A Preliminary Report on the Simulation of Proposed ATC Procedures for Civil Jet Aircraft

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A PRELIMINARY REPORT ON THE SIMULATION OF PROPOSED ATC PROCEDURES FOR CIVIL JET AIRCRAFT*

SUMMARY

This report describes an extensive simulation program which was conducted by the CAA Technical Development Center to study operational requirements and control techniques for handling civil jet aircraft in present and future air traffic control systems Starting with a brief review of current simulation methods, the report discusses the special problems associated with the control of civil jet aircraft

A significant development which emerged from the simulation tests was the paradox that, in high-density terminal operations, an over-all fuel saving would result if low-altitude holding procedures were used instead of the high-altitude procedures formerly considered essential. It was found that the reduction of delays, made possible by the higher efficiencies of approach systems utilizing low-altitude holding procedures, would more than compensate for the increased fuel-flow rates of jet aircraft at the lower altitudes

The simulation tests explored a number of concepts in the field of arrival scheduling control, including the use of velocity control, en route delay patterns, and various methods for sequencing arriving aircraft It is expected that much of this work can be applied in the development of operational philosophy and equipment design for future air traffic control systems

SIMULATION METHODS

Simulation has been used for a number of years in the study of air traffic control (ATC) problems The result of earlier work led to the establishment of the dynamic ATC simulator at the CAA Technical Development Center (TDC) in 1950 The use of this facility has led to a number of improvements in the present ATC system, as well as a number of new concepts which are expected to have application in future systems The application of earlier simulation studies to the operating ATC system has produced sufficient field data to evaluate their effectiveness Comparison of the simulation results with actual field data has indicated extremely close correlation This has led to an increased demand for the expansion of simulation activities

Present simulation techniques include graphical, dynamic, and fast-time methods Graphical analysis is a paper-and-pencil technique Fast and cheap, this method of simulation is used to determine the effect of varying certain system parameters It also is used to determine the ideal performance of a specific ATC system for comparison with the results obtained from dynamic simulation tests Graphical plots include altitude-time, altitude-distance, fuel-distance, space-time, and aircraft-time presentations.

Dynamic simulation is a real-time simulation technique which enables certain portions of the ATC system to be tested in a realistic control environment using human controllers who are confronted with the same workloads and decisions that they would have to face in the actual operation of the system under study

The ATC system is a highly complex, large-scale, information-handling system Figure 1 is a diagram of the basic control function showing the general flow of information around the loop In the dynamic simulator, the aircraft, radars, and radio channels are replaced with more economical and easily managed substitutes, as shown in Fig 2 However, human beings are retained in the controllers' and pilots' positions and the total flow of information around the loop duplicates the flow in the actual system

Figure 3 shows the servo-controlled projectors which move spots of light across a large movie screen to simulate the movement of individual aircraft in the system Each projector is manned separately in order to provide the real-time communications workload

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*Reprinted for general distribution from a limited distribution report dated May 1958

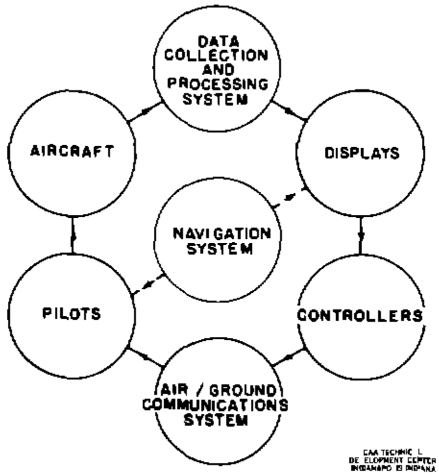


Fig 1 Functional Diagram of ATC System

and the aircraft characteristics affecting the control problem. Due to space limitations in the projection room, the pilot consoles for some of the projectors are located in another room, as shown in Fig 4 Two television cameras, shown near the center of Fig 3, televise the resulting traffic situation on the screen for presentation as radar data on different types of displays Fifteen interphone channels simulate air/ground/air and landline communications facilities Figure 5 shows a typical terminal-area equipment layout and Fig 6 shows an arrangement of two new bright tube displays in the en route traffic control room

Figure 7 shows the role of graphic and dynamic simulation in the ATC development cycle The various phases follow an ascending cost scale, with the cheaper processes used first This sequence tends to reduce research costs by providing a maximum opportunity to weed out or revise impractical solutions before a large amount of money has been spent on their evaluation

Perhaps the most obvious justification for the use of dynamic simulation is that it provides a means of measuring, or at least incorporating, the effects of human factors in the

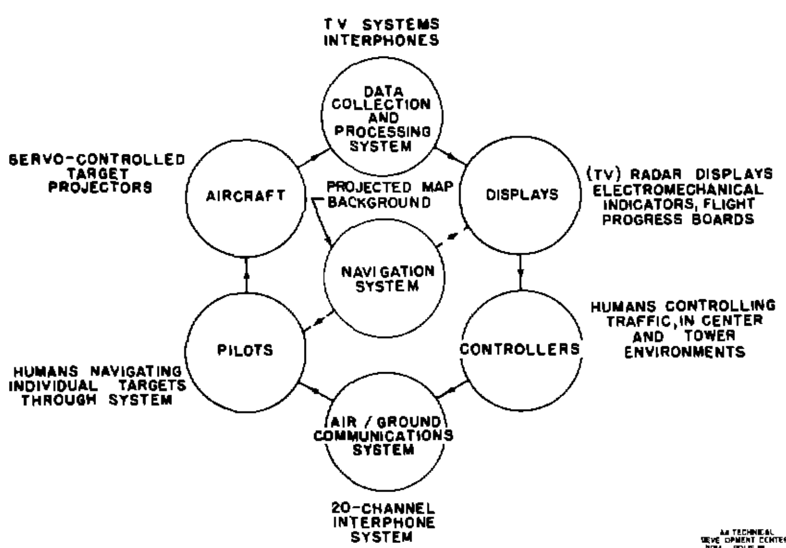


Fig 2 Functional Diagram of ATC System with Analogues Employed in Dynamic Simulation

