8
1
92
3

APPLICATION OF SIMULATION TECHNIQUES IN THE STUDY OF TERMINAL-AREA AIR TRAFFIC CONTROL PROBLEMS

By
C. M. Anderson
T. K Vickers

Navigation Aids Evaluation Division

TECHNICAL DEVELOPMENT REPORT No. 192

Prepared for
The Air Navigation Development Board
Under
Project 6.7
by
CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA

365

November 1953

U S DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary

CIVIL AERONAUTICS ADMINISTRATION
F B Lee, Administrator
D M Stuart, Director, Technical Development and Evaluation Center

LIBRARY
CIVIL AERONAUTICS
TL 568
.A21
Copy 2

TABLE OF CONTENTS

Prepared for
The Air Navigation Development Board
Under
Project 6 7
by
CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
Indianapolis, Indiana
November 1953

This is a technical information report and does not necessarily represent CAA policy in all respects

APPLICATION OF SIMULATION TECHNIQUES IN THE STUDY OF TERMINAL-AREA AIR TRAFFIC CONTROL PROBLEMS

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 is an interim report summarizing the work which has been completed to October 1953 in the study, through the use of simulation techniques, of air traffic control problems The objectives of this study, conducted at the Technical Development and Evaluation Center of the Civil Aeronautics Administration, were to evaluate improvements of the present system, to explore new methods of control, and to minimize the time lag between the initial concept and the operational use of new developments in control procedures and equipment

Simulation processes included both graphical methods, developed by Franklin Institute Laboratories, and test runs on the dynamic air traffic control simulator installed at this Center Because of limitations in the present capacity of this simulator, most of the tests run on it have been concerned with the study of terminal-area, rather than with en route, traffic problems Simulation has proved to be a safe, fast, inexpensive, and accurate method of investigating the effect of such basic factors as aircraft characteristics, airport characteristics, navigational aids, and human reactions on the capacity or acceptance rate of a terminal area, the comparative air-traffic-flow characteristics of various proposed layouts of navigational aids for specific terminal areas, and the operational requirements and procedures for new types of air traffic control equipment such as automatic data-transfer systems and approach computers

A by-product of the dynamic-simulation program has been the development of improved control techniques This work has been directed toward the twin objectives of increasing traffic capacity while decreasing the actual work load involved in the control of individual aircraft in the system

INTRODUCTION

Graphical Simulation

The development of simulation techniques has greatly accelerated the study and analysis of air traffic control systems Prior to 1949 the testing of any new system of traffic control required the use of actual aircraft, as well as the use of actual navigation and communication facilities This method was inflexible, slow, and very expensive

In the spring of 1949, a form of graphical simulation was developed in connection with a study by the CAA of the effects of communication delays on the acceptance rate of approach control systems Through the use of this technique, which was essentially a simple plot of altitude versus time certain laws concerning air-traffic-flow characteristics were determined The immediate result of this study was the justification for direct very-high-frequency (VHF) air/ground communications facilities for Air Route Traffic Control (ARTC) Centers[1] In addition, certain control procedures were modified in order to take advantage of the principles discovered for maintaining steady traffic flows from approach control systems

Shortly afterwards, the Franklin Institute undertook a study of the feasibility of analyzing air traffic systems by simulation techniques[2] This study was sponsored by the Air Navigation Development Board Electronic and electromechanical simulators were first contemplated but were finally shelved in favor of the simpler and more economical techniques of graphical simulation The application of graphical techniques, with particular emphasis on space-time (S-t) curves, was subsequently developed to a high degree by Franklin Institute personnel[3]

The S-t curve is a graphical plot in which the ordinate S is the projected distance of the flight path and the abscissa t is time A separate curve is drawn for each aircraft in the traffic situation Altitude data may be entered at appropriate points on the curves in order to give a running picture of the progress of each aircraft through the traffic system A section of a typical S-t curve is shown in Fig 1

The altitude-time (A-t) curve is a graphical plot in which the ordinate A is altitude and the abscissa t is time This type of curve has a useful application in showing the effect of communications delays on the operation of certain portions of the air traffic control system A section of a typical A-t curve appears in Fig 2

Graphical simulation is inexpensive, fast, and versatile It is especially useful in studying the effects of various separation standards or of other operating restrictions on the flow of air traffic It is valuable as a means of setting up a standard of comparison when evaluating the human factor in dynamic-simulation tests or in actual traffic control operations The most obvious limitation of graphical simulation is the fact that four-dimensional traffic problems can be drawn simultaneously in only two dimensions However, this limitation can be alleviated in many cases through the addition of supplemental data directly on the curves Color coding can also be used to clarify the presentation when a number of different routes must be shown at the same time

Dynamic Simulation

The dynamic simulator is a laboratory device which provides in air traffic control research a function analogous to that which the wind tunnel provides in aerodynamic research This device furnishes means of simulating, to a high degree, actual flights of aircraft through any specific area During this operation, the traffic situation is controlled through the use of standard clearance instructions which are issued to the "simulated pilots" by regular air traffic controllers Various control procedures and techniques can be

---

[1] "Terminal Area Time Study," CAA Office of Federal Airways, July 22, 1949

[2] S M Berkowitz, W W Felton, R S Grubmeyer, and R R Reid, "The Applicability of Simulation to the Investigation of Air Traffic Control Problems," Franklin Institute Final Report No F-2180-1, Philadelphia, Pa , March 17, 1950

[3] S M Berkowitz and Ruth R Doering, "Analytical and Simulation Studies of Several Radar-Vectoring Procedures in the Washington, D C , Terminal Area," CAA Technical Development Report No 222, as yet unpublished

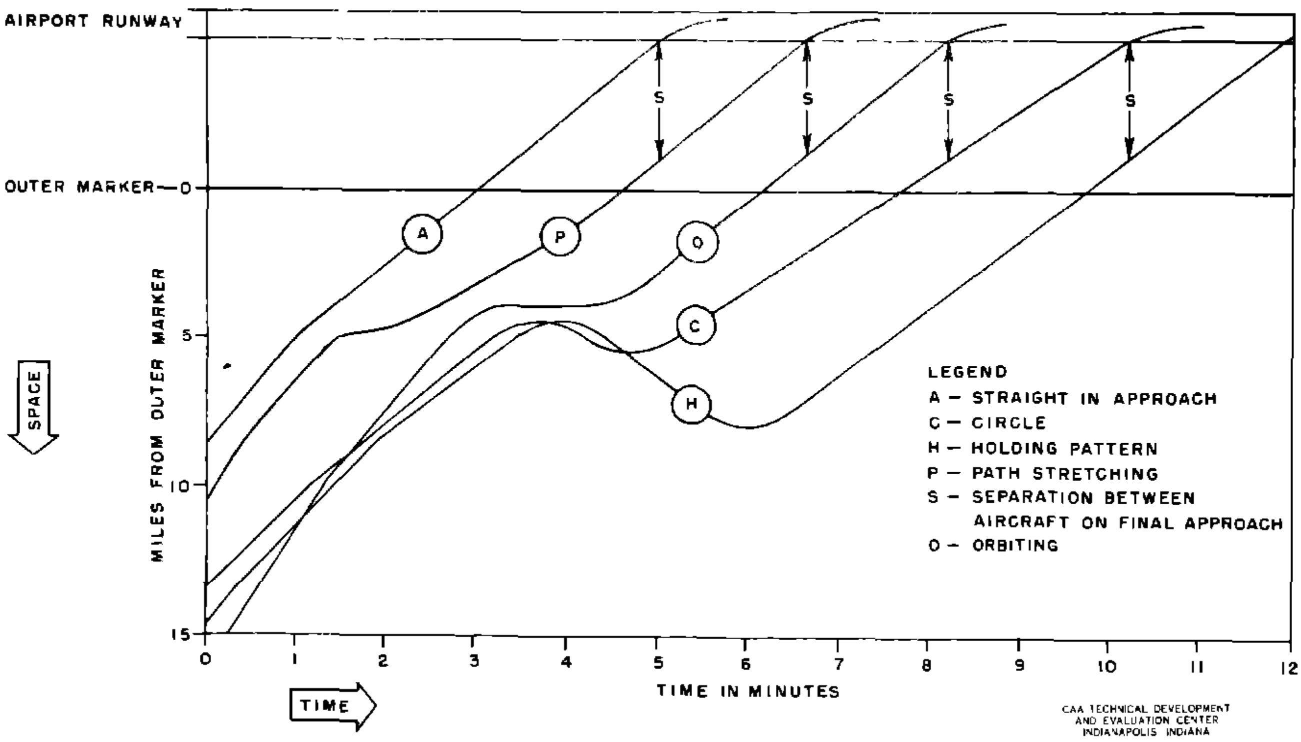


Fig 1 Section of Typical S-t Curve

tested and compared In addition, various arrangements of air navigation facilities and control equipment can be tested in order to determine which setup provides the most efficient traffic flow

A detailed description of the dynamic simulator appears in another publication[1] It can be described briefly as a combination of optical, mechanical, and electronic equipment including a large screen upon

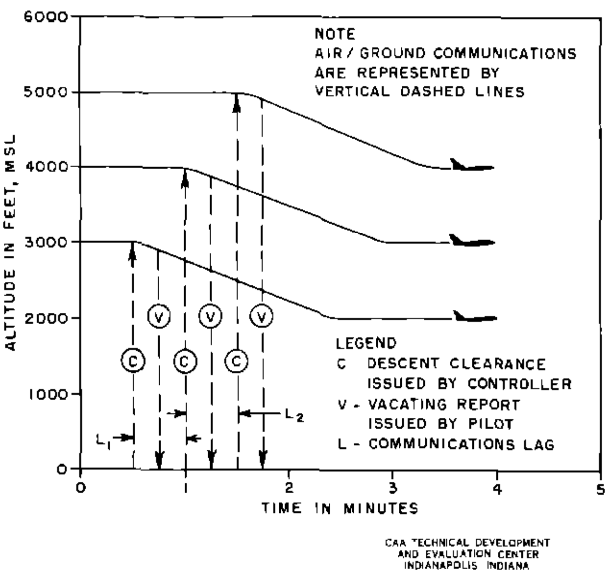


Fig 2 Section of A-t Curve Showing Typical Laddering-Down Procedure for 3 Aircraft

[1]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

which a map of a specific area is projected Controllable spots of light are projected on this screen to indicate the position of aircraft in the traffic situation These spotlight projectors are remotely controlled from pilot consoles Each pilot can control the speed and the heading of one spot of light on the screen to correspond to the movement of an aircraft through the area Standard-rate turns are made by the equipment when the direction of target travel is changed The pilots are also equipped with simulated altimeters, so that descents and climbs may be made at rates realistic for the types of aircraft being simulated The entire display on the screen is televised and is presented to the controllers at the control positions as a surveillance radar display A number of interphone channels connect the pilot consoles with the control positions to simulate air/ground radio channels An ARTC Center position is set up to simulate the ARTC function in feeding the terminal area Tests can be made with or without the radar display

Up to the present time, most of the work with the dynamic simulator has been concerned with the terminal phase, rather than with the en route phase, of the air traffic control system This was necessary for two reasons

1 At the time the simulator was commissioned, terminal-area problems constituted the greatest single barrier to increased capacity of the air traffic control system and therefore justified first consideration

2 During the period covered by this report, the capacity of the dynamic simulator was limited to a maximum of eight aircraft targets available for simultaneous use This number, while adequate for the simulation of traffic flow in small terminal areas, was inadequate to produce a sufficient density of traffic for studies of larger geographical areas such as complete en route traffic control sectors Present plans call for an increase in capacity of the present simulator to a total of 18 individual targets It is expected that this number will be sufficient for a study of many problems of en route traffic control

In air traffic control research, dynamic simulation can provide the following

1 The effects of the human factor can be observed and assessed directly Controller performance can be compared with idealized standards obtained from graphical analysis of the traffic problem under study

2 Actual control procedures can be used to feed aircraft through the system This is a valuable aid in the development of adequate procedures to handle traffic operations of the type simulated

3 Complete communications procedures are utilized Detailed measurements of this function are thereby possible

4 Actual traffic patterns are displayed in plain view This representation of the traffic situation is valuable in determining the amount or adequacy of the airspace used for the operation and in determining the flow characteristics of the system

In many cases the potential bottlenecks of a traffic control system can be discovered during the initial test of the system This feature makes possible rapid improvements in the procedures or in the facility layout

The limitations of dynamic simulation are those imposed by economic, rather than by technical, considerations For example, it would be possible from a technical standpoint to design a simulator capable of simultaneously reproducing all aircraft movements in the northeastern quadrant of the United States However, it is likely that the tremendous costs of building, maintaining, and staffing such an installation would far outweigh the possible technical advantages which might be obtained through a simulation program on so grand a scale This consideration is discussed in another report[3]

FACTORS AFFECTING TERMINAL-AREA TRAFFIC FLOW

One of the primary objectives of the simulation program was to determine the effects of the various factors which influence the acceptance rates of a terminal area These factors may be grouped under the following general headings

Aircraft Characteristics
Arrangement of Facilities
Separation Standards
Control Procedures
Human Reactions
Weather

[3]Ibid

The following discussion describes the results of this study Certain of the principles evaluated have an immediate application in the development and implementation of air traffic control procedures and facilities

Aircraft Characteristics

In an activity such as air traffic control where the start of a specific operation is dependent on the completion of a preceding operation, the most obvious method of increasing the capacity of the system is to reduce the amount of time required for each individual operation Because of this relationship between time, rate, and capacity, the acceptance rate of a terminal area is directly related to the characteristics of the aircraft using the system

When a specified amount of longitudinal separation is employed, the maximum acceptance rate is limited by the speed of the aircraft concerned This is illustrated by the simple formula for the maximum capacity of a single traffic lane

$$C = \frac{V}{S} \qquad (1)$$

where

C = capacity, in aircraft per hour,
V = average ground speed of aircraft, in miles per hour,
S = average separation employed between aircraft, in miles

For example, if V is 120 mph and S is 5 miles, then the capacity is 24 aircraft per hour

In order to maintain a specified minimum amount of longitudinal separation throughout a common approach course, it is necessary to establish additional separation when a faster aircraft is turned on to the approach behind a slower one This separation will decrease as they proceed down the course When a slower aircraft is turned on to the approach with a specified minimum amount of separation behind a faster one, the separation will increase as they proceed down the course These effects are shown in Fig 3

When altitude separation is being employed between aircraft, the maximum capacity is limited by their altitude-change (climb or descent) characteristics This is illustrated by the formula for the maximum theoretical capacity of a single-stack approach control system

$$C = \frac{60}{\frac{S}{R} + L} \qquad (2)$$

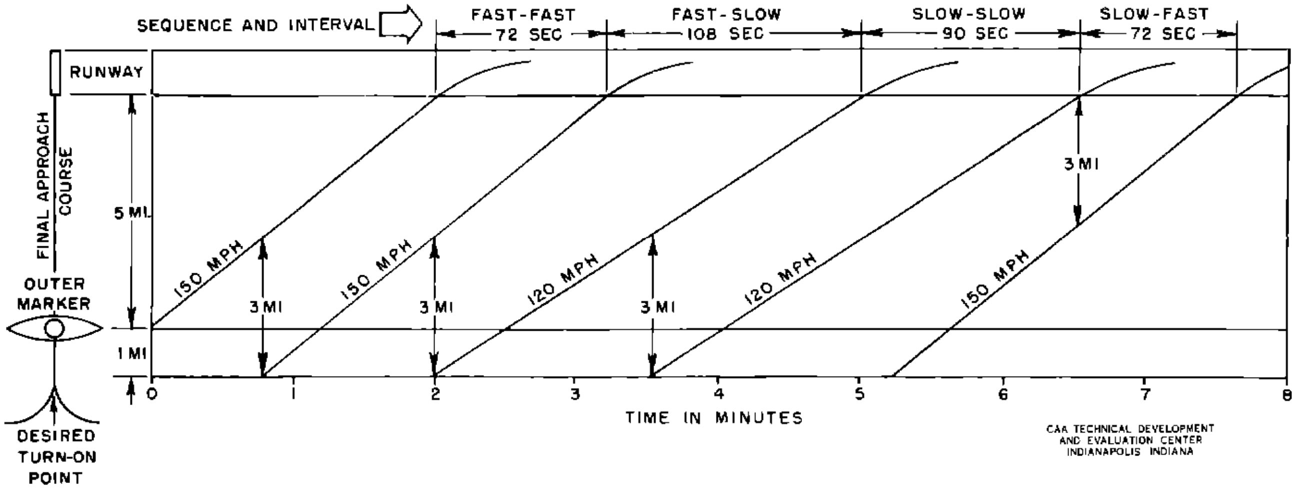


Fig 3 Effect of Different Approach Speeds on the Theoretical Approach Interval

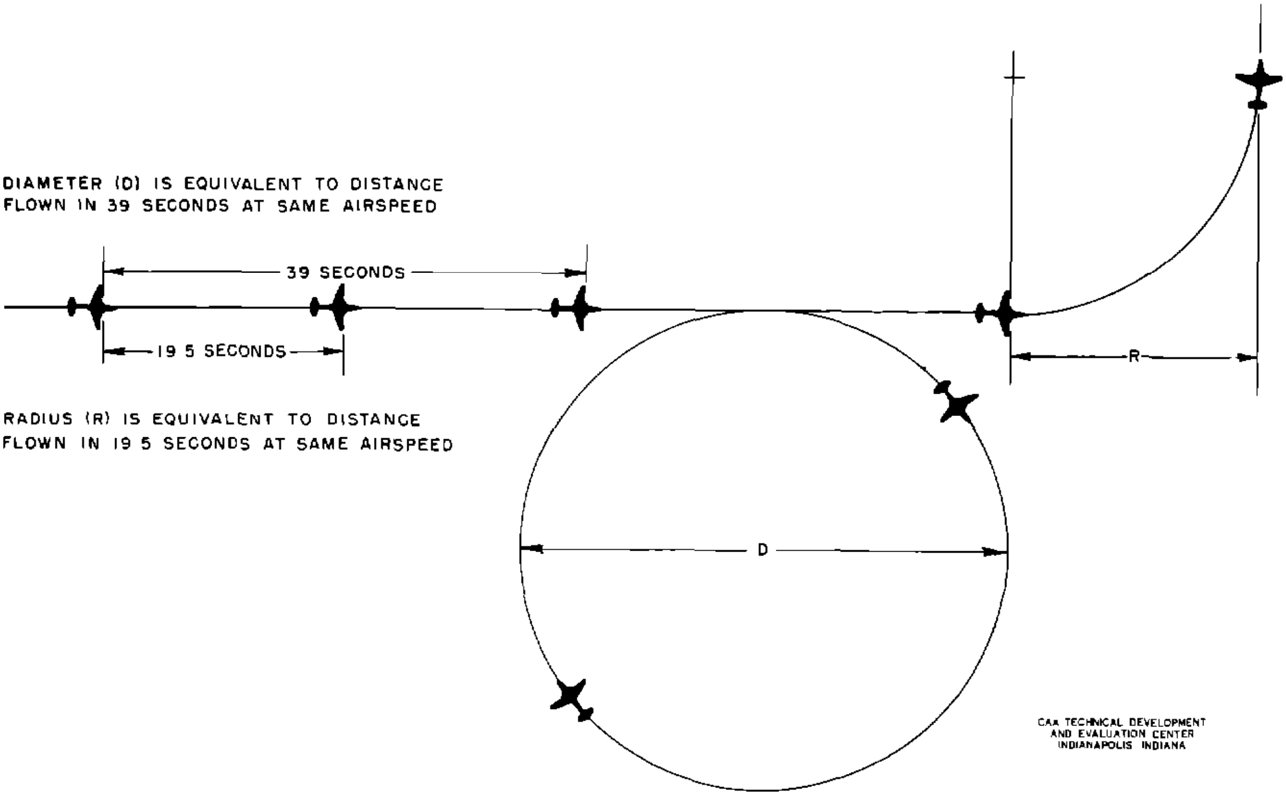


Fig 4 Characteristics of Standard Rate (3° per Second) Turns in Still Air

where
C = capacity, in aircraft per hour,
S = altitude separation, in feet,
R = average descent rate, in feet per minute (fpm),
L = communication lag (average time interval between issuances of descent clearances to successive aircraft), in minutes

Nonpressurized passenger aircraft are usually limited to a descent rate of 500 feet per minute, pressurized aircraft to 1000 feet per minute If an average communications lag of one-half minute is assumed, the maximum theoretical capacity of a single-stack approach control system with either type of aircraft would be

For pressurized aircraft if S = 1000 feet, R = 1000 fpm, and L = ½ minute, then C = 40 aircraft per hour

For nonpressurized aircraft if S = 1000 feet, R = 500 fpm, and L = ½ minute, then C = 24 aircraft per hour

Where both pressurized and nonpressurized aircraft enter the system at random, the capacity is still very closely related to the rates for nonpressurized aircraft since a pressurized aircraft which maintains altitude separation above a nonpressurized one ultimately becomes limited to the descent rate of the nonpressurized craft

Average maneuverability characteristics affect the amount of flexibility which the controller can utilize in path-stretching operations for the purpose of establishing precise spacing between aircraft in an approach system From the standpoint of terminal-area traffic control, maneuverability refers to aircraft turning characteristics These are affected by three factors inertia, or the lag of the aircraft in responding to the controls; the turning rate desired by the pilot, and the airspeed.

