to meet the corresponding outer-marker time minima

Fig 36 indicates that inadequate separation at $G_1$ would result, according to the $G_0$ entry times for No 2 M and No 3 F aircraft if these aircraft retained their respective comparative speeds and positions, therefore, No 3 F is delayed by an amount just sufficient to meet the particular outer-marker time minimum Entry No 4 S is fifth to land at $G_1$ and entry No 5 F is fourth to land, because No 5 F, a faster aircraft, is scheduled to arrive at $G_1$ before No 4 S, a slower aircraft However, because inadequate time separation at $G_1$ would exist for this order of arrival and for the resulting sequence of FS at $G_1$, entry No 5 F is unaltered but entry No 4 S is delayed to suit Further, it should be pointed out that should the delaying of entry No 3 F result in inadequate separation at $G_1$ between No 3 F and No 5 F, No 5 F would also have been delayed to suit but would still be No 4 to land However, this would result in an even larger delay of entry No 4 S, which is still No 5 to land For purposes of clarity, this case is not shown in Fig 36

An out-of-scale s-T graphical illustration of the method involved in the ideal analysis and of the order of runway acceptance of a hypothetical sample of arrivals and departures from the outer marker, $G_1$, up to and including the runway, is shown in Fig 37 Average performance data and rules, as outlined in a previous section, are used throughout

It is seen that No 1 arrival, a fast aircraft, arrived at the outer marker at a time less than 36 seconds before No 1 departure was scheduled to start its 30-second line-up time No 1 departure is cleared as No 1 runway operation and departs accordingly, and No 1 arrival comes in next as No 2 runway operation Since the No 2 departure is scheduled to start its line-up at a time less than 30 seconds after the preceding No 2 arrival has crossed the runway

TABLE XLVIII

SAMPLE NUMBER 3 OF ARRIVAL AIRCRAFT

| Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) | Period of Operation (hour) | Arrival Number | Route | Speed Class | Time of Arrival at $G_0$ (seconds) | Period of Operation (hour) | Arrival Number | Route | Speed | Time of Arrival at $G_0$ (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 1/2 | 1 | A | F | 10 | 1 to 1 1/2 | 25 | B | M | 4290 | 1 1/2 to 2 | 50 | G | S | 6880 |
| | 2 | C | F | 180 | | 26 | A | M | 4360 | | 51 | B | M | 7110 |
| | 3 | A | S | 350 | | 27 | G | F | 4390 | | 52 | A | M | 7180 |
| | 4 | A | M | 420 | | 28 | E | M | 4540 | | 53 | B | M | 7190 |
| | 5 | G | F | 710 | | 29* | A | F | 4550 | | | | | |
| | 6 | B | F | 1480 | | 30 | F | S | 5100 | 2 to 2 1/2 | 54 | A | S | 7320 |
| | 7* | G | F | 1790 | | 31 | A | F | 5250 | | 55 | E | S | 7350 |
| | | | | | | 32 | F | S | 5300 | | 56 | F | S | 7420 |
| 1/2 to 1 | 8 | B | M | 1820 | | 33 | B | M | 5350 | | 57 | G | M | 7430 |
| | 9* | B | S | 1870 | | | | | | | 58 | G | S | 7800 |
| | 10 | A | S | 1980 | 1 1/2 to 2 | 34 | B | B | 5700 | | 59 | C | S | 7990 |
| | 11 | C | F | 2230 | | 35 | E | M | 5890 | | 60* | A | S | 8000 |
| | 12* | A | S | 2240 | | 36 | G | M | 5900 | | 61* | B | S | 8130 |
| | 13 | G | S | 2330 | | 37 | C | S | 5970 | | 62 | G | F | 8180 |
| | 14 | F | M | 2620 | | 38* | E | M | 6020 | | 63 | G | M | 8190 |
| | 15 | B | F | 2710 | | 39 | A | F | 6110 | | 64 | E | M | 8860 |
| | 16 | A | M | 3020 | | 40 | C | S | 6160 | | 65 | A | M | 8990 |
| | 17 | A | S | 3090 | | 41* | E | S | 6450 | | | | | |
| | 18 | A | M | 3580 | | 42 | F | M | 6460 | 2 1/2 to 3 | 66* | E | S | 9640 |
| | | | | | | 43* | G | S | 6510 | | 67 | E | S | 9670 |
| 1 to 1 1/2 | 19 | B | F | 3650 | | 44 | B | F | 6520 | | 68 | E | F | 9680 |
| | 20* | G | S | 3780 | | 45 | B | M | 6530 | | 69* | C | S | 9930 |
| | 21 | G | S | 3790 | | 46 | G | S | 6540 | | 70 | B | S | 9960 |
| | 22 | E | S | 4000 | | 47 | F | F | 6610 | | 71 | C | S | 10270 |
| | 23 | A | F | 4010 | | 48 | E | F | 6640 | | 72 | C | M | 10380 |
| | 24* | B | S | 4240 | | 49 | B | M | 6770 | | 73* | C | M | 10790 |