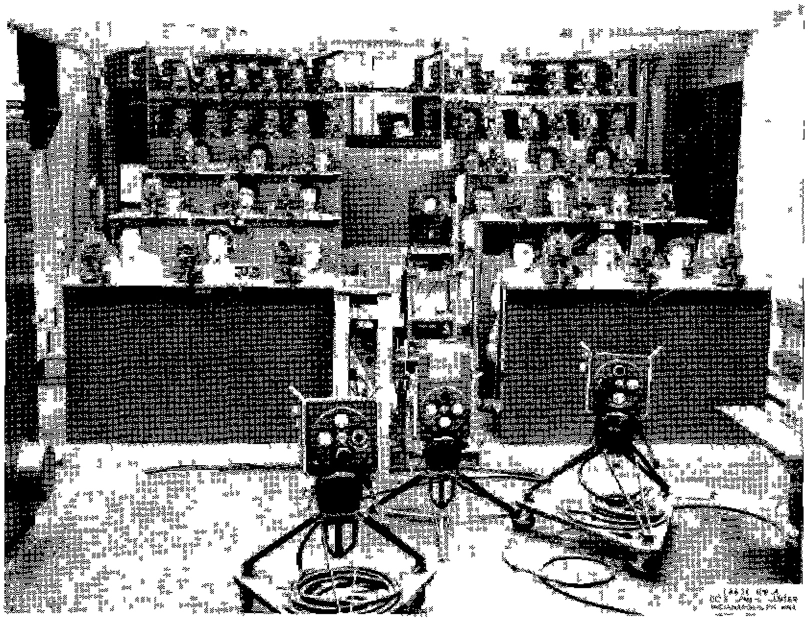


Fig 3 Pilot Consoles, Target Projectors, and Television Equipment

operation of the system under test However, the feedback loops at the right of Fig 7 show a very important by-product of the development program, namely, the generation of new ideas and the refinement of old ones as a direct result of the program Dynamic simulation, which usually provides the first look at the operation of a new system, has proved to be a potent stimulus for new ideas and improvements

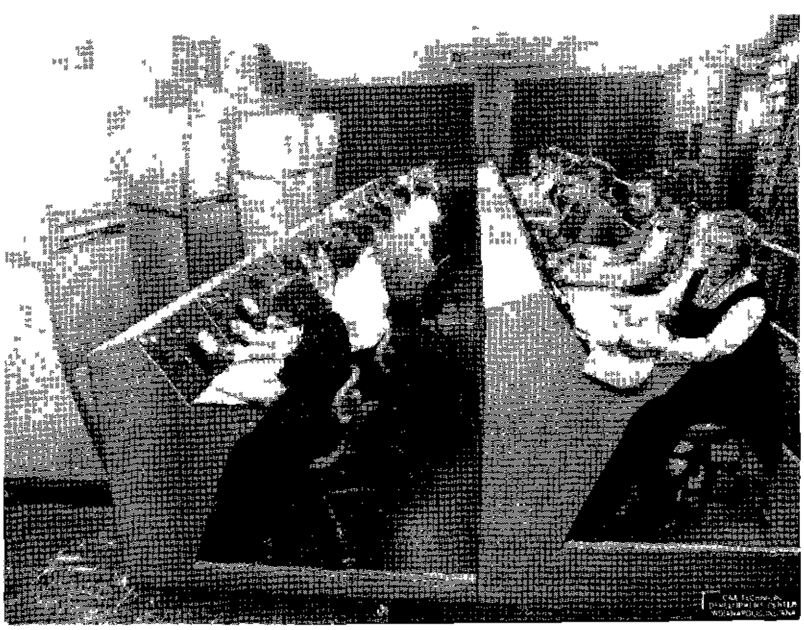


Fig 4 Remote Pilot Console Positions

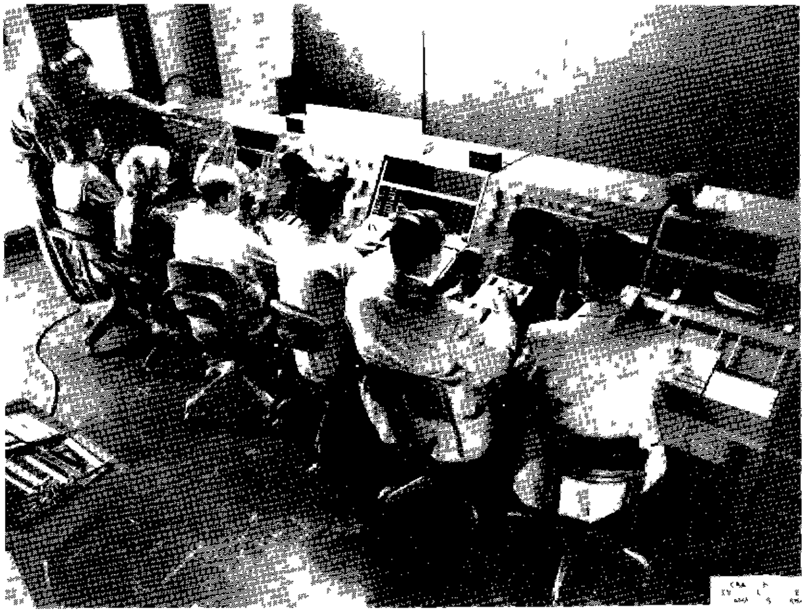


Fig 5 Terminal Area Control Room Layout

Fast-time simulation is a relatively new technique which utilizes a digital computer in nonreal-time operation Unfortunately, the title presently applies only to the problem running time, and not to the time required to set up the initial program. The advantages of this method include rapid running of extremely large traffic samples, low error rates, and the automatic collection and processing of test data Disadvantages include the complex

Fig 6 En Route Control Room Layout

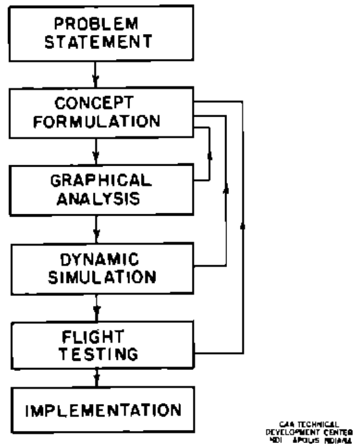


Fig 7 Normal Development Cycle for ATC System Improvements

programming operation and the inability to incorporate human factors The capabilities of fast-time simulation relate it more closely to graphical, rather than dynamic, simulation Actually, these various simulation methods complement each other and a complete simulation study facility will use all three methods in a coordinated and cooperative manner When detailed human behavior data are obtained through actual operational or dynamic simulation tests, they can be applied to the graphical and fast-time methods to gain the benefits of these methods