Inertia has the effect of slowing the response of the aircraft while starting or stopping a turn From the control standpoint it is more noticeable in the case of large aircraft, and allowance should therefore be made in the issuance of heading instructions

During instrument flight, the turning rate of an aircraft is normally held to a standard rate of 3° per second *As shown in Fig 4, this produces in still air* a turn of theoretical diameter equivalent to 39 seconds of straight flight at the same air speed The turning radius is thus a direct function of the air speed In order to minimize acceleration forces at high air speeds, turns made during instrument flight at speeds above 180 mph are usually limited to half of the standard rate, or 1½° per second This produces in still air a turn of theoretical diameter equivalent to 78 seconds of straight flight at the air speed concerned and limits a great deal the flexibility which may be employed by the controller in stretching flight paths to space aircraft precisely in an approach sequence

Aircraft acceleration and deceleration characteristics directly affect runway-occupancy times and thus have *an important effect on the acceptance rate* The use of nosewheel steering, antiskid braking, and reversible-pitch propellers tends to reduce runway-occupancy times and thereby increases acceptance rates

Arrangement of Facilities

Extensive tests *made on the dynamic simulator* indicate that the arrangement of terminal airports and their associated navigational facilities has a marked effect on the traffic-flow characteristics and on the acceptance rate of the terminal area Some of the most important considerations which have been brought out by the simulation tests are discussed in the following sections

Airports

Airport location is dictated by such considerations as terrain, cost, and convenience to the metropolitan area When more than one major airport must be located within a terminal area, extensive study should be given to the provision of ample separation between them This is necessary in order to minimize interference between the arrival routes, the holding patterns, and the departure routes serving the different airports

Simulation tests indicate that if more than one major airport is necessary in a terminal area, every effort should be made in the selection of sites and in the alignment of facilities to create, insofar as possible, an independent system of traffic flow for each airport Tests indicate that, in order to provide relatively independent operations into and out of two high-capacity terminal airports, these airports should be at least 16 miles apart This represents a rather great increase over the separation deemed satisfactory in the past

As is true in programs of this type, minor increases in traffic flow which are gained through the times is shown in Fig 5 In order to retain the advantages of high-speed turn-offs during the hours of darkness, it is essential that such exits be well marked and well lighted

Runway-occupancy times of departing aircraft may be minimized through the provision of adequate taxi strips with engine run-up areas located near the ends of the runways and with high-speed entrances to the runway take-off positions, as shown in Fig 6 Because of traffic restrictions and because of delays in completing cockpit checks, aircraft cannot always take off in the same order in which they taxi away from the ramp To provide better utilization of airspace as well as to avoid airport congestion and long departure delays, it is essential that adequate pavement width be provided in the run-up area so that any aircraft can proceed directly from this point to take-off position without having to wait for preceding aircraft to take off first

A great amount of simulation work has been conducted on the problem of increasing runway capacity through the use of additional traffic lanes Basically, any gain over the capacity of a single-lane system must be due to the fact that more than one operation

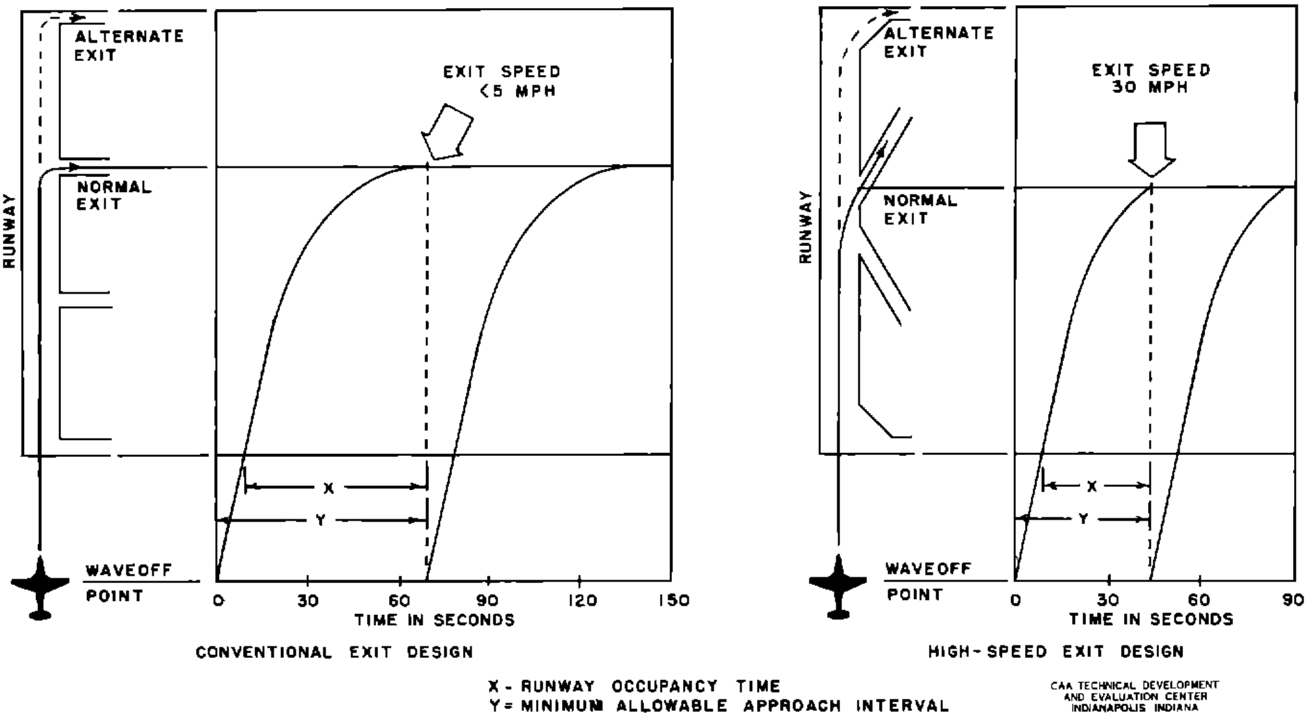


Fig 5 S-t Curves Showing Functional Advantages of High-Speed Runway Exit

elimination of one bottleneck often serve to uncover the existence of another at some other point in the system If this process is carried far enough, the final limiting factor in the capacity of the terminal area often turns out to be the airport itself

Two methods are available for increasing the capacity of a runway system, these are the reduction in runway-occupancy times and the provision of additional independent traffic lanes A very effective means of reducing the runway-occupancy times of arriving aircraft is the provision of adequate high-speed turn-offs, so designed and located that they can be used by arriving aircraft to vacate the landing runway while the craft is still rolling at a speed of 20 to 30 mph[4] The effect of this facility on runway-occupancy can be conducted simultaneously Therefore, it is essential that various lanes be as independent of each other as possible Fig 7 shows one of the most promising of the high-capacity, dual-lane, approach systems which has been developed in the simulation program Such a system would probably be justified only for airports having a demand rate exceeding 40 landings per hour Fig 8 shows three possible dual-runway layouts designed for segregated operations with take-offs on one runway and landings on the other

Approach Path

The alignment of the instrument runway is dictated by such considerations as the prevailing wind, the land available for airport use, the surrounding terrain, congested areas, and obstructions It is apparent that possible restrictions due to nearby airports, danger areas, or higher terrain should be carefully considered, since such factors have a critical effect on the acceptance rate of the approach system

[4]"Preliminary Report on Airport Configuration Studies," CAA Airport Engineering Bulletin No 1, CAA Office of Airports, June 1951

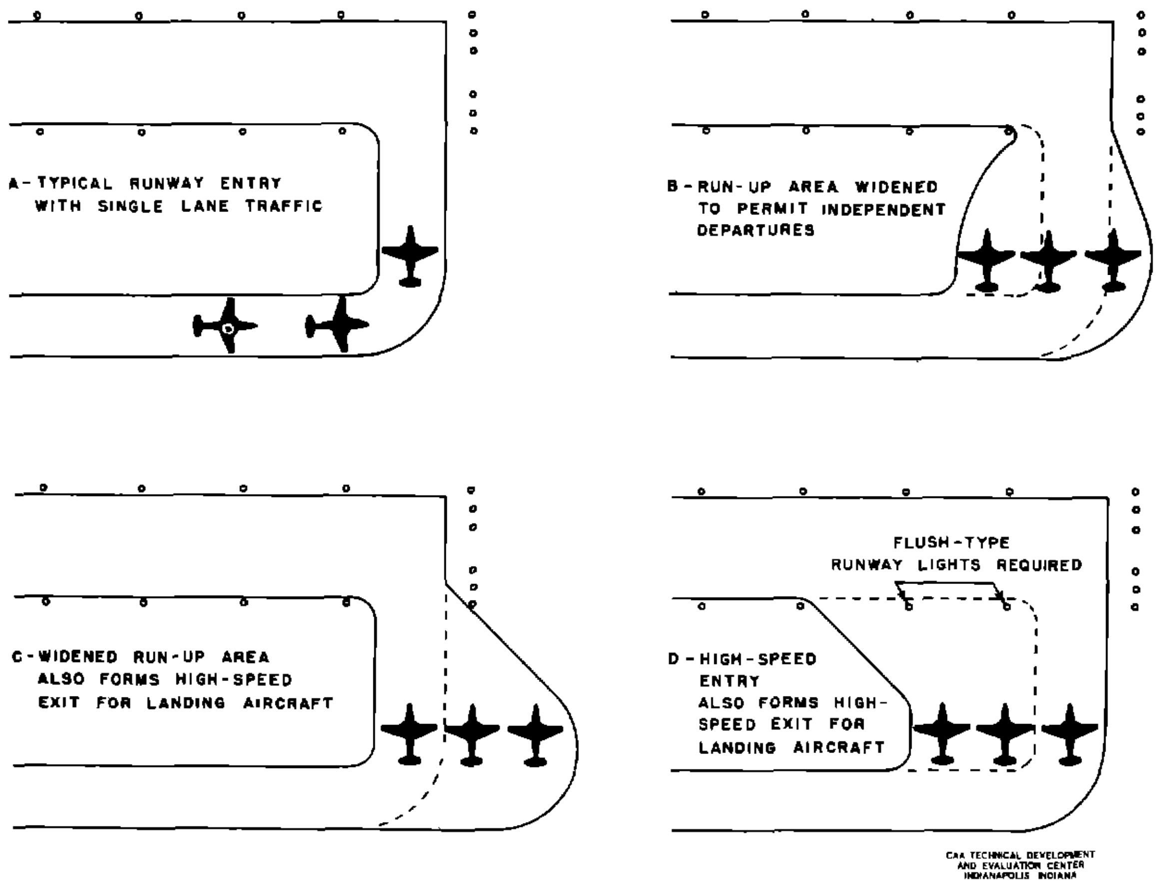


Fig 6 Suggested Runway Entry Modifications

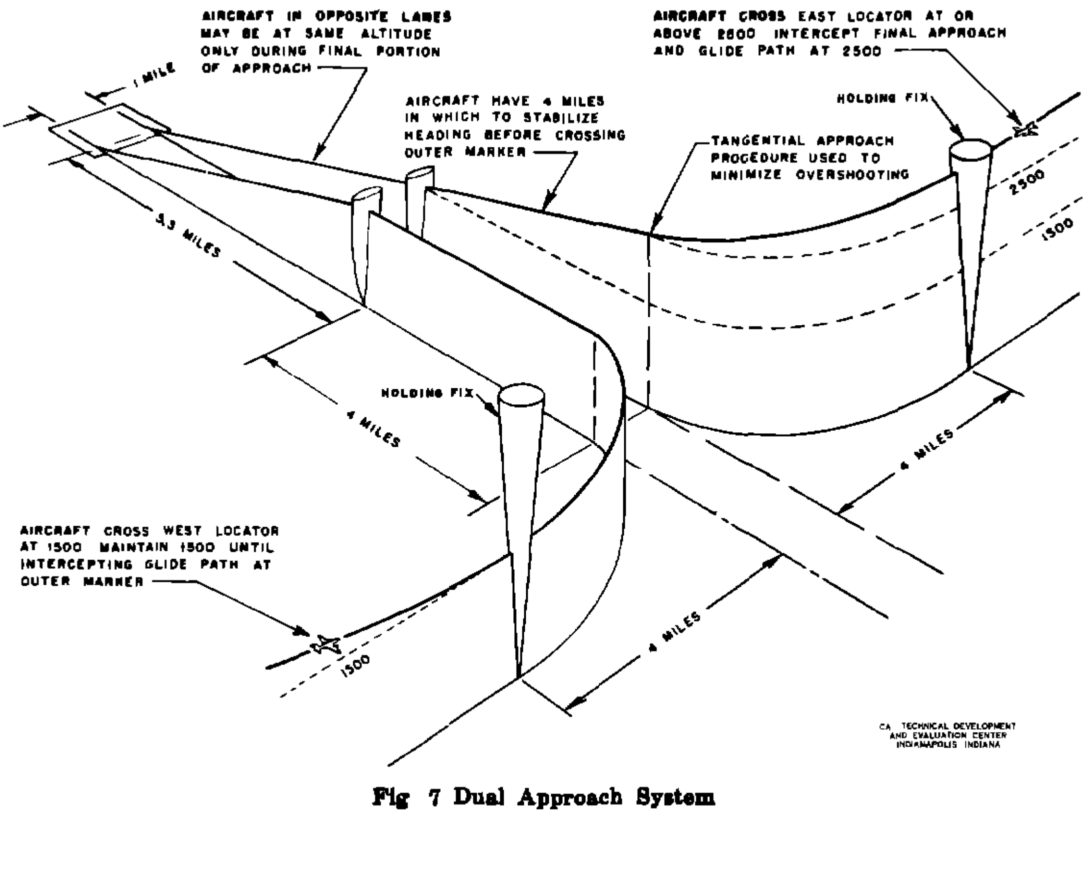


Fig 7 Dual Approach System

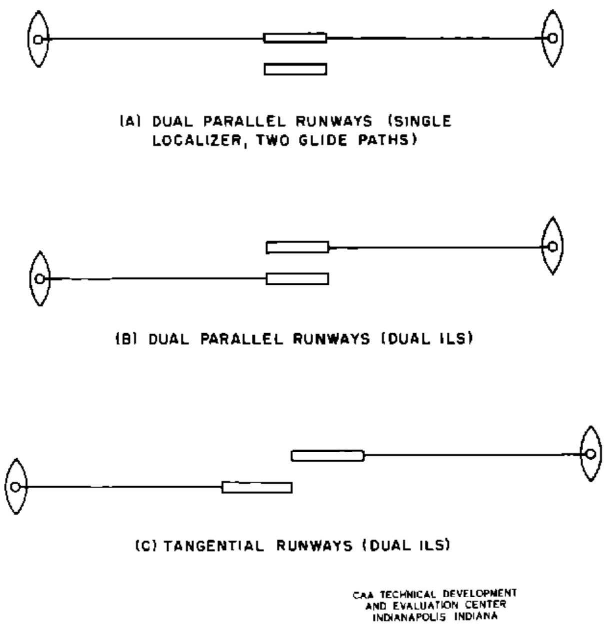


Fig 8 Other Examples of Dual-Runway Layouts

As previously indicated, the establishment of additional airports in a terminal area tends to complicate the traffic flow For this reason, the addition of a second airport in a terminal area seldom doubles the original acceptance rate If the approach paths to the two airports intersect, the resulting acceptance rate for the two airports may actually be lower than the acceptance rate for one airport alone

The location of the approach gate has an important bearing on the acceptance rate of the approach system The term "approach gate" refers to a point, on the final-approach path, from which all approaches are commenced Experience gained in thousands of approaches during the simulation program has pointed to the desirability of keeping the common approach path as short as practicable By minimizing the effect of speed differences between successive aircraft, a relatively short common final-approach path makes possible the closer spacing of aircraft on approach and enables the system to operate at a higher peak of efficiency This principle is shown in Fig 9 A close-in approach gate tends to shorten the flight paths of aircraft making undelayed approaches This, in turn, tends to reduce the delays of subsequent aircraft in the approach sequence

There is a practical minimum common final-approach distance which can be utilized At present, this minimum is based on the premise that the approach should be made straight in from the minimum holding altitude In most cases, this requires a common final-approach path at least six miles long The development of approach-coupling equipment, such as

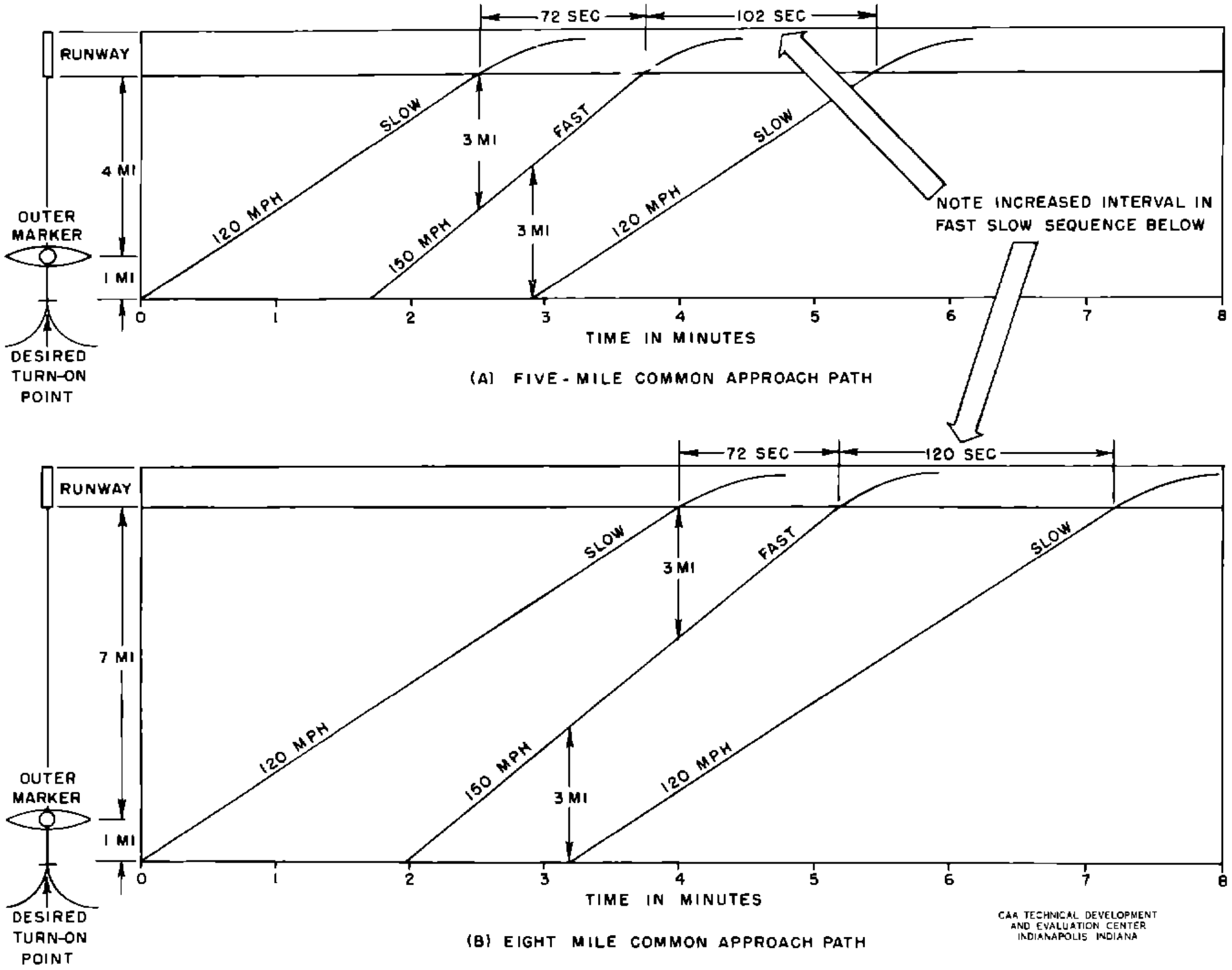


Fig 9 Effect of Length of Common Approach Path

the Sperry Instrument Company Zero Reader, should tend to make final approaches of this length unnecessary from a navigational standpoint