*Military

TABLE XLIX

SAMPLE NUMBER 1 OF TAKE-OFF AIRCRAFT

| Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 1/2 | 1 | 390 | 1 to 1 1/2 | 22 | 4600 | 2 to 2 1/2 | 43* | 7690 | 2 1/2 to 3 | 65 | 10430 |
| | 2 | 800 | | 23 | 5010 | | 44 | 7860 | | 66 | 10700 |
| | 3 | 810 | | 24* | 5380 | | 45 | 7890 | | 67 | 10750 |
| | 4 | 1220 | | | | | 46 | 8020 | | 68 | 10760 |
| | 5* | 1790 | 1 1/2 to 2 | 25* | 5450 | | 47 | 8070 | | | |
| | | | | 26 | 5660 | | 48 | 8400 | 3 to 3 1/2 | 69 | 11050 |
| 1/2 to 1 | 6 | 1860 | | 27 | 5690 | | 49 | 8530 | | 70 | 11120 |
| | 7* | 2190 | | 28* | 5760 | | 50 | 8580 | | 71* | 11270 |
| | 8 | 2320 | | 29* | 5930 | | 51 | 8590 | | 72 | 11660 |
| | 9 | 2510 | | 30 | 6100 | | 52 | 8760 | | 73 | 11910 |
| | 10 | 2720 | | 31 | 6250 | | 53* | 8870 | | 74 | 12320 |
| | 11 | 2990 | | 32 | 6420 | | 54* | 8940 | | 75 | 12330 |
| | 12 | 3340 | | 33 | 6630 | | 55* | 8990 | | 76* | 12580 |
| | 13 | 3570 | | 34 | 6980 | | | | | | |
| | | | | 35 | 7150 | 2 1/2 to 3 | 56 | 9080 | 3 1/2 to 4 | 77* | 12670 |
| 1 to 1 1/2 | 14 | 3660 | | 36 | 7160 | | 57 | 9130 | | 78* | 13220 |
| | 15 | 3790 | | 37 | 7170 | | 58 | 9380 | | 79 | 13230 |
| | 16 | 3880 | | 38 | 7180 | | 59 | 9570 | | 80 | 13620 |
| | 17 | 3950 | | | | | 60 | 9640 | | 81 | 13630 |
| | 18 | 3960 | 2 to 2 1/2 | 39 | 7390 | | 61* | 9710 | | 82 | 13680 |
| | 19* | 4010 | | 40 | 7400 | | 62 | 10080 | | 83 | 13710 |
| | 20 | 4100 | | 41 | 7450 | | 63* | 10110 | | 84 | 14380 |
| | 21 | 4430 | | 42 | 7660 | | 64 | 10220 | | 85 | 14390 |