In terms of results, flight tests of ATC systems inherently are slow, awkward, and expensive Since actual facility installations are involved, developmental and modification phases require lengthy periods of time Comparative performance measurements are almost impossible to achieve, due to the difficulty of duplicating the original traffic input and flight conditions on any subsequent tests In addition, it is difficult to get the weather to "cooperate" for the required test conditions Unless the test operations can be isolated from other air traffic, safety considerations usually prohibit complete tests under high-density traffic loads

Although live flight-testing is necessary to provide final proof that the system operates satisfactorily as installed, a large part of the system design and operational testing during the developmental phase can be handled through the use of simulation techniques

In preparation for the advent of civil jet operations, thousands of simulated jet operations were flown through many different arrangements of routes and traffic patterns, under high-density traffic conditions representative of those forecast for the next five years A peculiar advantage of simulation in this case was the fact that the required numbers of actual aircraft of this type were not in existence at the time

PROBLEMS OF SPEED, MANEUVERABILITY, CLIMB AND DESCENT

As a class, the new family of civil jet transports will be larger, heavier, and more powerful than the commercial aircraft they replace As shown in Fig 8, they will fly higher and faster than any other type of civil aircraft Dynamic simulation tests indicate that their higher speeds will present a problem to controllers who are not experienced in handling jet operations. This problem results not only from the higher rates of closure with other aircraft, but also because passenger comfort at these speeds requires the use of low turning rates This combination greatly increases the amount of time and airspace necessary for any maneuver, requiring controllers to make decisions a long way ahead of the aircraft It also makes impractical the old procedure of specifying certain turns for radar identification Implementation of the ATC radar beacon system should eliminate the need for this procedure Simulation tests show that the job of becoming adjusted to the increased operating tempo, to "stay ahead of the aircraft," is one of the most important factors which the controller will need to learn in handling the civil jet

Figure 9 shows the extensive distances which will be covered by jet aircraft in climbs and descents. As altitude separation cannot be used where one aircraft is crossing the altitude level of another, the long climb and descent distances of jet aircraft will increase

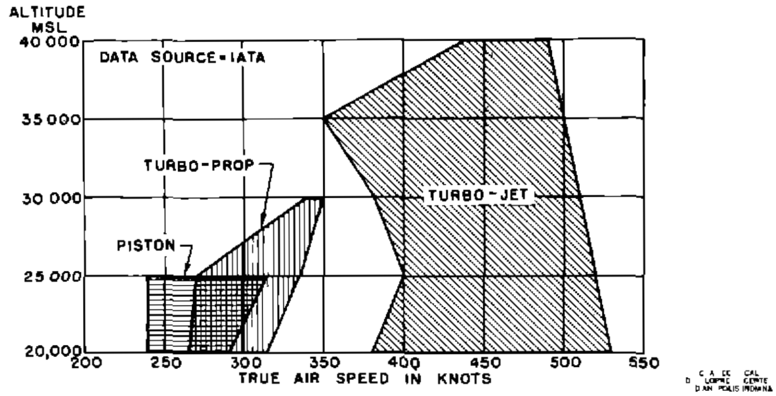


Fig 8 High-Altitude Cruising Performance of New Civil Transport Aircraft

greatly the area in which lateral separation must be provided, either by radar coverage or perhaps, someday, by the use of a navigation system which can provide passing lanes

Although the climb and descent rates of jet aircraft normally will be higher than those of other civil aircraft, their forward speeds also will be correspondingly higher As shown in Fig 9, the lower portions of their climb and descent paths often will coincide with those of other aircraft In such cases, a severe overtaking problem will occur unless lateral separation can be used

Figure 9 shows the wide variation in climb distances of the civil jet For example, although some aircraft will reach 20,000 feet only 30 miles out, others may require 100 miles to get this high There are three reasons for this variation

1 Fully loaded, some of the new jets can carry as much as 40 per cent of their weight in fuel Lightly loaded short-haul aircraft will have a much higher rate of climb than heavily loaded long-haul aircraft

2 The thrust output of turbojet engines is extremely sensitive to air temperature Higher temperatures result in less thrust and lower climb rates

3 Figure 9 represents the composite performance of various types of airframe/engine combinations For example, aircraft with the large J75 engines will tend to have better climbing performance than the same type of aircraft equipped with the lower-thrust J57 engines