In order to investigate the possibilities of shorter common approach paths, considerable simulation work has been completed in the development of the tangential-approach system This is a semiautomatic, radar, approach-coupling device which provides an infinite number of curved approach paths These paths all spiral gently into the desired final-approach path at a specific approach gate Simulation tests indicate that the approach gate for this system could be placed as close as one mile from the airport for approach operations down to present range-approach minima The tangential-approach principle, which is illustrated in Fig 10, is described in detail in another report[7]

Feeding Systems

As far as airport acceptance rate and controller work load are concerned, one of the most important factors in terminal-area design is the layout of the feeding system The term "feeding system" refers to the holding facilities and the arrival routes The feeding system normally includes one or more holding facilities These function as reservoirs for the convenient holding of inbound aircraft during periods when the traffic input exceeds the airport acceptance rate The simplest feeding arrangement is the single-stack system, illustrated in Fig 11 This arrangement utilizes one primary, or inner, holding fix and may also include one or more secondary, or outer, holding fixes

During the early days of approach control, certain single-stack approach systems exhibited a peculiar traffic-flow characteristic. Under saturated-traffic conditions when there was a continuous supply of aircraft, successive approaches would occur in groups followed by excessively long intervals between groups The long intervals at the end of each cycle lowered the over-all acceptance rate to a great extent

A simulation study of this situation revealed that the cyclic phenomenon was caused by periodic starvation of the inner stack due to an insufficient number of holding altitudes available at the inner holding fix Graphical simulation established the validity of the relationship

$$N = \frac{F}{T} \qquad (3)$$

where

N = number of holding altitudes necessary at the primary holding fix to maintain a continuous flow of traffic,

F = flying time, in minutes, between the secondary holding fix and the primary one,

T = time, in minutes, required for aircraft to descend from one assigned altitude level to the next one This factor includes communications delays

[7] C M Anderson, N R Smith, T K Vickers, and M H Yost, "A Preliminary Investigation of the Application of the Tangential Approach Principle to Air Traffic Control," CAA Technical Development Report No 149, October 1951

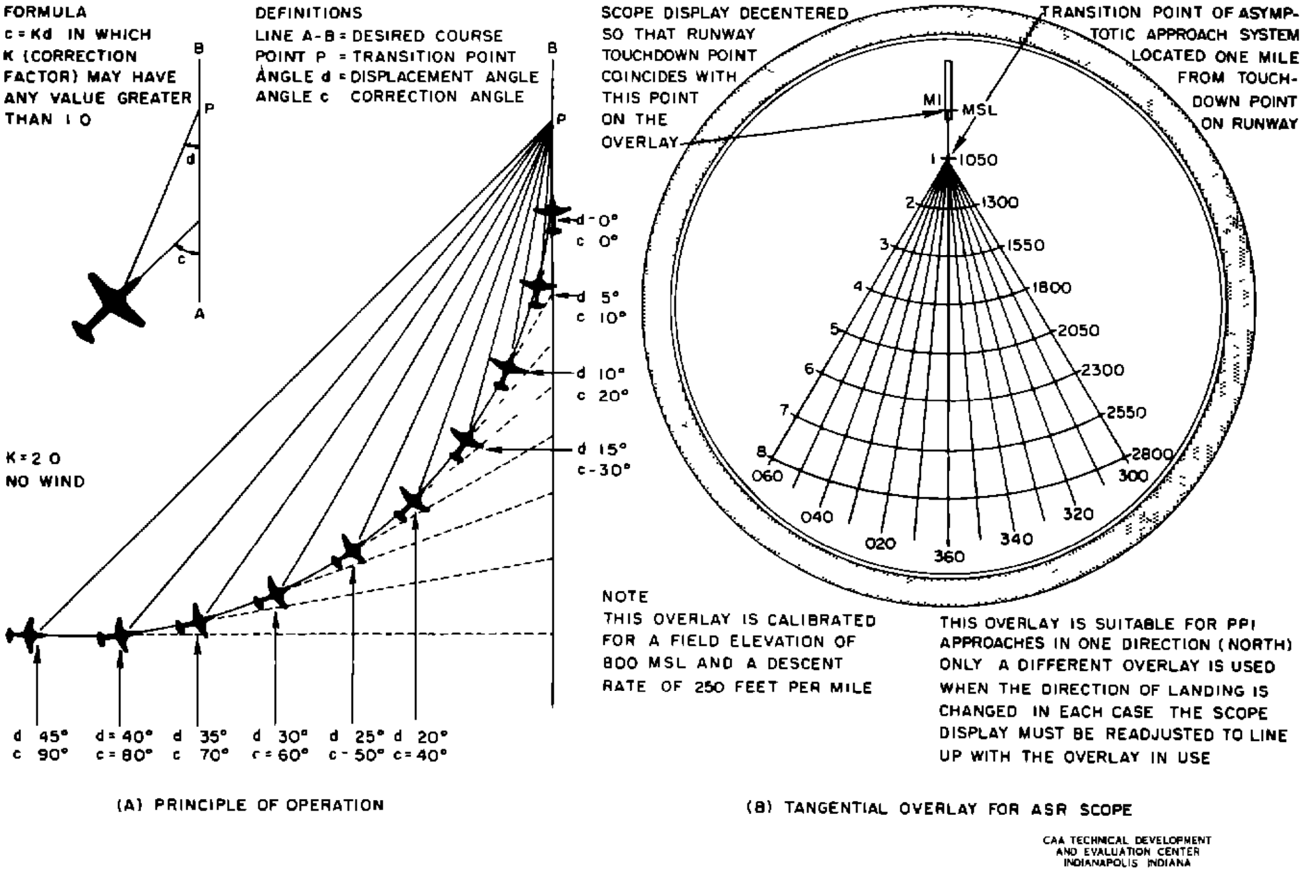


Fig 10 Tangential Approach

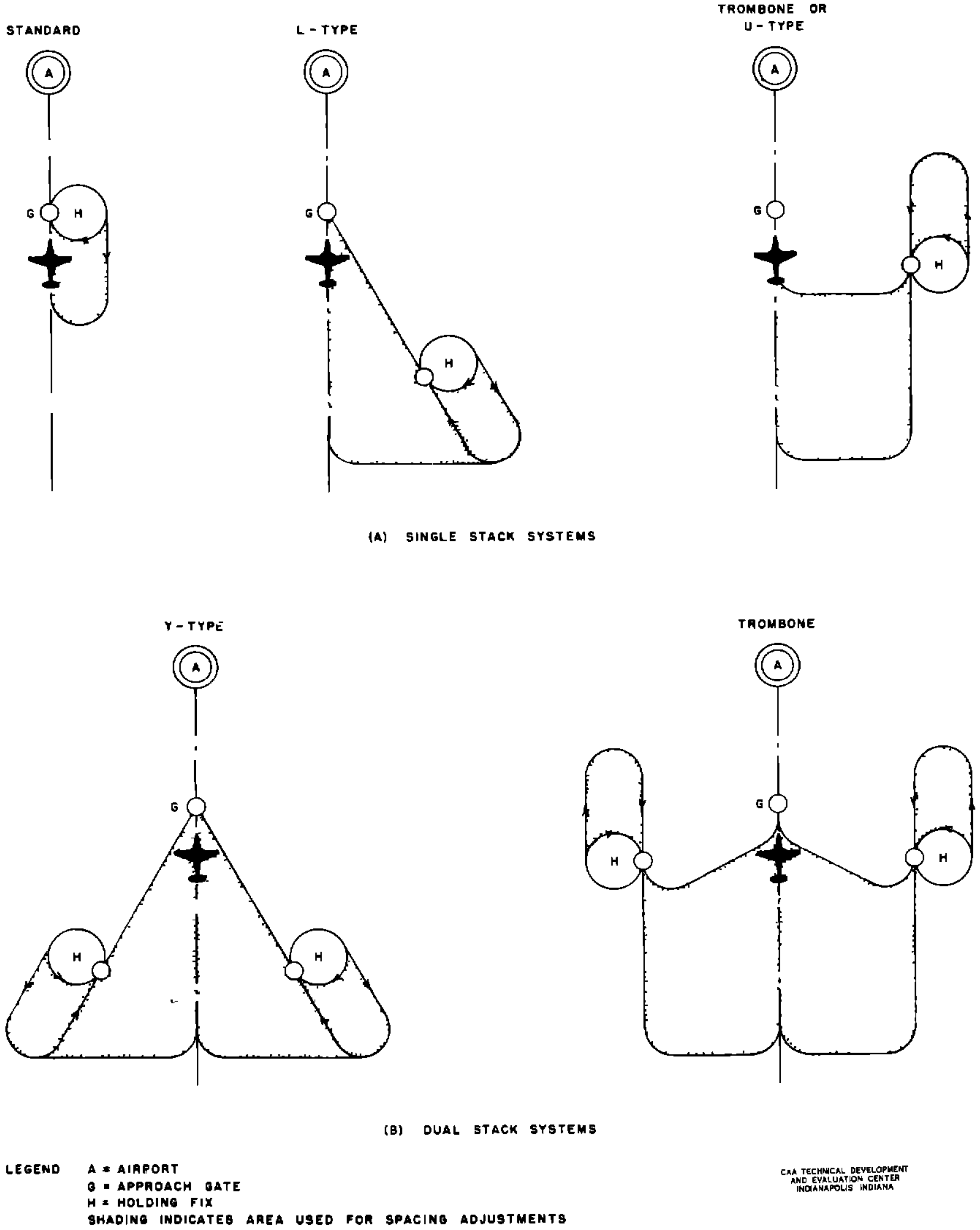


Fig 11 Types of Approach Systems

The provision of sufficient holding altitudes at the inner fix or the reduction of interfix flying time eliminates the cyclic characteristic of the single-stack operation and provides a continuous supply of aircraft at the approach gate The single-stack system has the advantage of requiring only a relatively narrow airspace for its operation The use of this system is sometimes dictated in congested areas where lateral restrictions prevent the use of a dual-stack system

Simulation tests made with mixed types of traffic indicate that it is very difficult to exceed an acceptance rate of 20 approaches per hour with a single-stack system Basically, this restriction is due to the low descent rate of the nonpressurized aircraft in the system

If the expected demand rate of a terminal airport exceeds 20 approaches per hour, it becomes desirable to establish a twin-stack feeding system This type of system, as illustrated in Fig 10, has three functional advantages over the single-stack type

1 Use of two independent holding systems makes possible the simultaneous descent of aircraft in two stacks Theoretically, this halves the restrictive effects of descent time and of communications lag However, no appreciable reduction in approach intervals can be obtained unless radar separation is used to space aircraft on the common approach path Without radar, the system would have to utilize timed-approach procedures The altitude separation inherent in these procedures would still limit the capacity of the twin-stack system to that of a single-stack layout

2 Use of two primary stacks instead of one tends to keep holding altitudes at a minimum at all times and thus makes more altitude levels available for nonlanding traffic

3 A properly designed twin-stack system provides the opportunity to split the terminal area cleanly into two approach sectors This enables two controllers to share the total work load

During the dynamic-simulation program, more than 10,000 approaches have been conducted on various twin-stack systems This work has uncovered several important facts regarding the effect of system layout on traffic-flow characteristics and on controller work load

Comparative tests of symmetrical and asymmetrical twin-stack feeding systems show that the symmetrical system with one holding fix located on either side of the final-approach course provides far more efficient traffic-flow characteristics. The symmetrical feeding system permits direct access to the final-approach course by aircraft coming in from either stack Flight patterns are short, simple, and relatively easy to follow on the radar display By using the final-approach course as the boundary line of demarcation between the dual approach-control sectors, opportunities for conflicts between aircraft or for confusion regarding sector jurisdiction are reduced to a minimum Consequently, traffic can be fed smoothly from either holding fix to the approach gate with minimum delay, minimum air/ground communications, and minimum co-ordination between controllers

The actual location of the holding fixes in relation to the approach gate has a critical effect on the controller work load Simulation has shown the desirability of establishing the holding patterns sufficiently clear of the final approach so that no disruption of the normal holding procedure need be made in order to accommodate a jet approach or an emergency descent through the holding altitudes Holding fixes should be located far enough away from the approach gate to provide sufficient room for adjustment of approach intervals and to allow aircraft to make easy transitions to the final-approach course without overshooting

The distance between the holding fixes and the approach gate has a direct effect on the radar navigational work load, since it determines the number of aircraft which have to be en route simultaneously between the holding fixes and the approach gate in order to keep the final approach full of aircraft at the desired spacing This simple relationship is expressed by the following formula

$$N = \frac{D}{S} \qquad (4)$$

where

N = number of aircraft required,
D = distance between holding fixes and approach gate, in miles,
S = desired spacing between aircraft at approach gate, in miles

Thus, for any desired spacing between aircraft, a greater distance between the holding fixes and the approach gate will require a larger number of aircraft to be en route simultaneously in this portion of the system This principle is illustrated in Fig 12

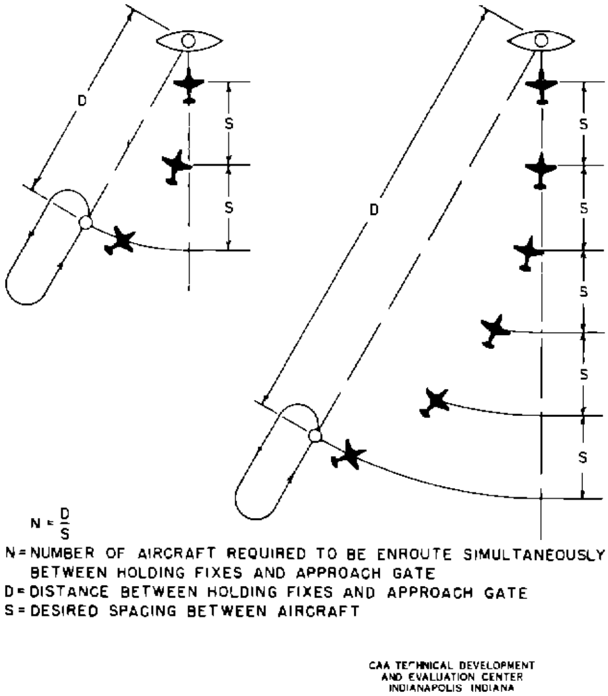


Fig 12 Effect of Distance Between Approach Gate and Holding Fixes

Dynamic-simulation tests with present types of aircraft indicate that there is no advantage in placing the primary holding fixes more than eight miles from the approach gate Locating them within this range offers the following advantages

1 With present standards, a total of no more than three aircraft need ever be simultaneously en route between the holding fixes and the approach gate, and the controller need make critical navigational decisions on only a small number of aircraft This keeps the radar-vectoring work load low and tends to simplify communications operations

2 Since the controller is critically concerned with the positive identification of only a small number of aircraft and since these aircraft are all located in a small sector of the scope well within the coverage of the radar, the radar identification problem becomes very simple

3 With only a few aircraft simultaneously under navigational control, the controller can devote a greater percentage of his time and attention to the path and progress of each one For this reason, he can do a much better job of spacing them properly in the approach sequence This tends to eliminate pull-outs, to minimize approach intervals, and to keep the system operating smoothly and safely at a high acceptance rate

4 Because the number of aircraft off the holding fixes is kept at a minimum, jet approaches or priority or emergency descents can be accommodated with a minimum of confusion Less advance notice is necessary for controllers to be able to reserve a space for such aircraft in the final-approach sequence

5 Close-in holding fixes save airspace This feature is particularly advantageous when there is more than one major airport in a terminal area In addition, a close-in arrangement tends to produce a minimum amount of detours or complications in the routing of departing aircraft.

Arrival and Departure Routes

The layout of arrival and departure routes has a critical effect on the traffic-flow characteristics and, consequently, on the acceptance rate of a terminal area Each area presents its own special problems When more than one major airport exists in a terminal area, the problem can become quite complex In such cases, it is seldom that a completely ideal solution can be worked out The result is usually a carefully balanced compromise between several desired objectives

1 Routes should be as short as practicable This objective is in line with the concept of absolute delay being any increase in time above that which would be necessary to complete the operation if no other traffic were involved

2 Various traffic routes should be as independent of each other as possible This is one of the most important factors in the achievement of a high acceptance rate It also has a profound effect on controller work load and fatigue Every point of conflict built into a system brings with it additional controller work load in the form of additional air/ground communications, additional intercontroller co-ordination, and additional attention required to guard against the possibility of making a mistake and creating a hazardous situation In designing a layout of navigational facilities for a terminal area, it is desirable to keep the inbound routes separate from the outbound if possible Where inevitable crossovers occur, it is usually possible to reserve certain altitudes for certain directions of traffic so that no co-ordination will be necessary between arrival and departure controllers in order to feed aircraft across this point The establishment of these blocked altitudes requires care to insure that outbound aircraft will not have to climb at an excessively high rate to cross the fix at the specified level and to insure that inbound aircraft will not have to cross a close-in fix at an excessively high altitude and incur a delay because of the time required for descent beyond this point.