*military

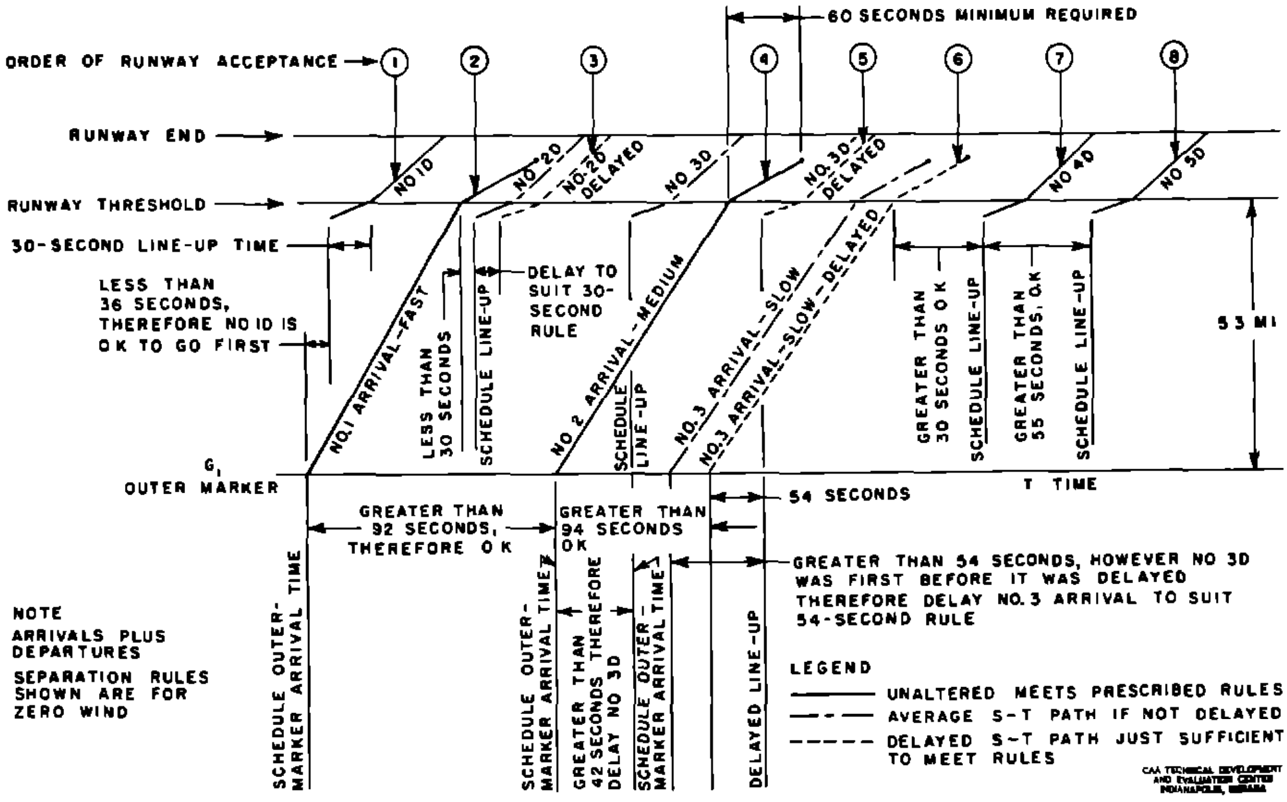


Fig 37 Graphical Illustration of Acceptance Order and Delays (Arrivals Plus Departures)

threshold, it is delayed an amount just sufficient to meet the 30-second rule and thus becomes No 3 runway operation Proceeding, No 2 arrival (medium) arrives at the outer marker at such a time that the scheduled line-up time of No 3 departure would be greater than 42 seconds later Therefore, No 2 arrival is given clearance to land as No 4 runway operation, and No 3 departure is delayed an amount sufficient to start its take-off at just 60 seconds after this preceding arrival has crossed the runway threshold No 3 departure then becomes No 5 runway operation

It is next seen that No 3 arrival (slow) would arrive at the outer marker more than 54 seconds before No 3 departure starts its delayed line-up time No 3 arrival is delayed to exactly suit the 54-second interval and becomes No 6 runway operation It should be pointed out that if No 3 departure's line-up time were scheduled instead of delayed, the No 3 arrival would have been accepted first, and no delay would have been imposed on it However, because the No 3 departure's originally scheduled line-up time occurred before the outer-marker time of No 3 arrival, No 3 departure is first served