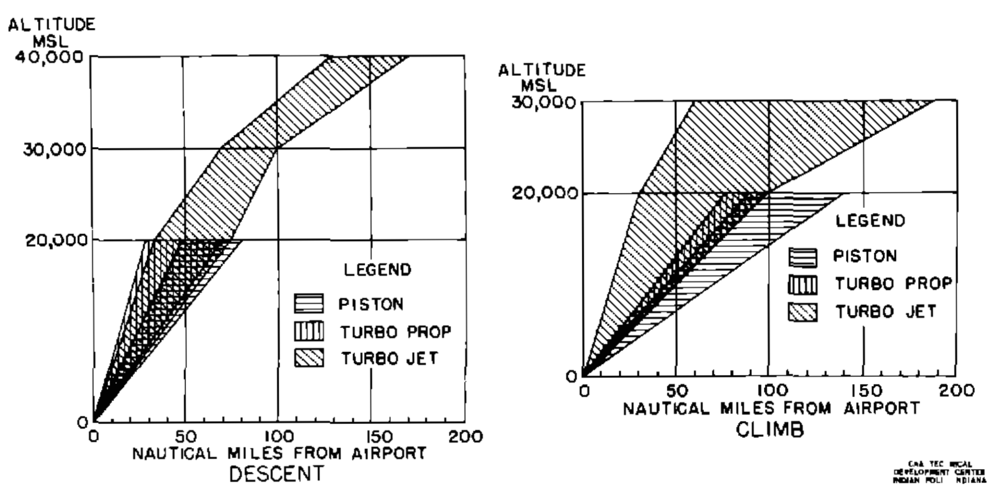


Fig 9 Climb and Descent Distances of New Civil Transports

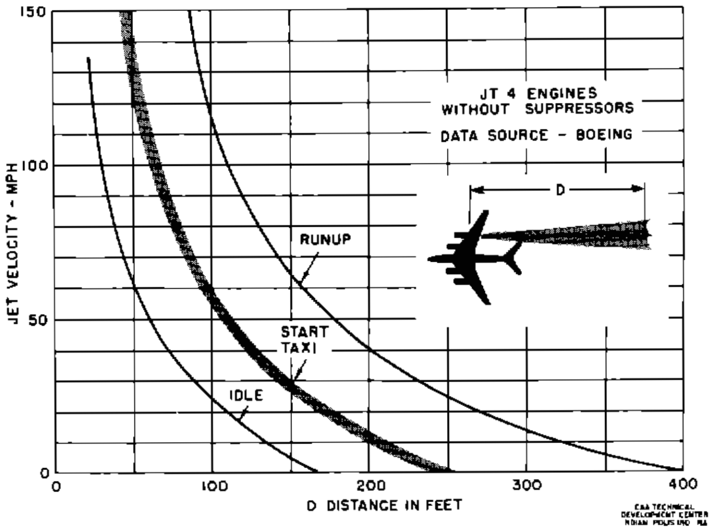


Fig 10 Jet Blast Effect During Ground Operations

GROUND OPERATIONS

Figure 10 indicates jet blast velocities at various distances behind a typical jet engine This effect, with its attendant heat and fumes, will require other aircraft to maintain a considerable distance behind jet aircraft operating on the ground The underslung jet pods, characteristic of the present generation of American jet transports, introduce another problem--the ingestion of debris and foreign matter which may be picked up by preceding aircraft and sucked into the intakes of the jet engines For this reason, jet aircraft should not be taxied closely behind other aircraft

Figure 11 shows the sea-level fuel flow of a typical jet engine It will be noted that a four-engine transport, taxiing at 50 per cent rpm, will burn 4 times 35, or 140 pounds of fuel per minute A half-minute runup at 100 per cent rpm would cost 1/2 times 4 times 117, or 234 pounds of fuel

The high rate of fuel flow probably will make it desirable for pilots to complete their pretakeoff cockpit checks before starting engines For the same reason, it may become common practice for jet pilots to secure their ATC clearances before leaving the ramp Once under way, it would be desirable for the jet to be able to continue uninterrupted to the takeoff position, since a high rpm is required to place the aircraft in motion again if it is stopped en route

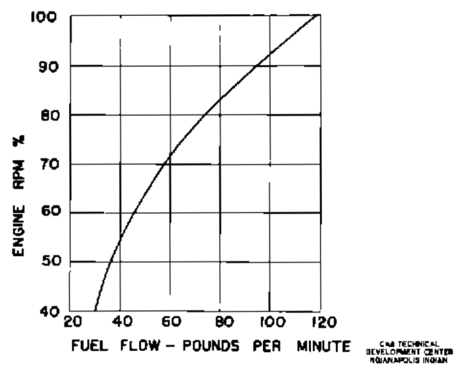


Fig 11 Typical Single-Engine Fuel Flow at Sea Level

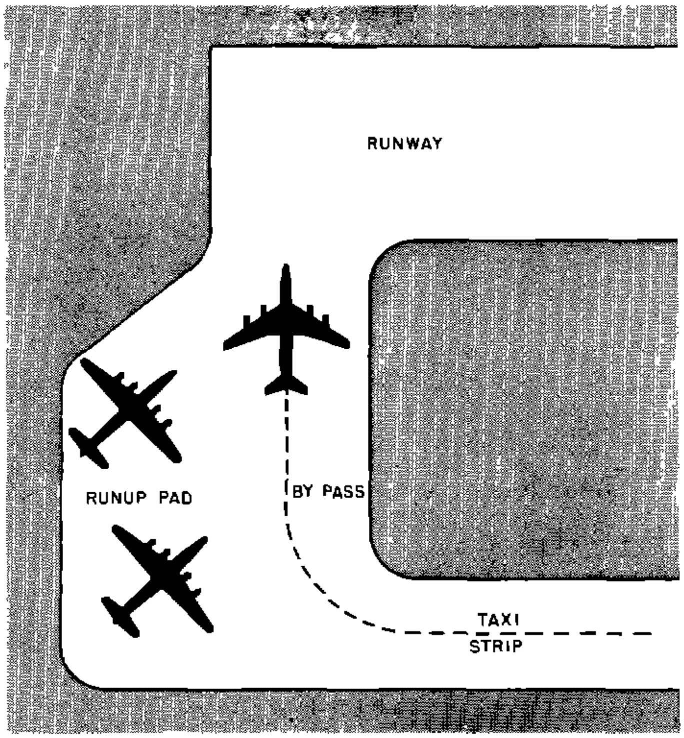


Fig 12 Bypass Taxiway

Turbojet engines do not require the warmup period characteristic of piston engine operations. Therefore, jet aircraft often will be ready for takeoff before other aircraft which have taxied out first For this reason, it will be particularly desirable for jet airports to be equipped with bypass taxiways, as shown in Fig. 12, so that departures can take off in the order in which they are ready to fly, rather than in the order in which they taxi out.