3 The system should provide flexibility in order to accommodate different distributions and densities of traffic To avoid surges of traffic entering one stack of a twin-stack system, a very simple provision can be made for diverting excess traffic into the opposite stack, as shown in Fig 13 This feature equalizes the work load of the two sector controllers and provides better utilization of available altitudes and communications channels

Delays during low-density traffic operations can be minimized by the provision of short-cut direct courses which can be utilized under such conditions This feature contributed to the very efficient operational characteristics of a proposed VOR navigation layout tested for the Norfolk terminal area

As in the evaluation of any improvements in air traffic control, the advantages to be gained by the provision of any specific feature must be carefully weighed in terms of the costs involved A particular advantage of dynamic simulation is that it provides a means of comparing the relative efficiency of various specific configurations of navigational aids

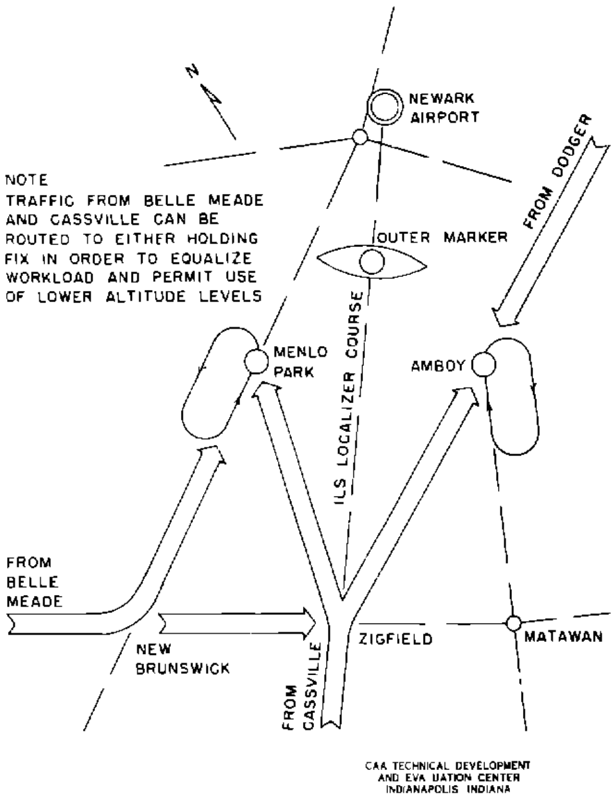


Fig 13 Flexible Feeding System Tested for Newark Airport

Separation Standards

Since the minimum spacing which may be employed between aircraft is governed by the restrictive effects of the current separation standards, these standards place an ultimate limit on the acceptance rate of any traffic system Therefore, in the exploration of possible methods of increasing the efficiency of air traffic control, a great amount of thought has been given to the effect of possible changes in them

All separation standards are based on the use of amounts of separation in excess of any deviations which are likely to occur in the operation of the system In other words, an excess of separation is imposed initially in order to insure that some will always remain in spite of any navigational or control errors which may occur

Vertical Separation

At the present time, 1,000 feet is the standard amount of vertical separation employed in the CAA air traffic control system It is clear that the acceptance rate of a single-stack approach control system could be increased if this standard were reduced It also appears that the air-route system could accommodate a greater number of aircraft through the provision of more flight levels in a given volume of air space However, because of the possible altitude deviations caused by turbulence, altimeter errors, or slight changes in the trim of high-speed aircraft, it appears very unlikely that the aviation industry will consent to a reduction in the 1,000-foot standard within the foreseeable future

Lateral Separation

The VHF omnirange theoretically offers possibilities for more efficient rearrangement of arriving aircraft and for reduced delays of departing aircraft through the provision of multiple diverging courses which can be used to provide separation between aircraft during descent and climb The capacity of this feature, in terms of the number of radial courses which can be used simultaneously, depends on the accuracy with which assigned courses can be flown This factor is largely dependent on the degree of accuracy with which the airborne receiving equipment is calibrated

Longitudinal (Time) Separation

The present longitudinal-separation standards are based on navigation and traffic control in a system where the exact position of aircraft is known only when such aircraft are directly over widely spaced radio fixes As long as this system is used, separation standards must remain large and extravagantly wasteful of airspace in order to exceed the possible errors which may accrue It is believed that the development and adoption of VOR-DME computor navigation will make possible much more precise navigation and reporting procedures, so that reduced longitudinal-separation standards may be employed with safety This would tend to reduce traffic delays by enabling the system to accommodate more aircraft in a given volume of airspace

Radar Separation

When radar is used to provide separation between aircraft operating in terminal areas under instrument-flight-rule (IFR) conditions, present standards require that a minimum of three miles of separation be maintained between such aircraft The three-mile standard appears necessary since existing air traffic control radars do not continuously display positive aircraft returns and since very little speed control is exercised in traffic control operations

It is believed that improvement in radar designs, supplemented by the development of satisfactory airborne transponders, will reduce the effects of precipitation, ground clutter, antenna-pattern nulls, and moving-target-indication (MTI) fadeouts and will provide a radar display which can be depended upon for showing all of the aircraft all of the time

If no attempt is made to control the speed of aircraft for air traffic control purposes, the pilot is free to select any speed within the available operating range Extensive photographic measurements made by the CAA indicate that air speed during the last 1,000 feet of the instrument-approach path varies from 1 2 to 1 9 times the stalling speed of the aircraft Even for different aircraft of the same type, the spread is only slightly less This characteristic was taken into account in dynamic-simulator tests through the assignment of random approach speeds to the various aircraft in the traffic sample These speeds were assigned in accordance with the normal distribution of speeds which had been observed in actual approach operations

To operate an approach system safely, the controller must make allowance for the widest variations which are likely to occur in approach speeds As shown in Fig 14, this consideration requires the use of greater separation between successive aircraft at the approach gate to make sure that sufficient separation will still exist at the end of the runway This increase lowers the actual acceptance rate

What is needed is not necessarily some standard approach speed but only the assurance by the pilot

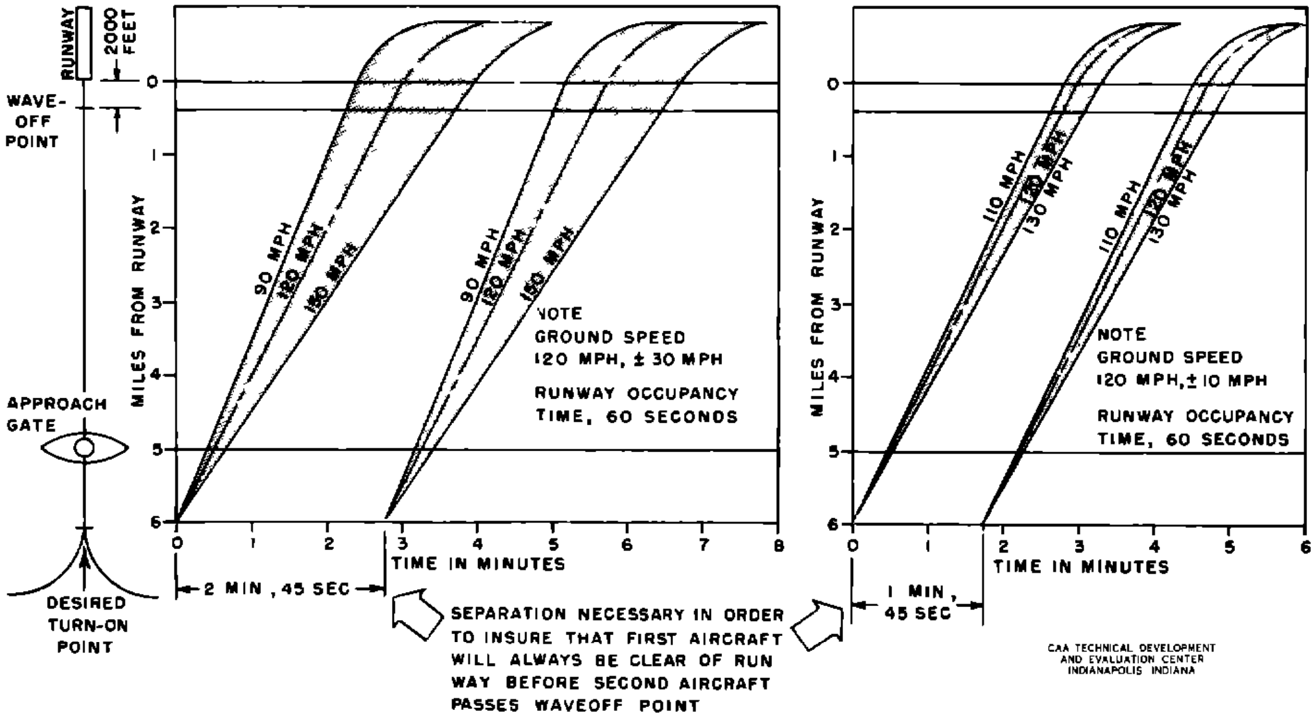


Fig 14 Effect of Variation From Desired Approach Speeds

that some approach speed designated by him will be maintained within a small tolerance such as ± 10 mph Fig 14 also shows the theoretical reduction in separation which would be possible through the use of more closely controlled approach speeds Provided the radar display and the communications procedures are dependable, it appears that this system should make possible a reduction to perhaps two miles in final-approach separation in order to take full advantage of high-speed, runway turn-off facilities

Control Procedures

Radar has a very important application in the operation of terminal-area approach systems, since it provides continuous-fix information of the position of all aircraft in the system The Ground-Controlled Approach (GCA) system, which is the present standard approach system of the military services, utilizes radar information as the basis for marshalling and spacing aircraft in the landing sequence and also for the actual navigational guidance of aircraft down the final-approach path

Because of the latter function, an individual GCA controller usually needs to give his entire attention to a single aircraft during the final approach Thus, it is difficult for a single GCA final-control position to achieve an acceptance rate higher than 12 aircraft per hour during low-ceiling and low-visibility conditions However, if additional sets of controllers, scopes, and communications channels are available, successive aircraft can be assigned to different control positions in sequence The acceptance rate of a multiple-GCA system of this type should equal the acceptance rate of any other type of manually operated approach system

From the military standpoint, the GCA system has the advantage of requiring less pilot proficiency and less airborne equipment than that needed in utilizing any other type of approach system However, GCA has the disadvantage of requiring a large amount of communications per aircraft and, consequently, a large number of control personnel to achieve a high acceptance rate

Simulation tests indicate that, for high-capacity terminal-area operations, it is preferable to utilize radar primarily for the aircraft-marshalling and spacing function and to utilize instrument landing system (ILS) or VHF omnirange (VOR) as the primary aid for navigational guidance down the final-approach path This preference is dictated by the sheer volume of communications which would be required to provide precision-radar approach guidance to every aircraft in a high-capacity GCA system The preferred system makes full use of radar in keeping the approach path full of aircraft at minimum spacing In addition, communication time is saved and navigational control of the aircraft on final approach is returned to the pilot The precision approach radar (PAR) in this system is used primarily as a safety check in monitoring approaches It also functions as a primary-approach aid in case of ILS or VOR failure or for occasional aircraft which do not have functioning ILS or VOR receiving equipment

For economic reasons, most major airports are equipped for instrument approaches to one runway only When the wind is such that landings cannot be made straight-in on the instrument runway, the usual procedure is for pilots to descend on the instrument-approach system to visual contact with the ground and then to circle the field in order to line up visually for the runway most nearly aligned into the wind

Since the latter portion of this type of approach involves low-speed turning flight at low altitude, it is much less desirable than other types of instrument approaches In addition, if the landing is to be made in a direction toward the instrument-approach path, the acceptance rate of the system is greatly reduced In order to guard against a collision in case the first aircraft misses its approach, the second aircraft is not cleared below initial-approach altitude until the first one reaches a point where its landing is assured Because of the additional time required by each aircraft to complete its approach to this point, the interval between approaches becomes excessively long It is difficult to achieve an acceptance rate of more than 12 approaches per hour under such conditions

Some of the worst traffic delays encountered at any of our major airports occur under conditions in which the wind is such that take-offs have to be made toward the direction of the final-approach path The landing sequence has to be interrupted before any take-off can be permitted The acceptance rate thus reaches a low ebb These conditions can be greatly improved through the use of plan position indicator (PPI) radar approaches to the runway in use This procedure requires somewhat higher weather minima than do either ILS or GCA approaches Because of the additional radar guidance required on each descent from the initial-approach altitude to the point where the pilot has the field in sight, communications are greatly increased over the amount required to operate a radar-fed ILS or VOR approach system

Owing to increased communications, the interval between successive approaches will in most cases be slightly longer than the time required to bring one aircraft from the initial-approach altitude down to visual contact Simulation tests indicate that an acceptance rate of 20 approaches per hour is possible with this system An additional advantage in the use of this type of approach procedure is the fact that take-offs are not made in a direction toward the arriving aircraft Therefore, it is seldom necessary to interrupt the landing sequence to permit departure operations

Human Reactions

Significance of Test Results

Dynamic simulation offers the opportunity to observe the performance and reactions of traffic controllers under the stress of handling realistic, controlled traffic inputs The performance of the controllers can be measured and assessed through the analysis of control errors and through a graphic comparison of theoretical delays versus actual delays encountered by the various aircraft in the traffic sample

It has been found, however that the type of quantitative data obtained so far in the course of the simulation program does not necessarily give a direct index of the relative difficulty encountered by the controllers in feeding traffic through different traffic systems It is believed that this inequality is due to the adaptability of the controllers themselves, by sheer concentration, a good controller can shoulder the added mental work load of an awkward traffic system and can turn in a performance surprisingly close to that obtained with an easily worked traffic system. Thus, differences in the relative difficulty encountered in handling widely different traffic systems show up on the test results as comparatively small differences in average approach intervals or in aircraft delays

The characteristically different mental work loads entailed by various traffic systems produce differences in controller fatigue However, up to the present time mental work load and controller fatigue remain intangibles which cannot be measured quantitatively For this reason, it has been necessary to adopt as a qualitative index the personal opinions of the controllers who have participated in the various test runs Much validity has been placed on these controller observations regarding the relative difficulty encountered in feeding traffic through the various systems

It is quite possible that there would appear greater quantitative variations in aircraft delays and in control errors encountered with different systems if the tests were extended to the point where controller fatigue became a definite factor in the breakdown in the system From results obtained so far, it is believed that such tests would have to continue for several hours under peak traffic loads before noticeable breakdown would occur from this cause Because such operating conditions are extremely rare in actual practice and because the built-in bottlenecks of a specific system can be revealed by much shorter tests, no workable terminal-area traffic control system has ever been tested to the controller-breakdown point

Importance of the Human Factor

The present control system depends on the ability of human controllers to make satisfactory decisions regarding the disposition of individual aircraft in the traffic situation These decisions are made on the basis of flight information supplied by other humans Control instructions based on these decisions must be formulated and transmitted to human pilots, who must comprehend and apply these instructions in the subsequent control of the individual aircraft

The art of guiding two or more aircraft into a final-approach path and of simultaneously establishing proper spacing between them is a fascinating navigational operation which requires a considerable degree of skill and judgment on the part of the radar controller It is believed that personnel should be carefully screened for this job, since the operation requires the ability to visualize spatial relationships and the imagination to project flight paths ahead, as well as the ability to integrate information from several different sources and to make rapid decisions with regard to a constantly changing traffic situation

Tests showed that controller performance is a widely variable factor which can have a profound effect on the performance of any approach system As would be expected, training and experience can raise the average to a higher level Although not designed specifically as a training device, the dynamic simulator has proved to be an extremely effective aid in improving the performance of control personnel in the use of radar traffic-control procedures

Because of the critical importance of the human element of air traffic control, much work in the dynamic-simulation program has been devoted to an analysis of the job of the terminal-area controller One point brought out in this study is that certain mental and physical limitations exist, an individual controller can be expected to see and do only so much during a specified increment of time Where the system requires that this capacity be exceeded, two alternatives are open One is to add additional control personnel The other is to find ways of simplifying the job of the controller to the point where he can control a higher traffic load

The addition of control personnel is a solution which has often been used in the past to meet increased traffic loads However, this procedure has two disadvantages First, the provision of even one extra control position on an around-the-clock basis represents a vast increase in operating costs In addition, each subdivision of the total work load by a greater number of control positions brings with it an increased amount of intercontroller co-ordination At some point, the co-ordination work load becomes so complex that it becomes a barrier to any further increase in the capacity of the system

Observation of simulated high-density traffic operations has revealed many opportunties to simplify the job of controlling terminal-area traffic Some of the more important findings are discussed in the following section

Aids to Controller Judgment

Because terminal-area traffic problems change rather fast, the controller must think ahead and make his decisions on the basis of current information plus a knowledge of projected flight paths of the aircraft involved Observations made during high-density-traffic simulation tests indicate that average judgment must be considered as a residual element after the mental energy utilized in thinking about other things has been deducted For example, if the attention of the controller is concerned with establishing and maintaining positive identification of a comparatively large number of aircraft, he will have less time for making critical decisions regarding the spacing of aircraft

When the controller must work under conditions which require a high mental work load, his spacing of aircraft on the final-approach path will become less accurate In order to make sure that adequate separation will be maintained at all times, the controller will usually tend to use more spacing than would be required if he had time to give more individual attention to the progress of each aircraft under his control This point was brought out during comparative work-load tests of a saturated radar-vectoring problem In one phase, individual controllers had a maximum of four aircraft under simultaneous radar-vectoring control In the other phase, each controller had a maximum of six aircraft under simultaneous radar-vectoring control Aircraft delays were 12 to 20 per cent higher in the latter phase This indicated that six aircraft is too large a number for one controller to handle simultaneously under present manual radar-vectoring procedures

These results led to the development of terminal-area systems which could continuously function at top capacity without ever requiring a single controller to have more than three aircraft under simultaneous radar-vectoring control Observations showed that such systems were far less fatiguing to handle over long periods Since in almost every human activity there is a causal relationship between fatigue and rate of error, the simpler control systems tend to be safer than those which require a high radar-vectoring work load

A traffic-control system cannot work at top efficiency if one man becomes overloaded In order to alleviate such a condition and in order to provide a more efficient utilization of manpower and of communications channels, it was found desirable to provide a means for equalizing the work load of the various control positions One method which worked out very well in simulation tests of twin-stack systems was the flexible feeding arrangement shown in Fig 13 In the operation of this system, both sectors carried their share of the work load Besides eliminating heavy surges of traffic into a single sector, this flexible arrangement tended to keep holding altitudes at a minimum at all times

It was found that the establishment of clean-cut jurisdiction between control sectors constituted an extremely important method of reducing controller work load This simplified the traffic picture, reduced the time spent in intersector co-ordination, and tended to eliminate jurisdictional confusions and misunderstandings

Another way of reducing work load was the elimination of conflicts between traffic patterns by means of the relocation of certain routes or by means of the establishment of blocked altitudes for certain directions of traffic flow This simplified the operation by providing automatic separation and by reducing the number of critical decisions which the controller had to make In many cases, it expedited departures by eliminating the need for prior co-ordination between controllers

Observations showed that mental work load could be reduced and the accuracy of spacing aircraft on the final approach could be increased through the use of a simple spacing reference on the map overlay This reference consisted of three concentric arcs spaced on radii of 3, 4, and 5 miles from the approach gate These arcs functioned as a ready reference for the controller in establishing optimum spacing of aircraft on the final-approach path

Since present rules require that a departure be held on the ground if an arrival on instrument approach is within two miles of the runway, an additional reference line was established across the approach path two miles from the end of the runway This line served as a go or no-go gage in the job of co-ordinating departures with arrivals Although the spacing reference lines, as shown in Fig 15, constituted a very simple feature, they greatly decreased the work load in making critical decisions and thus produced safer, more efficient, and more positive control

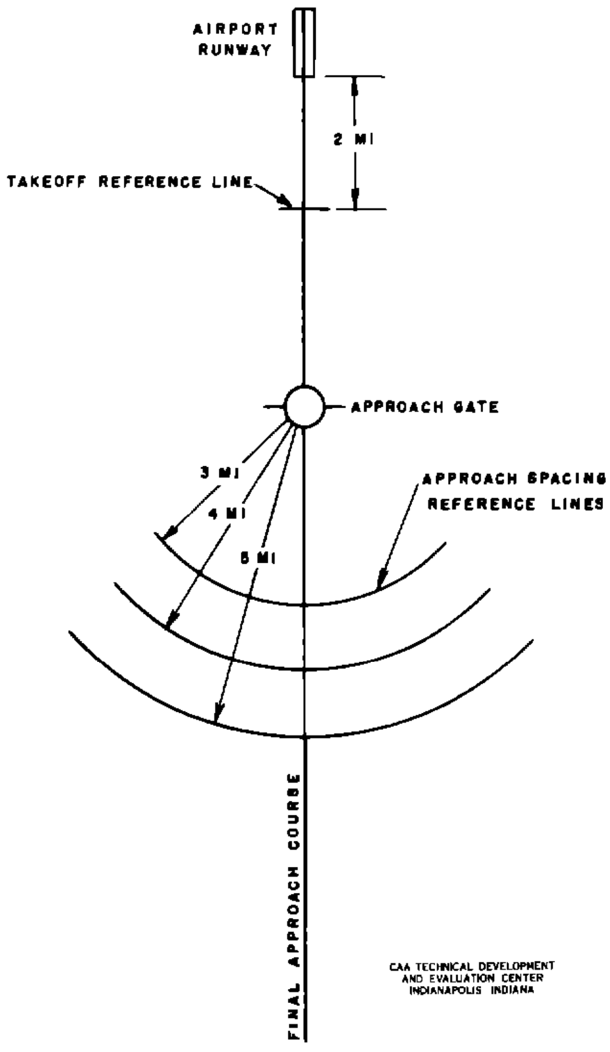


Fig 15 Reference Lines for Scope Overlay

It was found that for the controller one of the most important aids in making rapid decisions in heavy traffic conditions is an understanding of which factors are important to the immediate situation and which factors may be ignored, or at least deferred temporarily, without affecting the safety or the efficiency of the system

An example of this principle occurs in the operation of an approach system under saturated conditions Although the radar display of the holding area may appear very confusing because of the large number of aircraft circling the holding pattern, the experienced controller learns to disregard the exact positions of the aircraft at the higher levels and to concentrate on the identifications and spacing of only the two lowest aircraft, namely, the aircraft which has been cleared for approach and the one which will follow it down the final-approach path As long as the other aircraft in the holding pattern have altitude separation from each other and also remain in the desired vicinity of the holding fix, their exact radar identity and positions are not critical to the operation of the approach system Thus, the controller can be trained to disregard the confusing details of this picture and to give more attention to the two aircraft which are at critical positions in the approach sequence