The scheduled line-up time of No 4 departure occurs at more than 30 seconds after the preceding delayed arrival No 3 crosses the runway threshold. Therefore, No 4 departure is clear to go and becomes runway operation No 7 Since more than 55 seconds exists between the scheduled undelayed line-up time of No 4 and No 5 departures, No 5 departure is then cleared as runway operation No 8

The ideal analysis differs from the theoretical analysis used by other investigators in the past in that it considers representative random samples of traffic as they might occur from day to day and not a theoretically infinite average traffic rate It also considers differences in aircraft speeds and in separation requirements by accepting aircraft landing sequences according to the particular times of arrival of the aircraft at the outer marker and by subsequent delaying of the aircraft to suit As such, the ideal analysis has been demonstrated in previous investigations for ANDB to be a more realistic and, consequently, a more conclusive criterion for evaluation purposes in the determination of significant trends. This is especially important in the

TABLE L

SAMPLE NUMBER 2 OF TAKE-OFF AIRCRAFT

| Period of Operation (hour) | Departure Number | Desired Time of Take-off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 1/2 | 1 | 330 | 1 to 1 1/2 | 22* | 4660 | 2 to 2 1/2 | 43* | 7810 | 2 1/2 to 3 | 65 | 10690 |
| | 2 | 800 | | 23 | 4730 | | 44 | 7860 | | 66 | 10720 |
| | 3 | 1030 | | 24* | 5380 | | 45* | 7870 | | 67* | 10750 |
| | 4* | 1120 | | | | | 46 | 7880 | | 68* | 10780 |
| | 5 | 1790 | 1 1/2 to 2 | 25 | 5410 | | 47* | 8070 | | | |
| | | | | 26* | 5440 | | 48 | 8120 | 3 to 3 1/2 | 69 | 11090 |
| 1/2 to 1 | 6* | 2280 | | 27* | 5750 | | 49 | 8250 | | 70* | 11480 |
| | 7 | 2350 | | 28 | 6080 | | 50 | 8280 | | 71* | 11650 |
| | 8 | 2360 | | 29 | 6190 | | 51 | 8310 | | 72 | 11700 |
| | 9 | 2850 | | 30 | 6280 | | 52 | 8320 | | 73 | 11810 |
| | 10 | 3120 | | 31 | 6530 | | 53* | 8570 | | 74 | 12220 |
| | 11 | 3370 | | 32 | 6660 | | 54 | 8800 | | 75 | 12510 |
| | 12 | 3440 | | 33 | 6770 | | 55 | 8990 | | 76 | 12580 |
| | 13 | 3570 | | 34 | 6920 | | | | | | |
| | | | | 35 | 6970 | 2 1/2 to 3 | 56 | 9120 | 3 1/2 to 4 | 77 | 12810 |
| 1 to 1 1/2 | 14 | 3620 | | 36 | 7100 | | 57 | 9370 | | 78 | 13020 |
| | 15 | 3690 | | 37 | 7170 | | 58 | 9400 | | 79 | 13030 |
| | 16 | 3720 | | 38* | 7180 | | 59 | 9710 | | 80 | 13040 |
| | 17 | 4090 | | | | | 60 | 9940 | | 81 | 13350 |
| | 18 | 4560 | 2 to 2 1/2 | 39 | 7250 | | 61 | 10050 | | 82 | 13740 |
| | 19 | 4590 | | 40 | 7280 | | 62 | 10060 | | 83 | 14030 |
| | 20 | 4600 | | 41 | 7650 | | 63 | 10090 | | 84* | 14160 |
| | 21 | 4610 | | 42 | 7740 | | 64 | 10400 | | 85* | 14370 |