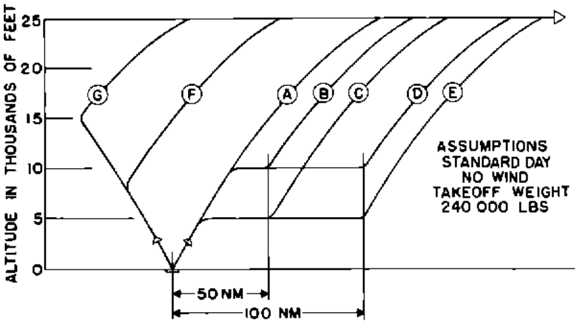
Once in takeoff position, jets will require about 10 seconds for a static thrust check at 100 per cent rpm before the pilot releases the brakes for takeoff. From the aircraft operator's point of view, it is desirable to perform this check on the runway to avoid the extra fuel cost of "revving up" the engines beforehand. Simulation tests indicate that the adverse effects of this runway occupancy time can be minimized by clearing the jet into takeoff position before the runway has been fully vacated by a preceding aircraft

CLIMB RESTRICTIONS

Basically, the jet airplane is a high-altitude, high-speed machine When operated at either low altitude or low speed, its fuel mileage is reduced considerably. In order to spend as little time at low altitude as possible, it would be desirable for the jet airplane to be able to climb to its cruising altitude immediately after takeoff However, many large terminal airports are surrounded by other airports, airways, restricted areas, or terrain obstructions which will preclude the use of unrestricted climbs directly on course In many cases, it will be necessary to either tunnel the aircraft at low altitude until it is clear of the restrictions or climb it out in some other direction before proceeding on course to destination.

Figure 13 shows the effect of several ATC departure restrictions on flight time and fuel requirements Although these comparative results may not always hold true throughout the range of variables which may occur, it is indicated that

1 In cases where a choice can be made between a certain length of tunnel versus a detour of comparative length to obtain an unrestricted climb, the tunnel should be less expensive in terms of flight time and fuel



FLIGHT PATH	DEPARTURE CLEARANCE	PENALTY	
		MINUTES	FUEL LBS
A	UNRESTRICTED CLIMB ON COURSE	0	0
B	TUNNEL TO 50 MILES AT 10 000 FEET	0 5	190
C	TUNNEL TO 50 MILES AT 5 000 FEET	1 3	520
D	TUNNEL TO 100 MILES AT 10 000 FEET	1 6	660
E	TUNNEL TO 100 MILES AT 5 000 FEET	3 4	1280
F	UNRESTRICTED CLIMB 50 MILE DETOUR	6 1	1540
G	UNRESTRICTED CLIMB 100 MILE DETOUR	10 3	3050

Fig 13 Effect of Certain ATC Restrictions on a Typical Jet Departure

2 Tunnel altitude should be as high as possible, and the length of tunnel as short as possible

3 Detours represent wasted mileage, with corresponding penalties in both fuel and flight time

CRUISE PROBLEMS

Economic Significance

From the operator's standpoint, the dispatching of civil jet aircraft will be an extremely important operation, since the economic penalties of a poor choice or decision will be much higher than corresponding penalties have been in the past Because many interacting variables are involved, flight planning for civil jets will be an extremely complex job, requiring close attention to details and the use of accurate forecasting techniques for wind, temperature, loading, and traffic conditions From the economic standpoint, one of the most important problems of jet operations lies in the choice, and the ultimate assignment, of cruising altitudes Some of the most important factors in this problem will be explained below

Characteristic Flight-Plan Profiles

For a given air temperature and aircraft weight, there is a definite altitude, known as the optimum altitude, at which a given aircraft will be able to operate at its lowest fuel consumption in pounds of fuel per mile This optimum altitude increases with a decrease in either the temperature or the aircraft weight Because the weight of the aircraft decreases steadily during flight, due to fuel burnoff, the optimum altitude gradually increases Ideally, the aircraft should climb immediately to the optimum altitude, and then be allowed to climb gradually (about 40 feet per minute) to coincide with the rising optimum altitude If wind were not a factor, the use of this drift-up cruise procedure, which is shown as Track A in Fig. 14, would result in the lowest fuel consumption per mile, and thus the greatest range with a given load of fuel

From the air traffic control standpoint, however, the use of drift-up cruising procedures would be quite expensive in terms of airspace, as it would practically rule out the use of altitude separation between aircraft in this stratum Thus, at least for domestic operations where maximum range is not critical, it is expected that aircraft will be required

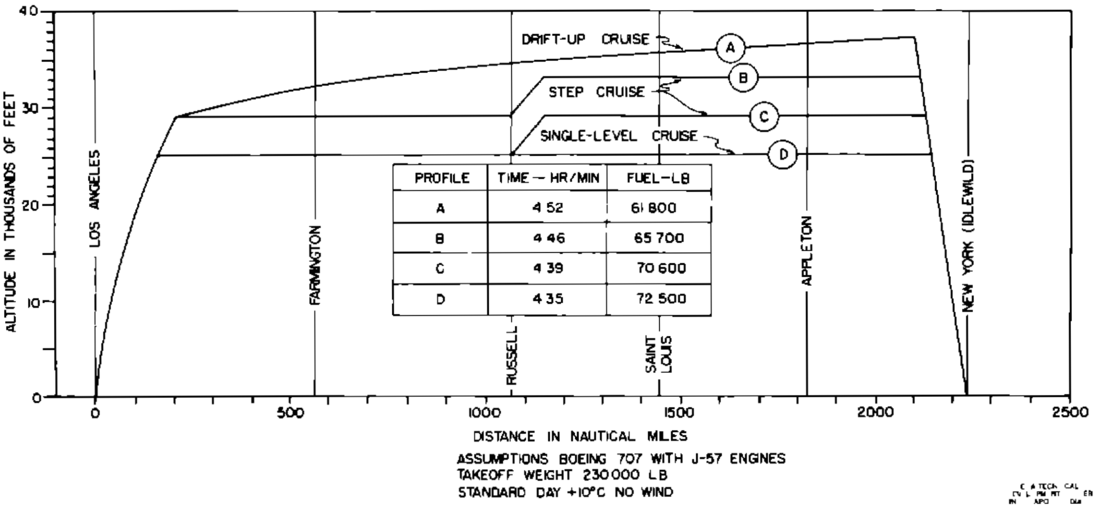


Fig 14 Comparative Time and Fuel Requirements for Some Possible Coast-to-Coast Operations

to conform to constant cruising altitudes, either in step climbs, as shown in Tracks B and C of Fig 14, or in single-level cruise, as shown in Track D of the same illustration

Figure 14 also shows the comparative time and fuel requirements of these flight paths Within this range of cruising altitudes, it will be noted that a decrease in altitude results in a small increase in cruising speed (shown by a decrease in block time) and a large increase in fuel consumption