Simplification of Voice Communications

In an asynchronous activity such as air traffic control where the start of one operation must wait for the completion of a preceding operation, rapid dependable communications become a necessity This fact was brought out in a foregoing section which analyzed the effect of communications lag on the approach interval of a fixed-block system Rapid, dependable communications are even more important in a radar-vectoring approach system, where a delay in receiving desired headings may cause a pilot to end up with too much or too little separation behind the aircraft ahead or may cause him to wander into a position from which he cannot complete his approach

The time spent in communications details reduces the time in which the controller can be planning his handling of the traffic situation It can also become a limiting factor to the number of aircraft he can control simultaneously Therefore, it is essential in the operation of a high-capacity traffic-control system that the communications time per aircraft be kept as low as possible

Several methods of reducing communications time have become apparent during simulation tests It is believed that a number of communications items which are now considered standard could be eliminated if they were to be publicized and made into a standard operating procedure Control could then be predicated on their use without specific reference to them on communications channels These items include radio-failure instructions (IF NO INSTRUCTIONS ARE RECEIVED FOR A PERIOD OF ONE MINUTE PROCEED TO——— AT LAST ASSIGNED ALTITUDE AND ADVISE) and cockpit instructions (CHECK GYRO AND DO NOT RESET FOR REMAINDER OF APPROACH) (PERFORM LANDING COCKPIT CHECK), (WHEELS DOWN AND LOCKED) It is believed that ceiling and visibility information could be eliminated when both items are above the limits published in the Flight Information Manual It is also believed that the phrase DESCEND TO AND MAINTAIN (altitude) could be shortened to DESCEND TO (altitude) with no detrimental effects on safety

A time-saving procedure which has become necessary in saturated-traffic simulation problems is the issuance of weather and runway information to groups of aircraft on the same channel simultaneously rather than separately to each individual aircraft This procedure is recommended for actual traffic operations provided that some check is employed to insure that each pilot receives the desired information

Use of Visual Information Displays

The job of the air traffic controller is made up of an almost continuous series of decisions or choices of action which must be made on the basis of available flight information and data This information may be classed in two different categories, status information and transient information

Status information is that data which does not change rapidly but which remains relatively fixed and up-to-date for long periods Under this classification come geographical layout, arrangement and characteristics of radio facilities, minimum altitudes, and other data regarding control procedures Much of this information can be memorized by the controller However, observations indicate that if there is any possibility that confusion or misquotation of such data could lead to a critical traffic situation, it is very desirable to have the items posted for rapid reference by control personnel

Transient information contains data which may change rapidly This type of information requires displays capable of indicating moment-to-moment changes Such displays may be symbolic, pictorial, or a combination of the two types Symbolic displays include flight-progress boards or other types of quickly changed tabulations of flight data Pictorial displays include radar scopes or plotting boards which show in effect a picture of the aircraft in the traffic situation

One promising method of reducing controller work load is to reduce the number of items which the controller must observe in normal traffic operations. This idea is based on the concept that the fewer the observations the controller must make to arrive at a satisfactory decision, the fewer opportunities will there be for him to fail to observe some critical item Therefore, it appears desirable to limit the number of displayed items to those which are actually critical to the decisions at hand

Because the pictorial display supplements and augments the symbolic display, observations made during simulation tests show that considerably fewer items of symbolic information are required when a combination display is available In connection with the development of automatic data-transfer equipment, it was found that with a positive and dependable pictorial display the terminal-area controllers needed only tabulated information on the identification, speed, altitude, and clearance limit or destination of each aircraft These items sufficed for high-density arrival and departure radar operations In case of failure of the pictorial display, the control system reverted to timed-approach procedures and additional items regarding expected approach-clearance times and proposed and actual fix-departure times were posted

The time and effort required for the actual operation of the symbolic display has been given a great amount of thought Where flight information has to be transferred between control agencies or control positions by interphone, it is important that the data be so arranged that it can be transcribed with the least amount of effort, confusion, and time The adoption of a straight left-to-right sequence in the arrangement of transcribed data offers much improvement over old systems which required the writer to transcribe successive flight-progress-strip items in an irregular order

The pictorial display furnished by the dynamic simulator is the equivalent of an airport surveillance radar with video mapping It is presented on 12-inch scopes by means of a rotating sweep The map range normally covers a radius of 20 or 30 miles, depending on the type of system being investigated Tests showed the superiority of large-scale displays over small-scale ones in helping controllers to space aircraft precisely on final approach Approach intervals were consistently less when the pictorial display was expanded to a larger scale There were also fewer aborted approaches due to insufficient separation between aircraft

Each aircraft target normally appears on the simulator screen as a single spot of light without identification Some tests were made with larger targets which consisted of a ring with a single numeral inside One result of this test was that approach intervals increased when the larger targets were used This indicated that controllers engaged in spacing operations were concentrating on the spaces between the targets rather than directly on the targets themselves In attempting to keep adequate space between targets, they actually increased the spacings between target centers when the large targets were used

During the course of the simulation studies, it was found possible to design terminal-area control systems which never required a single controller to know the exact identity of more than three radar targets simultaneously The use of such a system minimizes the need for separate target identifications in the terminal area These tests show that a trained controller has little difficulty in keeping straight the identities of one to three targets in an approach pattern, provided that he can see them continuously

These findings imply that for properly designed terminal-area layouts, it is far more important to provide a positive, continuous display of aircraft positions than to provide a display capable of showing different identifications for different targets in the pattern

For a long time, certain authorities have felt that traffic control radars required a relatively high rotation rate in order to be effective in guiding aircraft on approach courses Several thousand dynamic-simulator approaches made at a simulated scanning rate of 12 rpm, together with more than 300 comparative tests made at various antenna rates with actual radar equipment and aircraft, showed conclusively that a high rotation rate is not necessary for terminal-area traffic-spacing operations or for precise PPI approach guidance The results of the actual radar tests are detailed in another report[5]

From the standpoint of controller work load, it is very desirable that the radar display be able to maintain continuity in the display of each target track Comparative simulation tests made with and without radar trails showed that the presence of trails is a distinct advantage to the controller for the following reasons

1 Trails can aid in the identification of specific targets when these targets have been assigned different headings

2 Trails give a very good indication of speed, wind drift, and relative motion

3 Trails help maintain a semblance of continuity in the traffic picture under conditions where targets cannot be continuously observed

4 Examination of trails gives the controller an early indication whether or not certain instructions are being followed by the pilot

One subject which cannot be overemphasized is the importance of positive radar identification of all aircraft which are under radar navigational guidance Misidentification of a single target can lead to an extremely hazardous traffic or flight situation and thereby destroy public confidence in the radar traffic control system The use of turns to specified headings for the radar identification of individual aircraft is a procedure which consumes considerable time and adds to the communications work load Simulation tests indicate the following methods of obtaining radar identification will be preferable, when available

1 Use of a position report from a pilot leaving a suitable terminal-area radio fix on a specified heading

2 Use of a VHF-ADF bearing by the radar controller

3 Use of a bloomer aircraft safety beacon code, on request of the controller

4 Use of a pilot position report determined from an airborne pictorial display

Simplification of information displays has been mentioned as one method of reducing controller work load A further step is to increase the ease of observation of the remaining factors Under this category come such factors as arrangement, lighting, and legi-

---

[5] C M Anderson, N R Smith, T K Vickers, and M H Yost, "Effects of Various Antenna Rotational Rates on a Type ASR-1 Radar," CAA Technical Development Report No 182, September 1952

bility of displays Simulation tests show the importance of keeping the pictorial and symbolic displays adjacent to each other in order to present a complete picture of the traffic situation and in order to eliminate possible confusion

Use of present radar scopes in control operations presents a lighting problem, since stray light in the control room can obliterate the radar picture Three methods were tried on the simulator to furnish sufficient illumination for the control desk and for the symbolic display without interfering with the pictorial display on the radar scopes

The first system utilized amber filters over the radar scopes and a blue-filtered light on the control desk The combination yellow-blue filtering system eliminated stray reflections on the scope face, but the blue ambient light gave a peculiar color to other objects in the room This effect was slightly disconcerting at first but became unnoticeable after a long time

The second method utilized short metal shields over the scope faces and a red-filtered light on the control desk The red light maintained the dark adaptation of the controllers' vision, while the hoods shaded the scope faces from the red light source

The third system utilized a combination of three colored fluorescent lamps — red, blue, and green — which provided an apparently white ambient light in the room This light originated from an indirect-lighting fixture mounted behind the scope cabinets, and it was reflected off the white ceiling of the control room to flood the working space Short hoods were provided over the scope faces to reduce direct reflections from the ceiling, and the scopes were equipped with amber filters Because the illumination was actually deficient in the yellow-orange portion of the spectrum, the amber filters preserved the picture contrast on the scope faces

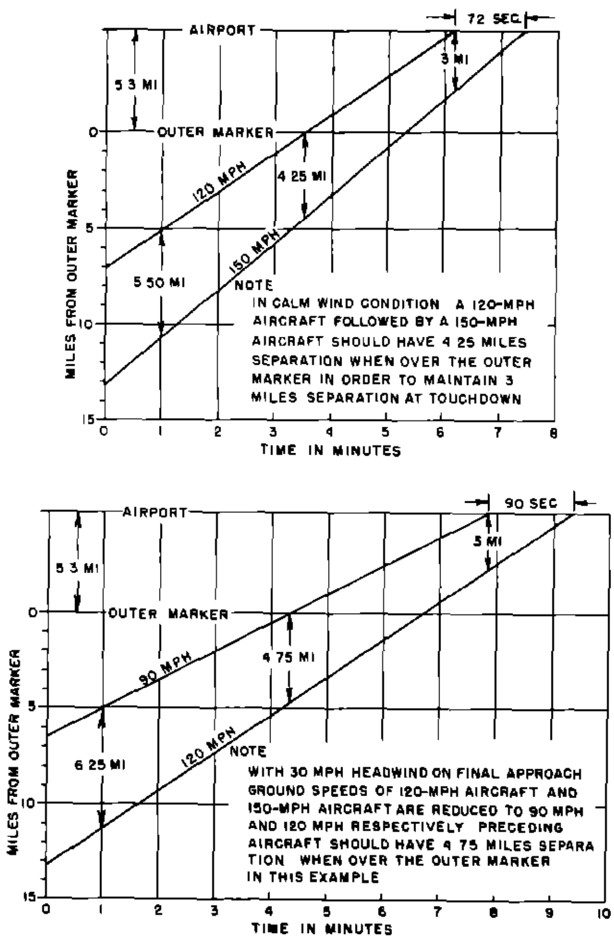
Controllers who worked with all three systems preferred the third system This one apparently reduced eyestrain by providing a not-too-unnatural form of ambient lighting in the area surrounding the radar scopes

Weather

As yet, a detailed study of the effects of ceiling and visibility on airport acceptance rates has not been made in connection with the simulation program However, several other weather effects are already known A head wind on the final-approach path has the effect of reducing the acceptance rate by decreasing the average ground speed of the aircraft concerned This effect is shown in Fig 16 Surface winds of low velocity offer a greater freedom of take-off and landing directions than do winds of high velocity If diverging runways are available, low winds usually permit a higher take-off rate than do high winds Precipitation tends to reduce visibility and often has a detrimental effect on the displays of present air-traffic-control radar equipment The deterioration is due mainly to the addition of scope clutter which may mask the aircraft targets completely or, at least, may make the targets difficult to follow Improvements in the design of ground radar and airborne safety-beacon equipment may alleviate these effects The detrimental effects of precipitation on runway braking conditions tend to reduce the acceptance rate by increasing runway-occupancy times of landing aircraft

RADAR TRAFFIC-CONTROL TECHNIQUES

The simulation program has presented the opportunity to try out and to observe, under loading conditions much higher than those normally encountered in present terminal-area operations, the operation of many types of traffic-control procedures Following is a description of the traffic-control techniques which have proved most effective during the thousands of simulated terminal-area flight operations completed during this program



CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS INDIANA

Fig 16 Effect of Headwind on Separation Required Between Aircraft on ILS Approach at Washington National Airport

Arrival Control

Aircraft Entry

The function of terminal-area arrival control is to assume control of inbound aircraft entering the terminal area and to feed them into the final-approach gate in an orderly, efficient sequence with proper separation between aircraft and on paths which will enable each aircraft to cross the approach gate inbound at the final-approach altitude

Normally, arriving aircraft enter the terminal area at times which are essentially random Each aircraft is cleared by the ARTC Center to an appropriate holding fix in the terminal area While en route to the fix, each aircraft has altitude separation from all other aircraft cleared to the same fix Whenever possible, entry altitudes are so arranged that the first aircraft will arrive at the holding fix at the lowest altitude, with successive aircraft at successively higher altitudes Each aircraft is released to terminal-area control at an appropriate time, place, or altitude at which it is expected to be clear of all other traffic except that which is bound for the same terminal area

Establishment of Approach Sequence

Whenever the terminal-area traffic input exceeds the acceptance rate, the traffic-control system will have to delay one or more aircraft in order to feed a methodical sequence of properly spaced aircraft into the final-approach path Several methods are available for adjusting these delays Coarse adjustments are made by holding techniques, and fine adjustments are made by velocity control or by path stretching

Holding patterns form convenient reservoirs for excess traffic which cannot be accommodated in the approach paths Aircraft holding at established radio fixes remain under the navigational control of their pilots Therefore, they require less attention from the controller than aircraft which are under radar navigational guidance For this reason, the judicious use of holding patterns under heavy-traffic conditions is a very important means of keeping the radar navigational work load at a minimum

As long as aircraft enter the terminal area in the proper altitude sequence, the establishment of the landing sequence can be made on a simple first-come, first-served basis, since the initial aircraft will be at the lower altitude and can be directed on the shortest practicable path to the approach gate Subsequent aircraft are cleared down to lower altitude levels as soon as such levels become available

Simulation tests indicate that the easiest and safest method of handling this operation is to run the terminal-area arrival routes and holding patterns as a fixed-block system employing altitude separation between all aircraft cleared to the same holding fix Altitude separation need not be employed between aircraft which have left the holding fixes and are inbound toward the airport, provided such aircraft have enough longitudinal separation that they could continue their approaches to the airport safely in the event of radar failure

Because of air-route traffic bottlenecks, inadequate airway communications facilities, or terrain-clearance restrictions on certain routes, it is not always possible for ARTC to clear arriving aircraft into the terminal area in an optimum altitude sequence Thus, reverse-stacking conditions sometimes develop With radar, it is often possible to unscramble a reverse-stacking situation and to maintain a first-come, first-served landing sequence even though the initial entry altitudes may be out of the desired sequence Before using this procedure, however, the controller must take into consideration the time and flight distance which will be required by an aircraft descending through the altitude of a lower aircraft In many cases, the additional time and space required for the descent may nullify any gains which would be expected by clearing in the higher, earlier-arriving aircraft ahead of the lower, late-arriving one

Because the amount of longitudinal separation required between two successive aircraft on the final-approach path depends on the relative speeds of the aircraft involved, it is necessary for the controller to know the speed classification of the preceding aircraft In the operation of a twin-stack approach system, this information is co-ordinated between controllers whenever an aircraft from one sector will follow an aircraft from the other sector

Simulation tests show that the establishment of the landing sequence from a twin-stack feeding system becomes a relatively simple matter if both radar controllers follow the rule that isolated aircraft will be landed in the same order in which they are ready to leave the holding fixes

When the approach system becomes saturated and two or more aircraft are holding in each stack, it is more advantageous to clear two aircraft from one sector followed by two aircraft from the other sector This procedure reduces the amount of co-ordination required between controllers The job of setting up the landing sequence is changed into a type of cyclic operation in which each controller gets a short breathing spell while the other controller is feeding aircraft into the final-approach path Controller observations show that, over long periods, this two-and-two alternating work cycle is less fatiguing than a first-come, first served system

Velocity Control

Control of aircraft velocity has not been much exercised by air traffic control in the past, since it appeared to encroach somewhat on the pilot's prerogative and since the specification of a speed too low for the prevailing flight conditions could lead to a hazardous situation However, simulation tests of high-density traffic operations indicate that, under certain conditions, the use of a limited degree of velocity control is desirable in order to simplify the traffic flow and in order to reduce the work load of the terminal-area controller For example, if two aircraft with similar speed characteristics are making straight-in approaches in trail toward the approach gate and the first one decelerates to approach speed, the second aircraft will begin to overtake the first unless the controller takes immediate action One method of maintaining separation between these aircraft would be through the assignment of S-turns to the second aircraft, but a simpler and more desirable method would be to advise the pilot of this aircraft to slow to approach speed

As shown in Table I, an aircraft can descend on a steeper path without increasing the descent rate if the forward velocity is reduced In many cases, an aircraft entering the terminal area at a relatively high altitude will be able to make a straight-in descent to the approach gate if it can be slowed down to intermediate or approach speed soon enough Otherwise, if it continues at cruising speed until it reaches the holding fix, it may not have time to lose its excess altitude before it reaches the approach gate unless the controller assigns some holding or other path-stretching maneuver Therefore, when a controller sees this type of situation coming up, it is usually desirable that he advise the pilot to slow down early in the approach

TABLE I

FLIGHT DISTANCE REQUIRED FOR 1,000-FOOT CHANGE OF ALTITUDE

Ground Speed (mph)	Rate of Altitude Change: 500 fpm (miles)	1,000 fpm (miles)
120	4	2.0
150	5	2.5
180	6	3 0
240	8	4 0
300	10	5 0

TABLE I FLIGHT DISTANCE REQUIRED FOR 1,000-FT CHANGE OF ALTITUDE

As illustrated in Fig 4, the radius of a standard-rate turn is a function of the speed of the aircraft. Most holding patterns are based on the use of timed straightaways, the length of which is also a function of speed Therefore, the use of reduced speeds in holding patterns enables aircraft to utilize less air space and to remain closer to the desired holding fix at all times

Simulation tests, as well as hundreds of actual radar approaches, show that it is much easier to align an aircraft precisely on a desired final-approach course if the rate of closure with the desired course is reduced One method of reducing the rate of closure is by the use of small angles of interception Another method is by the reduction of the forward speed of the aircraft

Occasionally a situation arises wherein it is apparent that a large gap followed by a heavy traffic demand rate will develop in the approach sequence In such a case, it appears desirable to advise an aircraft to increase speed slightly in order to reduce an excessive interval behind the aircraft ahead Since changes in speed usually result in changes in aircraft trim, as well as in other increases in the work load of the pilot, this procedure should be used with discretion It is not recommended for use after an aircraft is within two miles of the approach gate

Path Stretching

Path stretching is probably the most useful of radar control procedures It may be defined as the control of the length of a flight path by means of the issuance of heading instructions to the pilot In most cases, this procedure is utilized to enable an aircraft to lose time in order to establish separation behind a preceding aircraft or to lose altitude before crossing a specific fix The actual stretching operation is usually combined with the operation of guiding the aircraft to a desired course or approach gate At the start of an approach sequence, arriving aircraft can enter the approach paths without any holding if the number of aircraft in the area between the holding fixes and the approach gate does not exceed the optimum capacity

In establishing proper separation between such aircraft, the aircraft at the lowest altitude is assigned the most direct path to the approach gate while successively higher ones are fanned out on successively longer courses as necessary to place them in the proper sequence with proper separation and at the proper altitude as they cross the approach gate Excess aircraft are cleared to the appropriate holding pattern They are cleared in succession off the bottom of the holding pattern as necessary to keep the approach area operating at its optimum capacity When holding patterns are arranged as shown in Fig 17A, aircraft leave the holding pattern on the downwind leg of the approach pattern For radar identification, pilots are requested to report when leaving the holding fix outbound The course is extended as necessary to secure proper separation from the preceding aircraft in the approach sequence The aircraft is then turned onto the base leg of the pattern, at which time a further spacing adjustment may be made Because of the resemblance of this spacing method to the action of a well-known musical instrument, this type of approach layout is called a trombone system