*Military

TABLE LI

SAMPLE NUMBER 3 OF TAKE-OFF AIRCRAFT

| Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) | Period of Operation (hour) | Departure Number | Desired Time of Take-Off (seconds) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 1/2 | 1* | 590 | 1 to 1 1/2 | 22 | 5200 | 2 to 2 1/2 | 43 | 8010 | 2 1/2 to 3 | 65 | 10650 |
| | 2 | 1020 | | 23* | 5350 | | 44* | 8060 | | 66 | 10760 |
| | 3 | 1550 | | 24 | 5380 | | 45 | 8130 | | 67 | 10770 |
| | 4 | 1680 | | | | | 46 | 8160 | | 68 | 10780 |
| | 5 | 1790 | 1 1/2 to 2 | 25 | 5510 | | 47* | 8430 | | | |
| | | | | 26* | 5540 | | 48 | 8460 | 3 to 3 1/2 | 69 | 11030 |
| 1/2 to 1 | 6 | 2160 | | 27* | 5590 | | 49 | 8490 | | 70 | 11420 |
| | 7 | 2330 | | 28 | 5660 | | 50 | 8540 | | 71 | 12050 |
| | 8 | 2420 | | 29 | 5710 | | 51 | 8650 | | 72* | 12160 |
| | 9 | 2610 | | 30 | 5900 | | 52 | 8720 | | 73 | 12170 |
| | 10 | 2660 | | 31 | 5950 | | 53* | 8810 | | 74 | 12220 |
| | 11 | 2970 | | 32* | 6140 | | 54 | 8940 | | 75 | 12510 |
| | 12 | 3160 | | 33 | 6330 | | 55* | 8990 | | 76* | 12580 |
| | 13* | 3590 | | 34 | 6700 | | | | | | |
| | | | | 35 | 6710 | 2 1/2 to 3 | 56 | 9380 | 3 1/2 to 4 | 77 | 12650 |
| 1 to 1 1/2 | 14 | 3620 | | 36 | 6980 | | 57 | 9410 | | 78 | 12820 |
| | 15 | 3730 | | 37 | 7070 | | 58 | 9500 | | 79 | 13110 |
| | 16 | 3880 | | 38 | 7180 | | 59* | 9810 | | 80* | 13120 |
| | 17 | 4170 | | | | | 60* | 9900 | | 81 | 13650 |
| | 18 | 4180 | 2 to 2 1/2 | 39 | 7290 | | 61 | 10230 | | 82 | 13780 |
| | 19 | 4470 | | 40 | 7300 | | 62 | 10240 | | 83 | 13990 |
| | 20 | 5020 | | 41 | 7390 | | 63 | 10370 | | 84 | 14120 |
| | 21* | 5110 | | 42 | 7900 | | 64 | 10440 | | 85* | 14370 |

*military

determination of the suitability of one, two, three, or more representative random-traffic samples for proper use in the preliminary design of a traffic control system or for a reasonably conclusive preliminary evaluation of various proposed procedures, rules, or other systems

In the graphical method of analysis, perfect knowledge and perfect execution is assumed This includes the probable variations in performance on both the glide slope and the runway However, contrary to the ideal method, the procedures required to meet altitude, lateral, outer-marker, runway, and other separations are followed step by step as they might occur in the dynamic simulator and in actual practice Limits of turning, finite stacking times, times to turn and to vector, and so forth are followed by projecting the x and y flight co-ordinates of the aircraft with time The human element is ignored except in cases of previously described constant time delays which are assumed for observations, time for making decisions, and time for reaction

Graphical analysis is basically the plotting on a grid of which the ordinate s is the projected distance and the abscissa T is the time of the path of an aircraft as it travels through certain airways and paths of a given traffic-control configuration and system This method gives a continuous physical picture of the procedures followed and of the decisions made to meet the particular rules and layout Where the path is on a specific airway, the slope of the s-T curve is the projected speed of the aircraft at that point A constant slope indicates constant velocity Where an aircraft must delay, a wavelike trace (sinusoidal if the aircraft circles) is shown on the s-T grid Colors are used to identify different airways and entry paths, and various dashed, solid, and broken lines identify altitudes