Speed Limitations

The operating speeds of present civil jet transports are limited by both structural and aerodynamic restrictions, as shown in Fig 15 The normal operating velocity (Vno) of the aircraft in this example is limited to about 350 knots equivalent airspeed (EAS) in order to maintain a conservative safety margin below the never-exceed velocity (Vne) of 383 knots, which is a structural limitation At higher equivalent airspeeds, gust loads could result in damage to the structure

The decrease of air density with altitude allows the true airspeed (TAS) for any given EAS to increase at the rate of about 2 per cent per thousand feet of altitude In Fig 15, the TAS corresponding to the 350-knot Vno increases to approximately 500 knots at 21,000 feet, a speed which corresponds to Mach 0 82 (82 per cent of the speed of sound, at this altitude) Here the aircraft finds itself on the threshold of an aerodynamic limitation, associated with compressibility Beyond this speed, the drag of the aircraft increases sharply At about Mach 0 88 the aircraft in this example would be on the threshold of buffeting, instability, and flutter problems

Pounds Per Hour Versus Pounds Per Mile

Jet engines operate most efficiently at high rpm Their fuel consumption, in pounds per hour at normal cruising rpm, decreases gradually with increasing altitude In level flight at altitudes below 21,000 feet, the engines must be throttled back to prevent the aircraft from exceeding the structural limitation shown in Fig 15 Thus, at low altitudes, the fuel consumption in both pounds per hour and pounds per mile is very high

At the maximum Vno altitude, around 21,000 feet, fuel consumption in pounds per hour still is quite high, so that the consumption in pounds per mile still is rather high

In the normal cruising range of the civil jets, between 21,000 feet and the optimum altitude, the speed of the aircraft is reduced slowly with increased altitude, due to the aerodynamic limitation shown in Fig 15 However, the fuel consumption in pounds per hour decreases at an even greater rate, resulting in a gradual increase in pounds per mile until the optimum altitude is reached

At altitudes above the optimum, the cruising speed drops off rapidly due to reduced thrust Although the fuel consumption in pounds per hour still is decreasing, the net result

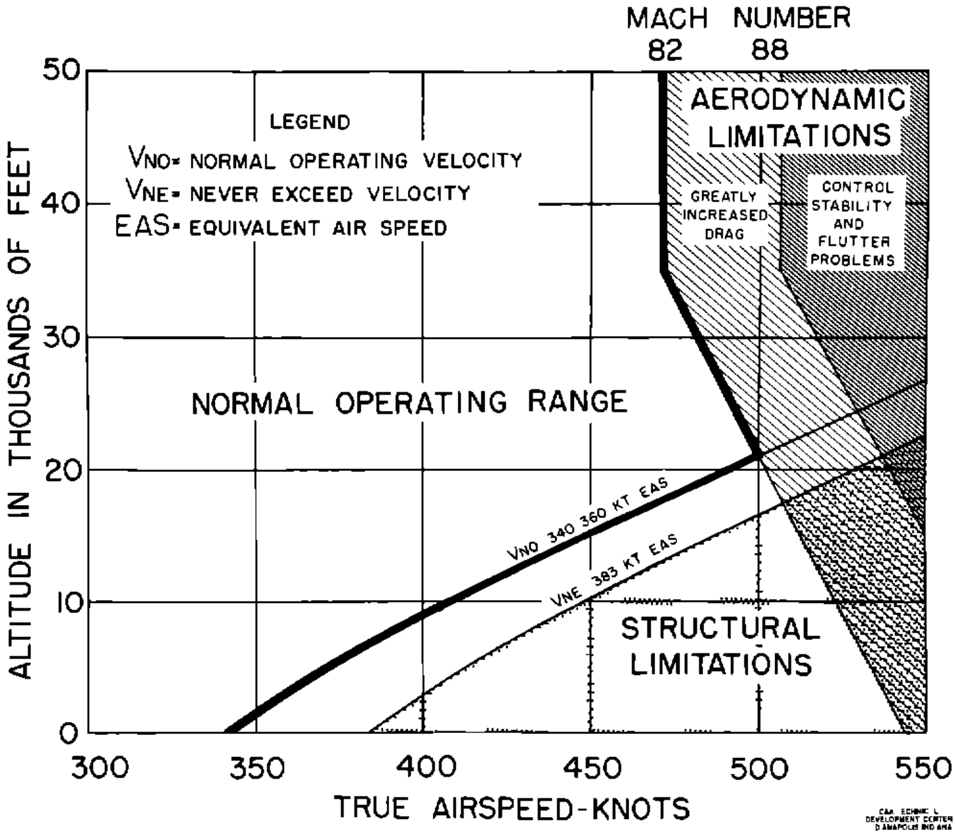


Fig 15 Speed Limitations of a Typical Civil Jet Transport

is a higher consumption in pounds per mile For this reason, civil jets normally will not be operated above their optimum altitude However, because of the relatively low fuel consumption in pounds per hour, operation in this stratum sometimes would be advantageous in losing time en route for traffic control purposes, or in waiting out a weather delay at the destination

Wind and Other Factors.

It must be emphasized that the foregoing explanation does not take into account the effects of wind in the choice of cruising altitude Occasionally, a relatively more favorable wind at some other altitude will provide an over-all gain in ground speed which will produce a net reduction in pounds of fuel per mile

It also should be noted that fuel cost, while large, is only one of the economic factors involved in aircraft operation. When maximum range is not critical, the higher operating speeds possible with lower-than-optimum cruising altitudes tend to reduce the number of crew hours and increase the number of miles per aircraft overhaul, thus offsetting part of the cost of the extra fuel required From the air traffic standpoint, this type of operation also should tend to relieve some of the congestion at the higher optimum altitude levels

System Limitations

The capacity of an air traffic lane can be expressed in simple form by the formula $N = V/S$, where N = number of aircraft per hour, V = average velocity of aircraft in knots, and S = average separation between aircraft in nautical miles Inspection of this formula will show that the capacity can be increased if either the velocity is increased or the separation is reduced If we assume that these two quantities are fixed, the total capacity of an airway system depends ultimately on the number of independent traffic lanes which can be operated simultaneously This leads to what may be the most serious problem in the economical operation of jet aircraft, namely, the scarcity of desirable operating lanes