The job of spacing aircraft properly on the final-approach path can be facilitated through the use of a spacing table posted at each arrival radar control position A typical table is shown in Fig 18 This table is based on a minimum separation of three miles between any two airborne aircraft For cases where a faster aircraft follows a slower aircraft down the final-approach path, the three-mile standard is increased by an allowance for the speed differential involved A further allowance is made in all cases to compensate for the normal distribution of speed variations from the desired air speeds The ultimate purpose of spacing tables is to set up enough separation between successive aircraft at the approach gate so that the first aircraft will always have time to vacate the airport runway before the second aircraft reaches

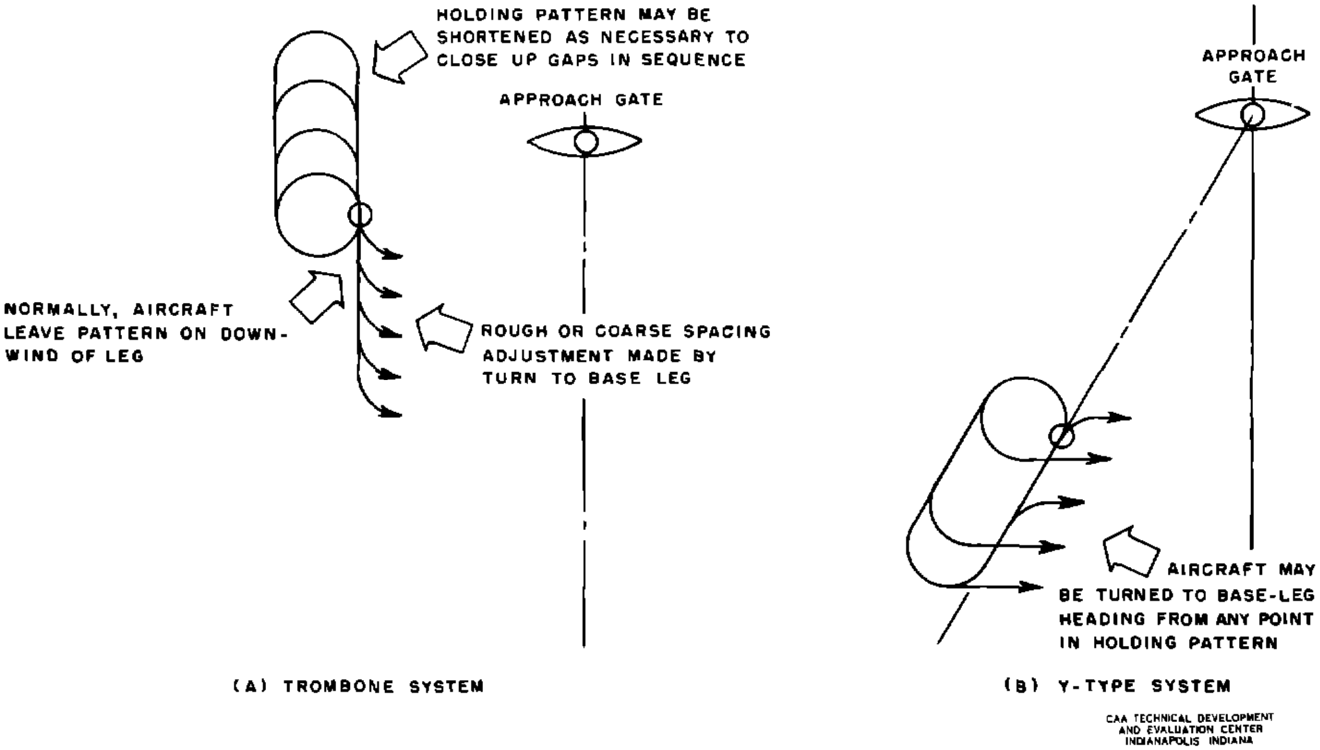
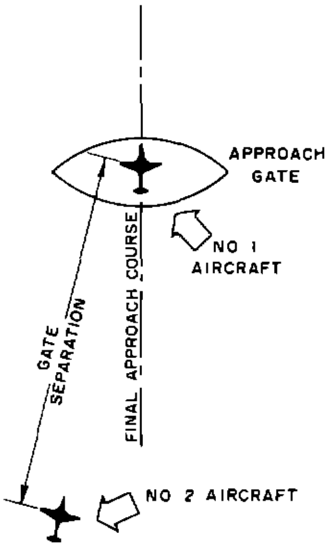


Fig 17 Peel-Off Procedure



NOTE
GATE SEPARATION REFERS TO SPACING BETWEEN TWO SUCCESSIVE AIRCRAFT AT MOMENT NO 1 AIRCRAFT IS OVER THE APPROACH GATE

OPTIMUM AIRCRAFT SPACING

WASHINGTON ILS ZERO WIND CONDITION

AIRCRAFT SEQUENCE		GATE SEPARATION (MILES)
NO 1	NO 2	
S	S	4 0
S	M	5 0
S	F	5 5
M	S	3 0
M	M	4 0
M	F	4 5
F	S	3 0
F	M	3 5
F	F	4 0

AIRCRAFT CATEGORY	APPROX APPROACH SPEED (MPH)
S	120
M	140
F	150

CAA TECHNICAL DEVELOPMENT AND EVALUATION CENTER INDIANAPOLIS INDIANA

Fig 18 Typical Spacing Table

the wave-off point Design considerations for spacing tables are discussed in detail in a companion report[9]

As previously indicated, simulation tests have shown the desirability of keeping the final-approach path short and the maneuvering area confined to a relatively small sector well within the expected coverage of the radar Therefore, when it becomes apparent that an aircraft on the downwind leg of the approach pattern is going to require a delay of two minutes or more to secure proper spacing behind other traffic in the landing sequence, it is often preferable to have an aircraft lose time in a 360° turn instead of allowing it to continue on a long, outbound pattern As shown in Fig 19, a 360° turn away from the final-approach course permits much greater flexibility in path stretching than a turn toward the final-approach course Because of the precise approach spacing which this maneuver permits, the 360° turn away from the final-approach course is a very useful control procedure Simulation tests indicate that when assigning this maneuver, it is usually advantageous for the controller to instruct the pilot to report when passing through certain specified headings or when completing the 360° turn Under heavy-traffic conditions, these reports serve as a useful reminder to the controller that it is time to consider further action regarding the flight of the circling aircraft

When holding patterns are arranged as shown in Fig 16B, aircraft may be cleared to leave the pattern in either of the ways that are illustrated Usually, the pilot is instructed to leave the pattern on a specified heading and is requested to report upon reaching this heading In many cases, this report serves as a means of radar identification, as well as a reminder to the controller that the aircraft is approaching a key position where an additional spacing adjustment can be made

An opportunity of decisive importance for the precise adjustment of the approach interval occurs when the aircraft is on the base leg of the approach path, as shown in Fig 20 If the controller can size up the situation quickly when the aircraft reaches this key position, he usually has the opportunity to increase, maintain, or decrease the current separation between this aircraft and the one ahead This adjustment is made by turning the second aircraft to a heading which will either shorten or lengthen its normal path, so that it will be able to reach the approach gate with the desired separation behind the first aircraft

The controller must be conscious of the relative speeds of the two aircraft, the effects of the prevailing wind conditions, the turning radii of the aircraft, and the amount of separation which will be required between the aircraft when the first one is over the approach gate As previously stated, the desired separation at the approach gate is a function of the speeds of the two aircraft, as well as of the distance between the approach gate and the airport Fortunately, the effect of the speed differential between successive aircraft is minimized when the final-approach path is kept short Therefore, the use of relatively short final-approach paths simplifies the job of judging the amount of spacing required between successive aircraft

Fig 21 shows a common illusion which can lead to insufficient separation between aircraft at the ap-

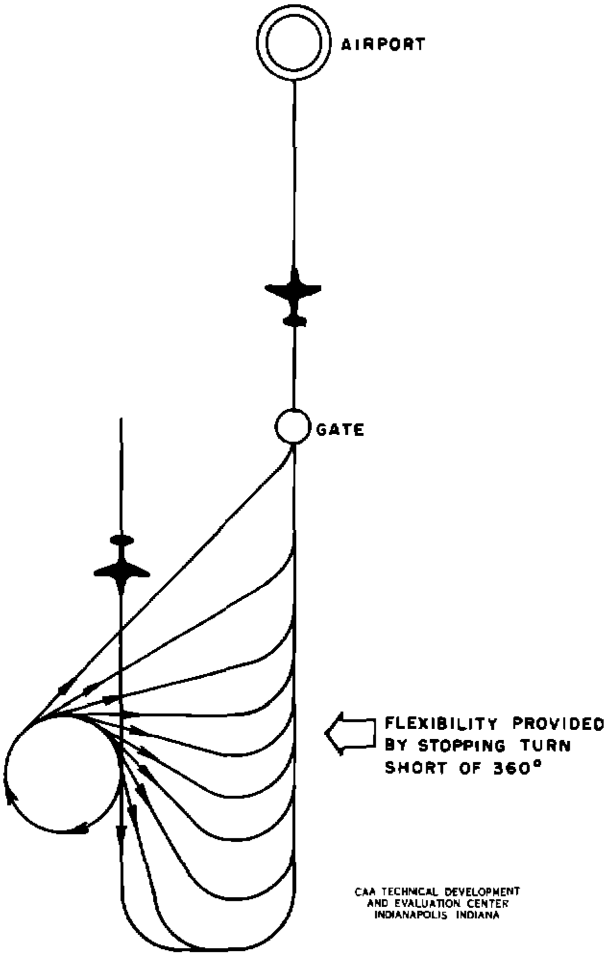


Fig 19 Path-Stretching Flexibility Possible After Starting 360° Turn Away From Course

[9]Berkowitz and Doering, *op cit*

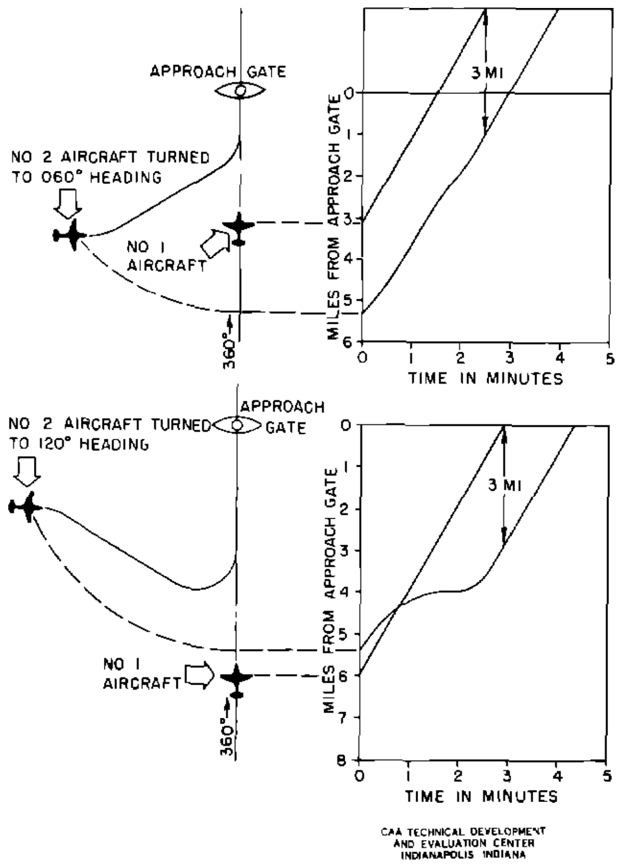


Fig 20 Typical Base-Leg Spacing Adjustments

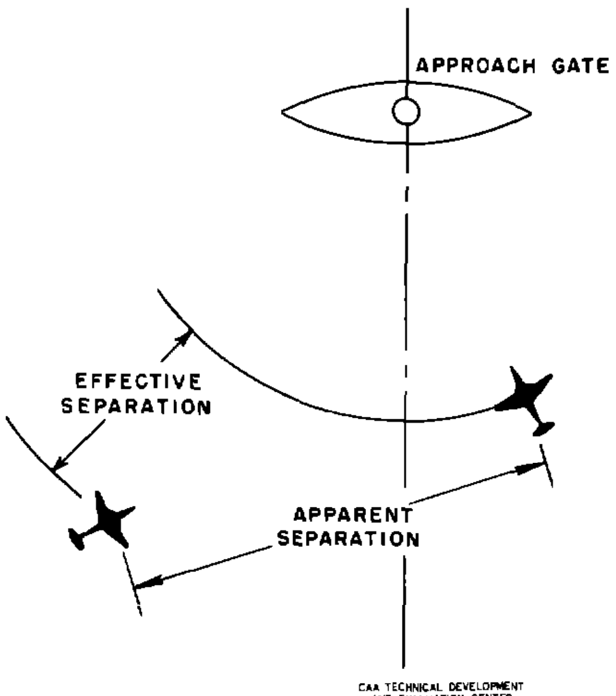


Fig 21 Operational Illusion

proach gate if the controller fails to consider the projected distance of the first aircraft from the gate when he turns the second aircraft toward the gate The effective separation between the two aircraft, in terms of their relative distance from the approach gate, is much less than their apparent separation from each other

When it becomes evident that an aircraft on the final-approach path will not be able to maintain sufficient separation behind the one ahead, the controller should take immediate corrective action If the overtaking aircraft has already slowed to approach speed, the only appropriate action will be some form of path-stretching

If the overtaking aircraft is still a rather long distance from the approach gate, an S-turn may be assigned, as shown in Fig 22 The initial turn should be at least 60° off course Simulation tests show that turns of less than this amount do not produce enough path stretching in the short distance available for the maneuver to make their use of any practical value As soon as it becomes apparent that adequate final-approach separation has been re-established, the controller should turn the aircraft back to intercept the final-approach course as soon as possible Before assigning an S-turn maneuver, the controller should make sure that enough space will be available for the maneuvering aircraft to become re-established on the final-approach course before it reaches the approach gate If adequate air space for the maneuver does not exist, the next best alternative is to direct the aircraft into a 360° turn This maneuver will delay the aircraft at least two minutes, producing a large gap in the approach sequence

If the overtaking aircraft is being followed by another aircraft in the approach sequence, a 360° turn may not be desirable, because it may return the circling aircraft to the final-approach path with insufficient separation from the other traffic In such cases, it is usually better to remove the overtaking aircraft from the approach sequence and to feed it back into the first available gap in the landing sequence

Simulation tests of twin-stack systems indicate that to avoid unnecessary co-ordination, complication, and jurisdictional confusion it is desirable that all path-stretching operations be conducted in the control sector of the controller who is directing the maneuver For example, if it is necessary for the west-sector controller to direct one of his aircraft into an S-turn off the final approach, it is desirable that the turn be made toward the west sector rather than toward the east-sector traffic

Orbiting Technique

As shown in Fig 23, the use of concentric spacing lines on the radar scope makes possible a very simple technique for obtaining accurate spacing of aircraft at the approach gate For path adjustment, the second aircraft is turned on a course which is essentially tangential to the approach gate This orbiting technique keeps the aircraft at an almost constant distance from the approach gate while the first aircraft is proceeding toward the gate on final approach The moment sufficient separation exists between the two aircraft, the second one is headed directly toward the turn-on point of the final-approach course With a relatively small amount of practice in using this method, controllers can space aircraft precisely on the final-approach course

Interception of Final-Approach Course

It is important that each aircraft become aligned on the final-approach course before it crosses the approach gate As shown in Fig 24, the radar trail may be projected ahead to determine whether a specific heading will enable the aircraft to intercept the course at the desired location