The number of desirable cruising lanes for long-range operations is reduced first by the sensitivity of the specific fuel consumption to any deviation from the optimum cruising altitude A second limitation is caused by the inherent errors in certain types of altimeters presently in use At the present time, these errors dictate the use of 2,000-foot vertical separation at altitudes above 29,000 feet mean sea level (MSL) This restriction imposes a 50 per cent reduction on the number of cruising levels available in the desirable jet operating region above this level

A further limitation in the number of independent flight paths is caused by azimuth errors in the VOR and TACAN navigation systems In order to straighten high-altitude routes and reduce the number of navigation aids which must be tuned in by pilots flying at high speed, certain facilities spaced up to 360 miles apart have been designated to form a network of high-altitude airways However, because of the increased magnitude of the navigation errors possible between stations this far apart, the width of such airways must be increased proportionately with distance, up to 40 miles This will seriously limit the possibility of providing suitable parallel lanes to separate the civil jets from each other and from the extensive amount of military traffic which already uses this airspace

The economic penalties of off-optimum operations due to basic ATC system limitations will be most pronounced under conditions where takeoff weight becomes a critical factor To load the additional fuel necessary to cope with a lower assigned altitude or a severe climb restriction may require, in many cases, the reduction of payload (passengers and cargo) in order to stay within the maximum allowable takeoff weight for the runway and temperature conditions existing at departure time Even when takeoff weight is not critical, the policy of always carrying a large excess of fuel for such contingencies is in itself quite expensive For example, referring to Fig. 13, suppose the aircraft is loaded with an additional 10,000 pounds of fuel, tc take care of an unfavorable altitude assignment or other ATC restriction Even though no ATC restriction materializes, the additional fuel consumption caused by the increased gross weight will use up 2,000 pounds of this additional load in carrying the remaining 8,000 pounds from coast to coast

APPROACH SYSTEMS

Functions

In common with other forms of traffic, air traffic has an inherently random characteristic, normally, aircraft tend to arrive in bunches, rather than at equally spaced intervals Even though each aircraft in any given airway lane is spaced properly from preceding aircraft in the lane, the total input of aircraft from all lanes into an approach system follows what the statisticians call a Poisson distribution This implies that there are many more smaller intervals than larger ones

The function of an approach system is to accept this input of random types of aircraft, from random routes and altitudes, at random times, and accomplish the following

1 Meter or regulate the flow of traffic to avoid overloading the approach path

2 Establish an optimum arrival sequence, arranging the landing order in such a fashion that each aircraft in the group will have a landing time as close as possible to the time at which it would have been able to land had it been the only aircraft in the air

3 Descend each aircraft from its entry altitude to an altitude at which it can intercept the glide slope for an approach

4 Space each aircraft properly behind the one ahead on the common path to the runway

5 Guide each aircraft to a point where it can intercept the approach course and proceed inbound toward the runway

6 Separate every aircraft properly from every other aircraft during this entire operation This implies the use of at least 3 miles' horizontal or 1,000 feet vertical separation at all times

The ultimate objective of the approach control system is to adjust the arrival time of each aircraft so that it meshes smoothly into the stream of arriving traffic in an orderly landing sequence There are four basic techniques for adjusting the arrival time of aircraft

1 Holding

2 Path-stretching

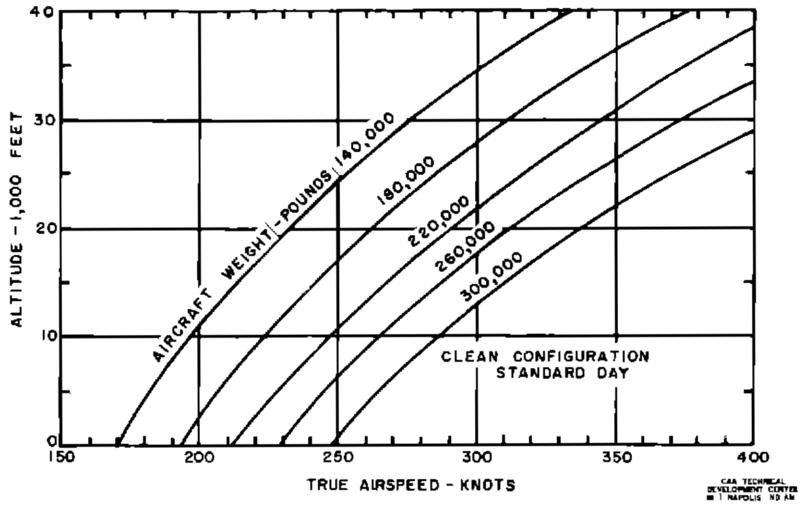


Fig 16 Holding Speeds of a Typical Civil Jet Aircraft

3 Velocity control
4 Preassigned departure time

The first two have been utilized for several years Although the last two are not in general use at this time, simulation tests indicate that they will offer certain advantages in the operation of future systems All four techniques have been studied in connection with their application to the control of jet aircraft The highlights of these studies are reviewed in the following paragraphs

Present Approach Techniques

Holding

Where jet aircraft are concerned, the use of holding patterns to absorb delay presents a number of closely interrelated problems Figure 16 indicates the holding speeds of a typical civil jet transport. Each curve defines what actually is a constant equivalent airspeed for a certain aircraft weight condition Here again the decrease of air density with altitude causes the true airspeed to increase at the rate of about 2 per cent per thousand feet of altitude, with the result that high holding altitudes dictate the use of high holding speeds

The airlines have indicated that, for passenger comfort, they do not want their jet aircraft to exceed a 30° bank angle at any time As shown in Fig 17, this limitation will