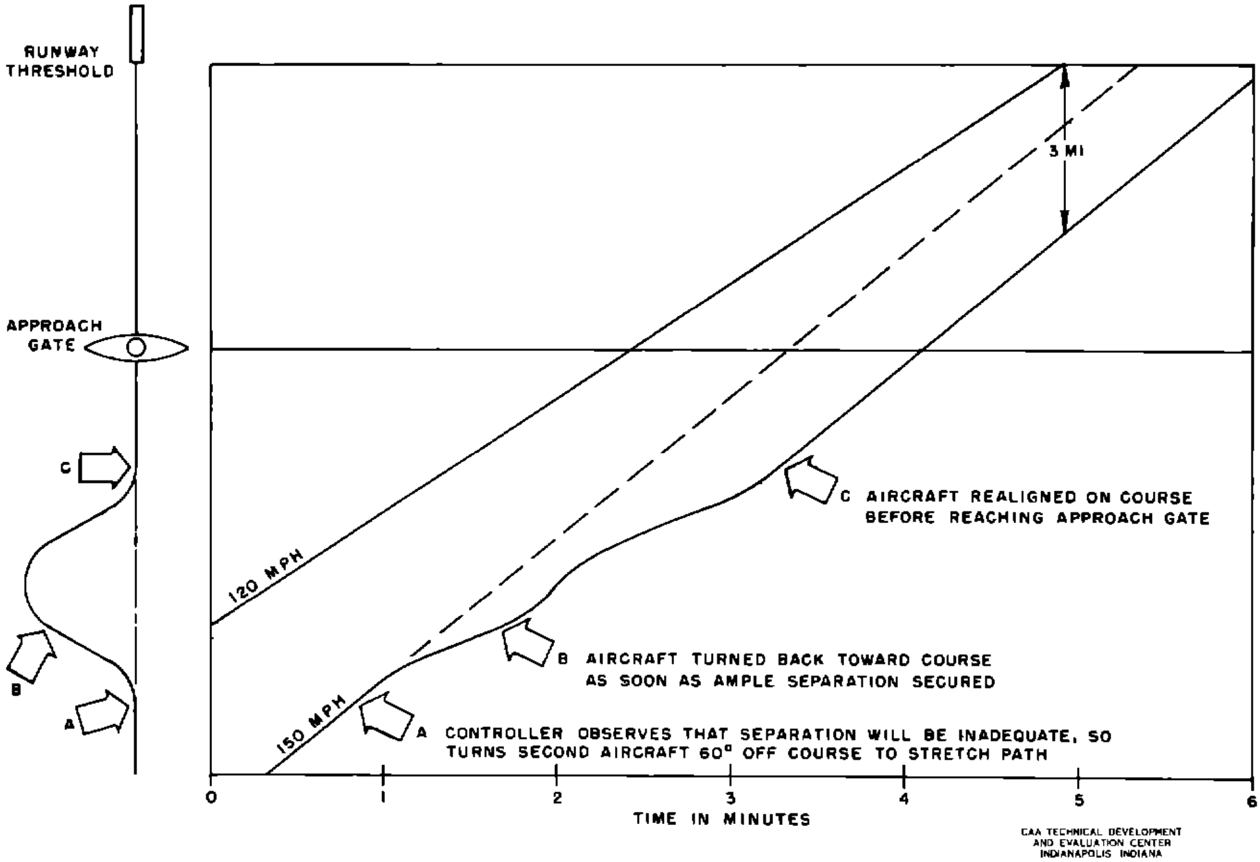


Fig 22 Use of S-Turn for Path-Stretching Operations

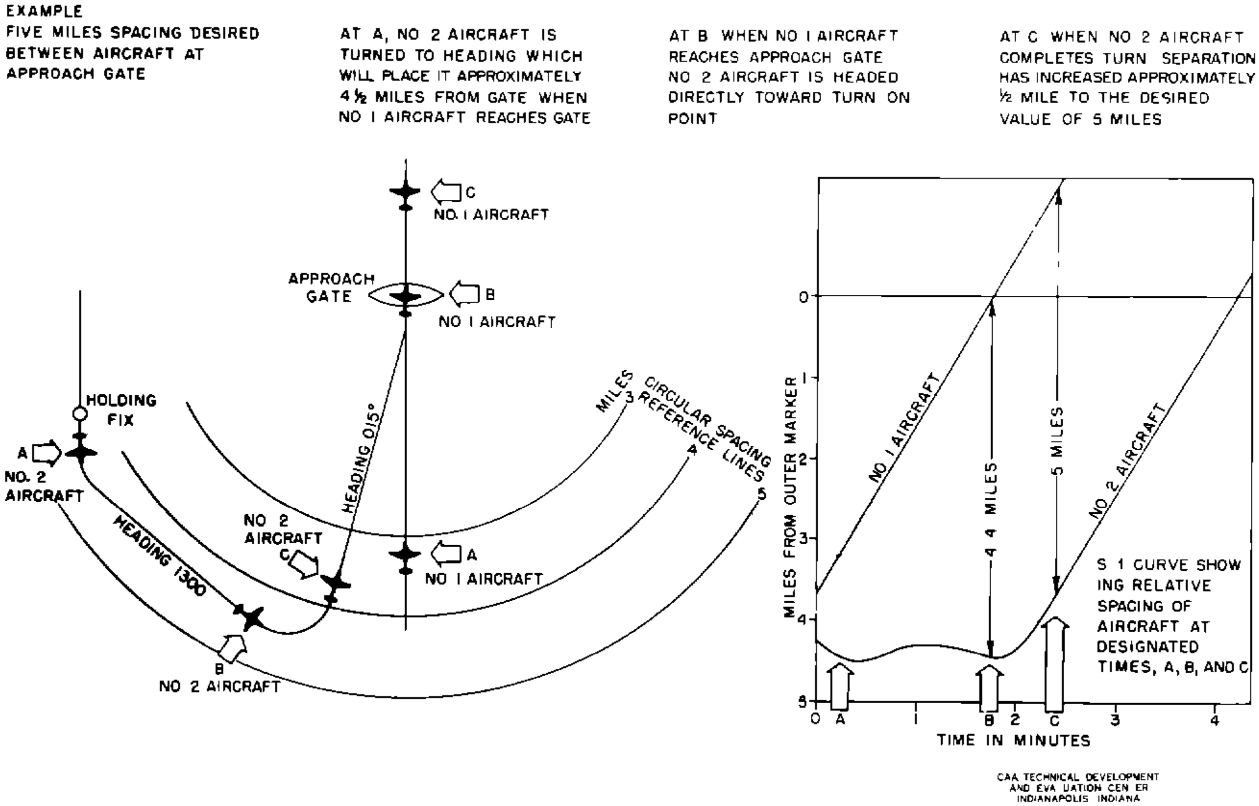


Fig 23 Use of Circular Spacing Reference on Radar Scope

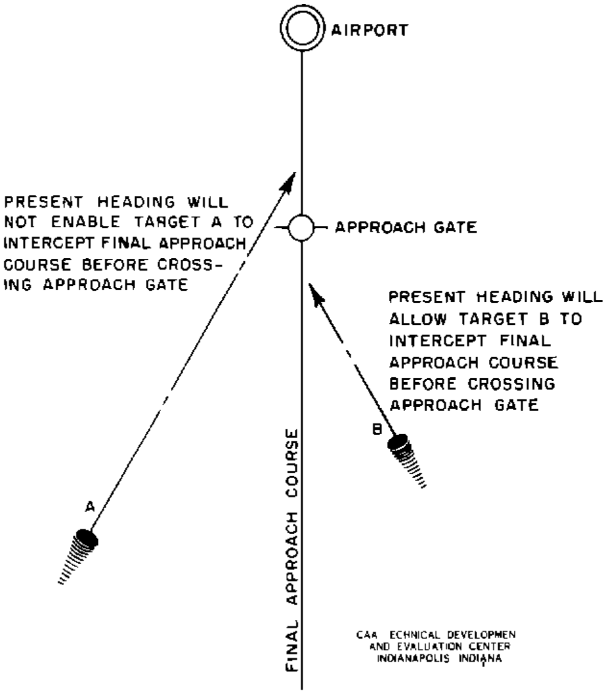


Fig 24 Use of Projected Radar Trails

Aircraft fly a curved course in making a transition from one heading to another In guiding an aircraft into a desired track, the radar controller must make allowance for the radius of the required turn As indicated in Fig 25, the amount of this allowance or lead depends on the amount of angular change required It is also affected by the air speed, the rate of turn, and the wind All these effects decrease as the angle of interception is reduced For this reason, it becomes relatively easy to turn an aircraft precisely on a final-approach course when the angle of interception is low

In vectoring an aircraft toward a localizer course for a subsequent ILS approach by the pilot, it usually is not necessary for the controller to align the aircraft on the localizer course if the interception angle is not greater than 20° Simulation tests indicate that it is desirable in handling this procedure to utilize the capitalized phraseology of the following example

(Identification) TURN left, HEADING zero-two-zero,

YOUR POSITION, two miles southwest of outer marker,

TAKE OVER FOR ILS APPROACH,
TRAFFIC four miles AHEAD

Missed-Approach Procedures

A missed approach can be an awkward, if not a critical, traffic problem when radar procedures are not used However, simulation tests show that a missed approach becomes a very minor problem when adequate radar coverage is available Usually the aircraft is immediately returned to the jurisdiction of the arrival controller and is taken back to a safe maneuvering altitude which, in most cases, will be the minimum initial-approach altitude If the pilot desires to try another approach, the aircraft is fed back into the first available gap in the landing sequence and is simply handled as another arriving aircraft

Departure Control

The function of terminal-area departure control is to assign and to monitor flight paths which will allow outbound aircraft to depart in an orderly, efficient sequence with proper separation between them and on paths which will enable each one to continue into the ARTC area in accordance with specific ARTC

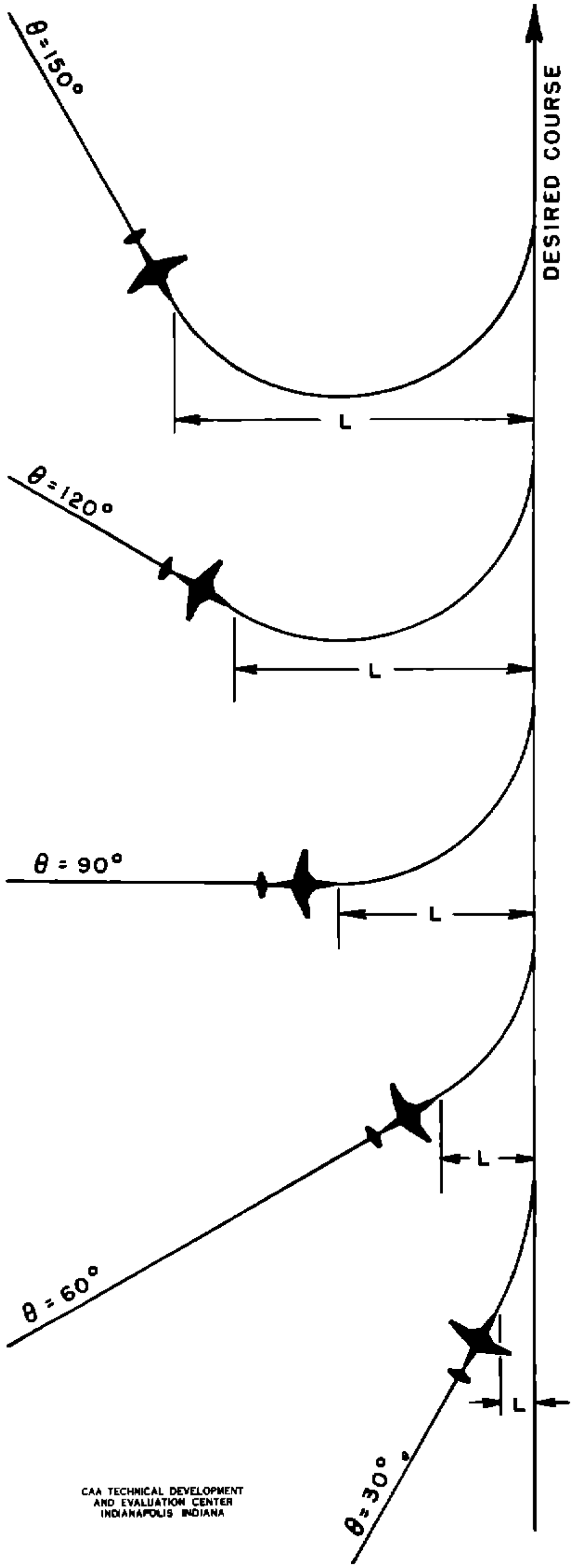


Fig 25 Effect of Angular Change of Heading θ on Amount of Lead (L) Required

clearance instructions Departure traffic usually has diverging, rather than converging, flow characteristics For this reason, it generally produces less of a control problem than arrival traffic Therefore, it is often possible for a single departure controller to monitor safely the paths of as many as six aircraft simultaneously

Simulation tests indicate that one of the most important aids to increased departure flow is the establishment in the terminal area of specific departure routes completely independent of the arrival routes With such a system as shown in Fig 26, co-ordination between arrival and departure controllers is completely eliminated The only terminal-area restrictions to departure flow are the take-off restrictions imposed by landing traffic at the airport itself These restrictions may be further reduced through the use of multiple runways laid out as shown in Fig 27

Prior to an aircraft take-off on IFR flight plan, an ARTC traffic clearance is relayed to the pilot At locations where direct ARTC air/ground communications will be available after the aircraft is airborne, the initial ARTC clearance need include only a clearance limit and an assigned altitude In most cases, the clearance limit is a radio fix located near the boundary of the terminal area Occasionally, to insure that the aircraft will be able to reach the assigned altitude before it passes out of radar coverage, it may be necessary for the terminal-area departure controller to direct the pilot to make a 360° climbing turn As soon as the departing aircraft reports at the assigned altitude and is observed to be on course and clear of all other terminal-area traffic, control of the aircraft is transferred to ARTC As soon as ARTC establishes communication with the aircraft, the remainder of the air-route clearance is issued to the pilot

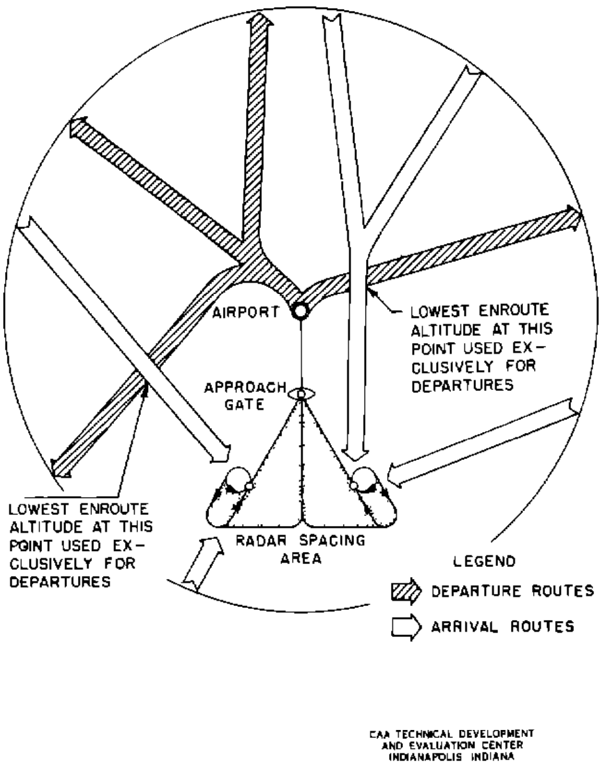


Fig 26 Example of Independent Departure Routes

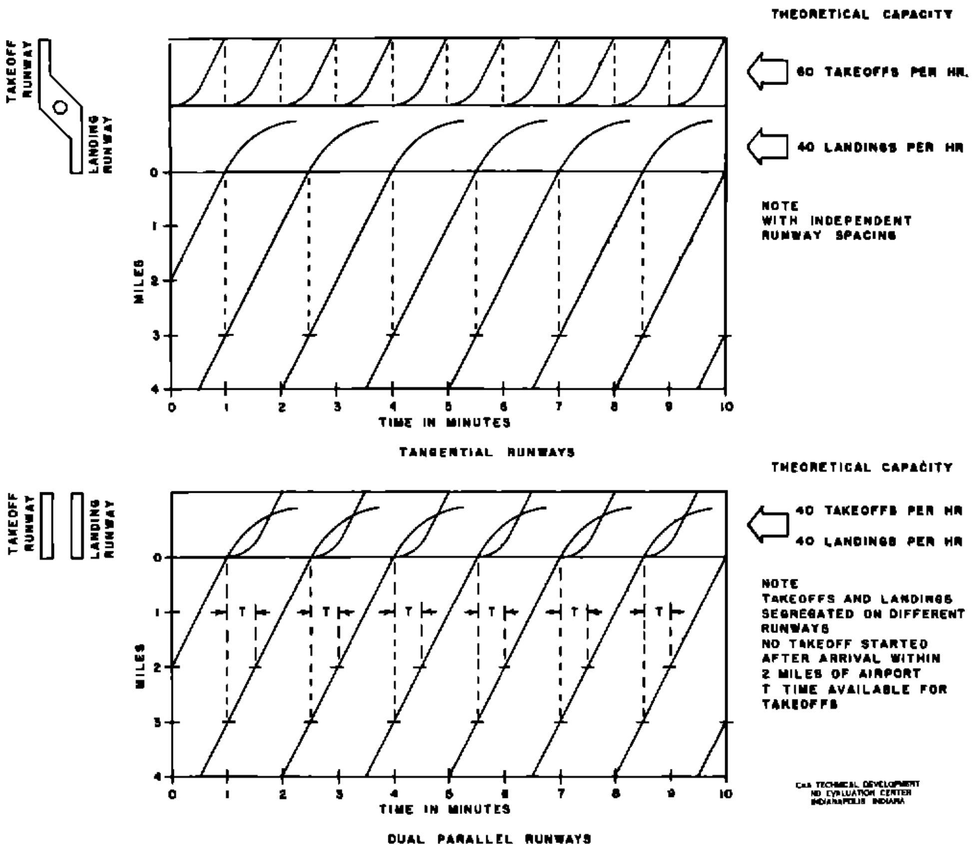


Fig 27 Multiple-Runway Operations

Because of the modern trend toward single-direction airports, considerable simulation work has been devoted to the problem of securing maximum utilization from a single runway used for both arrival and departure operations One of the first questions was whether it was more efficient to run traffic in groups of successive arrivals and successive departures or to mix the two types of traffic with alternate arrivals and departures As shown in Fig 28, a higher utilization is possible when take-offs and landings are alternated This procedure has several other operational advantages

1 A good airport-utilization rate can be achieved even though the arrival system may have a relatively low acceptance rate, since the interval between successive approaches is utilized for departure operations

2 Because the desired separation between successive arrivals is seldom less than six miles, the arrival controller works under very little strain or anxiety regarding the maintenance of adequate radar separation between aircraft on the final approach

3 Since the separation between successive departures is seldom less than six miles, the departure radar controller has plenty of time in which to establish radar identification and radio communication with each departure before the next one is airborne This procedure is known as the "sandwich system," since individual departures are sandwiched between successive arrivals The procedure operates in the following manner

a When departures are imminent, arrivals are deliberately spaced a distance of about six miles apart at the approach gate More separation is used if braking conditions are bad or if the runway is not equipped with high-speed turn-offs

b If an arrival is within two miles of the airport, the departure is held in run-up position 200 feet off the active runway

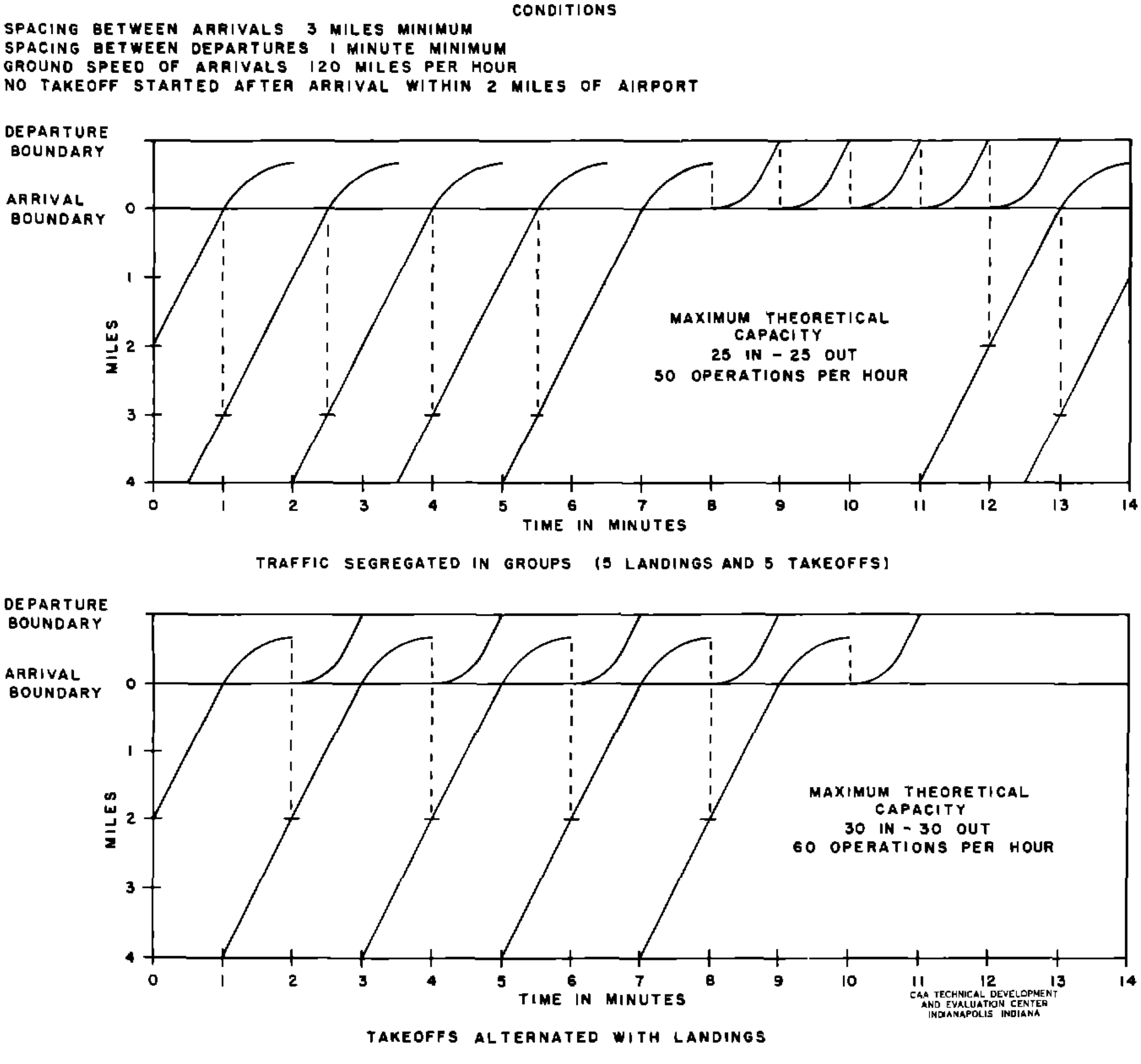


Fig 28 Single-Runway Operations

c As soon as the arrival passes the take-off position, the departure is cleared into take-off position on the runway

d The departure, ready for take-off, pulls into take-off position while the arrival is decelerating on the runway

e As soon as the arrival is clear of the runway, the departure is cleared for immediate take-off, provided that the next arrival is still more than two miles from the airport and that adequate lateral separation will exist in the event of a missed approach

f In the rare cases where the provisions of Item e cannot be met, the departure is taxied back off the runway to make room for the arriving aircraft

When the runway is equipped with a high-speed entrance, as shown in Fig 6D, the departure may be held 200 feet clear of the runway until the first arrival is off the runway If the provisions of Item e can be met, the departure is cleared for immediate take-off The take-off roll can be started from the run-up position This procedure saves at least one radio contact per departure and avoids the necessity of ever having to taxi the departure off the runway because of insufficient separation from the next arrival

Integration of Jet Operations

A great amount of simulation work has been devoted to the problem of integrating the operation of jet aircraft into the air traffic control system Although several basic principles have been learned, much work has yet to be done on this subject

The development of the gas turbine has made possible much higher power and hence higher speed for modern aircraft Unfortunately, this performance is obtained with a very high fuel consumption This characteristic places a critical importance on the time factor which dominates every aspect of present jet operations

A jet aircraft requires little warm-up time, but during ground operations it burns about five times as much fuel per minute as an equivalent piston-engine aircraft does For this reason, it is desirable that departure clearances be available before, or immediately after, the time the aircraft leaves the parking ramp The provision of high-speed taxi strips and unrestricted runway entrances becomes even more valuable when jet aircraft are concerned

Because of their generally high wing loadings and characteristically low propulsive efficiencies at low speeds, jet aircraft usually require a long runway distance for take-off In many cases this requirement may limit the take-off direction to the longest runway available Surface temperature has a critical effect on the distance required for take-off High temperatures greatly increase the length of the take-off run, as well as the amount of fuel required for this operation After accelerating to climbing speed, jet aircraft usually climb at forward speeds and climbing rates higher than those of piston-engine aircraft

The most important en route characteristic of jet aircraft is that, for efficient operation, they must be flown at their optimum altitudes, which are much higher than those of piston-engine aircraft For example, a typical jet aircraft has a maximum range of 1890 miles at 30,000 feet This range drops to 1080 miles if the aircraft must cruise at 10,000 feet If held to near sea-level altitudes, the range with the same load of fuel is reduced to 820 miles Thus, to avoid seriously decreasing the range of jet aircraft, it becomes important that the air traffic control system be able to permit unrestricted climbs to optimum altitudes This requirement emphasizes the importance of providing multilane departure routes for congested terminal areas It appears that the use of surveillance radar and the further implementation of TVOR facilities will do much toward solving this part of the problem

The optimum altitude of a jet aircraft gradually increases as the weight progressively decreases because of the consumption of fuel during flight For maximum range, the optimum jet flight plan does not utilize a constant cruising altitude Instead it is made up of a fast climb to optimum altitude, a gradual cruising climb as the optimum altitude increases, and a fast descent to the destination If followed, the cruising-climb procedure would limit the use of altitude separation between jet aircraft during cruising flight Thus some form of lateral separation, through use of multiple navigational tracks or of en route radar surveillance, would be desirable for operations of this nature

Present regulations require that aircraft departing on IFR flight plans carry enough fuel to proceed to the destination, thence to the alternate airport, plus 45 minutes reserve The reserve fuel requirement assumes critical importance in jet operations because reserve-fuel weights for a jet are always large compared to the weight of the aircraft itself They are extremely large compared to the weights of reserve fuel for piston-engine aircraft

Owing to increased fuel consumption by jet aircraft at low altitudes, it was formerly considered essential that all holding of such aircraft be accomplished at an altitude of 20,000 feet or above and that they be issued irrevocable landing-sequence numbers before leaving that altitude Actual experience with later types of jets indicates that holding at lower levels is permissible for moderate lengths of time However, the potential diversion range is seriously reduced as altitude is lost It appears that the main penalty in low-altitude holding is not the additional fuel consumption during the holding operation but the reduction in available diversion range should the weather drop below landing minima before the approach is completed [10]

Recent British experience in the operation of jet transports indicates that in many cases it will be possible to handle such aircraft in the normal holding sequence with piston-engine aircraft However, jet aircraft can descend at rates much greater than those now customary for piston-engine aircraft This characteristic constitutes a very important air traffic control advantage which can be fully exploited only if jets are fed into the approach system from an independent feeding system Whether or not this factor offers enough gains in safety and efficiency to justify the additional facilities and air space required for its implementation is an important subject for future simulation

Most of the jet aircraft handled in TDEC simulation runs were assumed to be tactical types with average descent rates of 3,000 feet per minute and descent speeds of 300 mph, slowing to 180 mph for the last ten miles of the approach The great difference between the speeds of such aircraft and the speeds of other aircraft in the approach system has given controllers a difficult problem in establishing radar separation on the final approach As a result, controllers consistently allowed far too much separation when such aircraft were concerned The biggest improvement in the reduction in approach intervals and consequently in aircraft delay came when the separation table, as shown in Fig 18, was extended to include sequences involving jet aircraft

Completed simulation tests show that jet aircraft can be integrated into an approach sequence with more safety, less controller work load, and less delay for all aircraft concerned if the holding patterns for other aircraft are offset from the final-approach course If other aircraft are held on the final-approach course, jet aircraft are faced with a much longer descent

---

[10] Captain A M A Majendi, "Civil Jet Operations," Journal of the Royal Aeronautical Society, Vol 57, No 513, p 539, September 1953

path and with a long drag-in at low altitude in order to tunnel under the holding stack For this reason, offset stacks are preferable for any approach system which will have to accommodate jet traffic

Jet interceptors characteristically produce poor radar targets because of their sleek configuration and their lack of rotating propellers It has been estimated that a typical jet fighter has about one-sixth the reflecting area of the F-51 piston-engine fighter [11] These factors make the use of radar safety beacons especially desirable for terminal-area traffic control operations when jet aircraft are concerned Because of their lack of drag-producing propellers, jet aircraft normally decelerate slowly from their rather high landing speeds Thus landing distances and runway-occupancy times are likely to be high for jet aircraft Here, again, the provision of suitably placed, high-speed runway exits is expected to greatly improve the situation

It is quite possible that within a few years over-all improvements in aircraft and engine design will relieve some of the more critical limitations which are characteristic of present jet operations Meanwhile, an important objective of the simulation program is to develop a traffic control system that will be able to accommodate increasing numbers of jet aircraft in orderly, democratic sequence, without the need of priorities or of special privileges for any specific type of aircraft, jet or otherwise

Multitrack Approach System

Some of the most advanced simulation work completed to date was in connection with the development of the multitrack approach system This system combined a number of new ideas in the operation of flight-path computers, pictorial computers, automatic data transfer, and simplified radio communications It also provided a smooth, efficient method of co-ordinating jet traffic with conventional aircraft in the terminal area

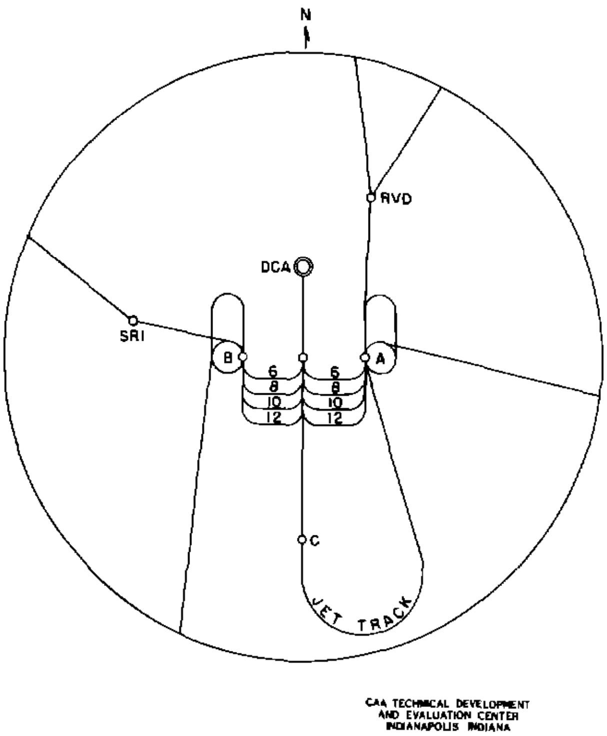


Fig 29 Multitrack Approach System

[11] "Jet Flight Planning," USAF Instrument Pilot School, U S Air Force Aircraft Accident and Maintenance Review, Vol VII, No 5, p 12, May 1952

The multitrack approach system, illustrated in Fig 29, was a twin-stack layout which fed a single approach lane from two close-in holding fixes A number of standardized, predetermined, approach tracks of various lengths were provided between each holding fix and the outer marker That portion of the terminal area en route to and including the holding patterns was operated as a fixed-block system The portion between the holding markers and the airport operated as a moving-block system Separation between aircraft on final approach was provided by a computing device which computed gate times at the outer marker and selected the approach track for each aircraft to enable it to arrive over the approach gate with the desired separation from other aircraft Thus, each aircraft had a guaranteed gate time at the outer marker before it left the holding fix The relatively short and simple approach tracks made it possible for aircraft to achieve this gate time within a small tolerance Since the amount of tolerance increased the size of the airspace block which was assigned to each aircraft on the final approach, it was essential that these tolerances be kept small in order to maintain short approach intervals and a high acceptance rate

Because of the fact that detailed traffic samples had already been established for the Washington terminal area, it was decided to use this area for the simulation tests In the initial layout, four holding fixes were established Because these fixes were at considerable distances from the outer marker, aircraft normally departed these points at cruising speed and gradually decelerated to approach speed en route to the marker This procedure introduced considerable error in computed gate times because of the inability of the pilots to adhere to a standard deceleration program while flying through the approach patterns In addition, several potentially dangerous traffic conflicts were caused by fast aircraft overtaking slower aircraft in the outer converging areas of the patterns

To eliminate these disadvantages, it was decided to reduce the number of holding fixes to two and to reduce track lengths by establishing these fixes relatively close to the outer marker Pilots were instructed to leave the holding fixes at approach speed This procedure eliminated computation errors due to deceleration problems However, tests showed that computed gate times often were in error, particularly when the longer tracks were assigned

In order to reduce the magnitude of these errors which were caused by slight variations in the approach speeds of the various aircraft, it was decided to eliminate as many of the longer tracks as possible and to retain only enough of the shorter tracks to insure continuous smooth operation of the approach system It was found that the total range of track lengths (from the shortest to the longest) need not exceed the distance traveled by the fastest aircraft using the system while flying a 360° holding pattern at the outer fix Since a 360° turn normally takes two minutes and since the fastest aircraft using this system had an approach speed of 150 mph (2½ miles per minute), the total range of track lengths needed was 5 miles

This range of track lengths would permit a pilot who just missed being able to take the longest track to make a 360° turn at the holding fix and to pick up a shorter track when again over the fix without causing any break in the approach sequence With a minimum track of 6 miles and a range of 5 miles, the longest approach track required for this system was only 11 miles long Theoretically, greater operational flexibility could be attained if a large number of successive tracks were established in the range between the longest and shortest tracks However, to avoid possible confusion in following a selected track on the display, it was decided to use only a small number of tracks, widely spaced for easy reference To cover the required range using 2-mile increments between tracks, the system was set up with track lengths of 6, 8, 10, and 12 miles

In order to integrate the operation of jet aircraft in the approach system, a jet letdown path was added The configuration of this path was based on the following tentative requirements

1 Jets would cross the approach fix at 20,000 feet and would descend at an average rate of approximately 3,000 feet per minute

2 Descent would be made at an indicated air speed of 300 mph, slowing to 180 mph for the last stage of the approach

3 Turns would be made at one-half standard rate, or 1½° per second

4 The straight-in final-approach path would be at least 15 miles long

An additional radio fix was established on the localizer course 12 miles from the outer marker to provide the following

1 An aid to jet pilots in intercepting the final-approach course

2 A check point for radar identification of jet aircraft

3 A close-in check point for obtaining additional accuracy in computing gate times of jet aircraft

The method of integrating jet and piston-engine aircraft worked satisfactorily as long as the proportion of jet aircraft in the system remained small Isolated jet aircraft could be fed into the approach system with minimum interruption in the regular landing sequence of piston-engine aircraft However since there was only one track available for jet aircraft, time separation had to be used between successive jet approaches In most cases it was possible to sandwich one or two piston-engine approaches between the jet approaches, so that very little time was lost from this lack of flexibility in the system However, this limitation could become serious if a higher proportion of jet aircraft had to be accommodated

As a result, the layout has recently been changed to a triple-stack system using a separate holding fix for jet aircraft Jets leave this fix at about 8,000 feet for approaches on one of four available tracks selected by the computer Tests indicate that this layout is able to integrate jet and piston-engine aircraft in any desired landing order

In the initial tests of the multitrack approach system, a special 10-inch circular slide rule known as a track selector was used to select tracks and to compute gate times A functional diagram of this device is shown in Fig 30 The circular slide rule, while simple and cheap, had the disadvantage of requiring several seconds to select an approach track Because the principles of the multitrack system show such promise as a future aid to traffic control, an electronic digital computer has been built for this operation The digital computer offers these advantages

1 It permits extremely fast push-button operation

2 It can compensate for various wind conditions

3 It should provide a means of coupling the computer function with the automatic data-transfer system by automatically displaying track-number and gate-time data on the flight-data board

4 Because the landing sequence is actually based on the chronological sequence of computed gate times of successive aircraft, the coupling function of the computer can transfer flight data in proper order from multiple-approach control displays to a single PAR display

In the initial tests of the multitrack approach system, it was assumed that all aircraft were equipped with some type of pictorial display to indicate to the pilot the actual position of the aircraft When it was also assumed that the map on each pictorial display showed the various designated approach tracks, communications were reduced to a minimum since pilots could navigate their own way around the assigned approach tracks

Actually, the operation of a multitrack approach system does not necessarily require pictorial displays in the aircraft, since the approach tracks would also be shown on the radar overlay In handling aircraft not equipped with a pictorial display, the controller uses the computer to select the most efficient track and then guides the aircraft around the selected track by means of radar-vectoring instructions

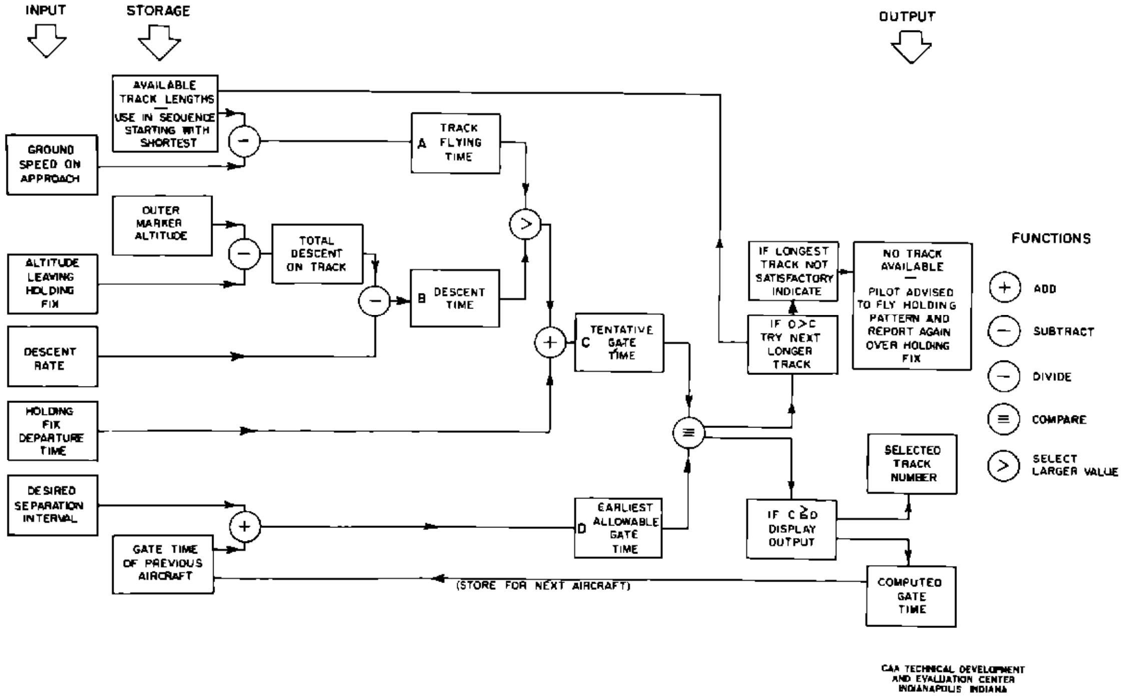


Fig 30 Functional Diagram of Track Selector

In the normal operation of this system most decisions are made by the computer, and the controller functions mainly as a monitor to insure that pilots are staying on their assigned tracks and that adequate separation is being maintained between all aircraft The controller stands ready to override the system at any time that an emergency occurs or that it becomes apparent that one aircraft is approaching too close to a preceding aircraft In this connection, it is interesting to note that the present layout provides two simple missed-approach paths to take care of this contingency Since the lowest altitude used by holding aircraft at the two holding fixes is 2,500 feet and the final-approach altitude over the outer marker is 1,500 feet it is possible for a controller to turn an aircraft back to either of the holding fixes at 1,500 feet if it becomes apparent that the aircraft does not have safe separation behind the one ahead In such a case, the aircraft can usually be given a new track assignment as soon as it reaches the holding fix

CONCLUSIONS

1 The development of simulation techniques offers an opportunity to place the planning of air navigation and traffic control facilities on a scientific basis Through systematic research, the simulation program has enabled many of the general principles which govern air traffic flow to be determined Some of these principles have an immediate application toward increasing the capacity of terminal-area traffic systems With simulation, detailed measurements of traffic flow in specific systems can quickly and easily be determined Many of these measurements would be impossible to obtain by any other means They form an equitable, valid method of comparing one traffic system against another Thus, simulation makes possible the rapid development of optimum arrangements of facilities for a specific area or purpose

2 The dynamic simulator was not originally designed or intended for use as a training device However, because of its realism and its ability to present a controlled traffic input with no risk to actual aircraft, it has proved to be an extremely effective device for training control personnel in the application of radar control procedures in terminal-area traffic operations

3 Simulation tests indicate that the type of terminal-area control system with the highest capacity per controller would be a system in which inbound pilots could navigate their way to the holding fixes unassisted and could complete their approaches unassisted after being turned on to the final-approach course In this type of system, radar would be used to establish and maintain separation between aircraft en route from the holding fixes to the approach gate Outbound pilots could navigate their own courses to the terminal-area boundary, radar would be used to provide separation between outbound aircraft until such aircraft were established on course with ANC separation from all others The philosophy behind this system places on the pilot a maximum of responsibility for the actual navigation of the aircraft It enables control personnel to concentrate their efforts on the establishment and maintenance of radar separation between aircraft in those portions of the terminal area where it is functionally more efficient to use radar separation instead of standard ANC separation

4 The provision of airport improvements as detailed in this report offers a relatively cheap method of providing gains in airport capacity that could otherwise be attained only by the construction of new runways at much higher cost

5 Tests indicate that the need for separate identification codes for airborne transponders may not be important for terminal-area traffic control operations, because it is possible to design high-capacity control systems which never require a controller to keep track of the identity of more than three aircraft simultaneously In such a system, it appears that a simple bloomer code which could be displayed on request would be sufficient for all practical purposes

6 The inauguration of jet IFR operations presents few fundamentally new traffic control problems However, the critical importance of the time factor in jet operations places a far greater emphasis on the need for uninterrupted climb and descent paths as well as on the need for minimizing traffic delays both in flight and on the ground It appears that several of the procedures developed in connection with the simulation program will assist in solving these problems, not only for jet aircraft but for other aircraft as well

7 The work completed to date indicates that new approaches to the en route traffic control problems are required It is necessary to consider in closer detail how the arrangement in sequence of aircraft en route affects the terminal-area problems

RECOMMENDATIONS

1 Many of the improvements in airports or in facility layouts which have been developed in connection with the simulation program have an immediate application toward increasing traffic capacity It is recommended that these features be studied carefully by groups responsible for airport planning and airway operations to determine which features can be utilized immediately to increase the capacity of existing or proposed terminal-area facilities

2 In the past, radar training programs for control personnel have consisted mainly of radar-alignment procedures as well as of methods for conducting PPI and PAR approaches Little emphasis has been placed on the most important application of terminal-area radar, its use in the proper spacing of aircraft in high-density approach and departure patterns Therefore, it is recommended that radar training programs be augmented to insure that all radar control personnel learn the most effective methods of applying radar in the actual control of air traffic Simulation, both graphic and dynamic, would be a valuable aid in the conduct of such training The establishment of a dynamic simulator for exclusive use as a training device is recommended as a promising means of raising the performance level of radar control personnel The explanatory material in this report may also be utilized in a training manual for this purpose Such training should provide an opportunity for control personnel to take advantage of the many principles which have been learned during the conduct of thousands of terminal-area operations in the simulation program

3 Simulation tests indicate that the most fundamental requirement for radar traffic control is a positive, dependable radar display Without it, the acceptance rate will suffer and the controller work load per aircraft will be high Therefore, it is recommended that full emphasis be given to the development and procurement of radar equipment capable of giving solid, dependable coverage of aircraft in the terminal-area traffic patterns, particularly during bad weather when the display is most needed It is recommended that the specifications for airport surveillance radar be re-examined with regard to the actual characteristics required to meet the operational requirements in use and those proposed for the near future

4 To take full advantage of the principles which have been discovered for increasing the traffic-handling capacity of terminal areas, it will be necessary in many cases to modify the adjacent air-route navigation and traffic control system to make it capable of handling the increased capacity of the terminal areas It is therefore recommended that the facilities of the simulation program be extended in order to study methods of improving the operation of air route traffic control

GPO 804254 — 1