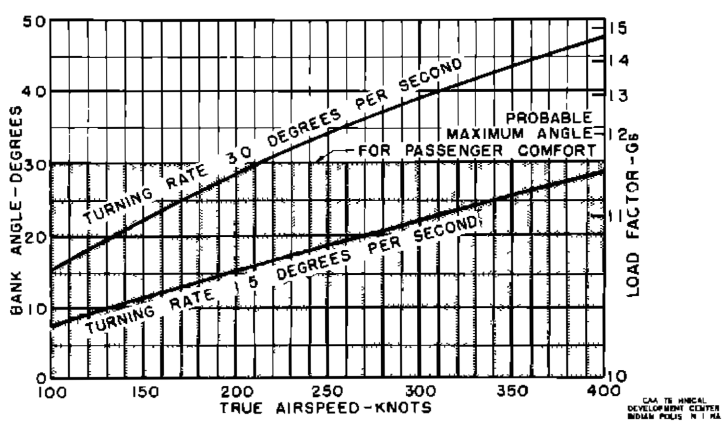


Fig 17 Relationship Between True Airspeed, Bank Angle, Turning Rate, and Load Factor

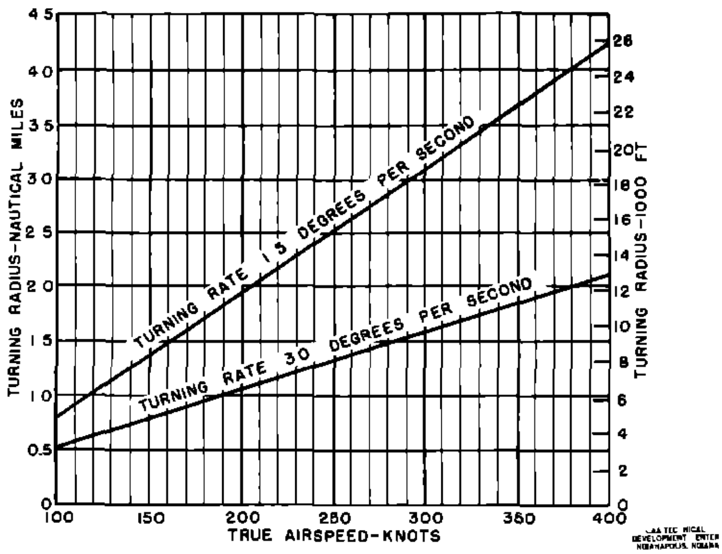


Fig. 18 Relationship Between True Airspeed, Turning Rate, and Turning Radius

prevent the use of standard-rate (3°-per-second) turns at speeds above 210 knots The high holding speeds characteristic of high-altitude holding operations will result in the use of half standard-rate (1 5°-per-second) turns, thus increasing the turning radius, as shown in Fig 18

Present holding area standards reserve an area of approximately 132 square miles for an aircraft in a 1-minute, low-altitude holding pattern The TSO holding area dimensions are doubled above 19,000 feet and tripled above 29,000 feet in order to compensate for the higher true airspeeds at the higher altitudes As a result, the present 2-minute holding pattern at 30,000 feet uses an area of 1,245 square miles, which is just 3 square miles less than the area of the State of Rhode Island

Actual radar checks of military jet holding operations indicate that, although most aircraft stay well within the length of the present holding airspace reservations, some of them get outside laterally, particularly in overshooting the holding area on their original entry from certain directions

Already the airspace reserved for holding operations puts a severe restriction on airway operations in the vicinity of complex terminal areas From the ATC viewpoint, these areas can hardly afford to be increased in size A better approach to this problem would be to develop new flight techniques to permit the pattern size to be reduced. Figure 19 illustrates a DME navigation technique, which has worked out well in simulation, to reduce the amount of airspace required for holding It appears that such procedures will become more necessary with the advent of civil jet aircraft.

Figure 20 shows the fuel consumption of a typical jet transport when holding at different altitudes and weight conditions It will be noted that the fuel consumption for any weight condition increases as the aircraft reaches lower altitudes For this reason, it formerly was considered essential that all jet holding be accomplished at an altitude of 20,000 feet or above However, dynamic simulation tests have brought out an extremely important fact--that airport acceptance rates can be increased considerably if jet holding altitudes at the feeder fixes are reduced Using a twin-stack system, a 100 per cent sample of jet aircraft was fed to an airport from holding altitudes of 20,000, 10,000, and 4,000 feet. Figure 21 shows the results of these tests

The increase in acceptance rates, as holding altitudes are reduced, is due to several factors. One important consideration is that the maximum descent rates of passenger-carrying civil jets will be limited to about 3,000 feet per minute. Assuming that the descent rate is fixed, the time required to complete an approach from the feeding fix to the airport is a function of the amount of altitude which must be lost, and the length of the shortest approach path which can be employed is a function of approach time and the average speed on this path To descend through 20,000 feet of altitude, the typical civil jet requires an approach path 40 to 50 miles long

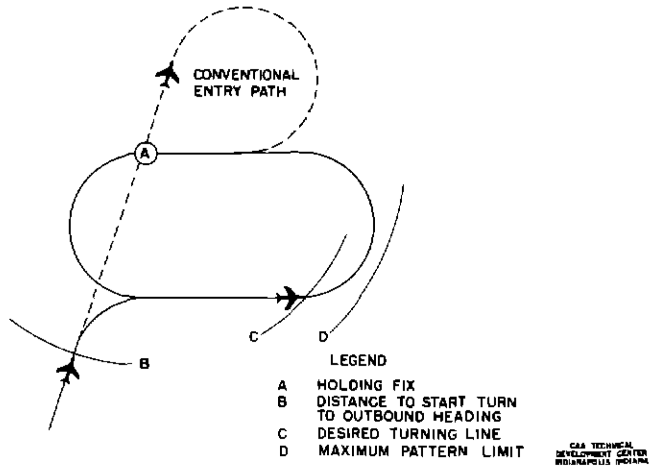


Fig. 19 Use of Distance Information to Reduce Holding Airspace

As shown in Fig 22, long approach paths tie up a large amount of maneuvering airspace, and require a large number of aircraft to be on approach simultaneously in order to keep the approach lane operating at full capacity Tests show that the more aircraft there are in the approach pattern, the higher the communications workload and the more inaccurate is the controller's final approach spacing This is because the controller's attention is divided between a larger number of aircraft so that he has less time to do a precise spacing job In addition, longer approach paths increase the opportunity for deviations in speed to affect the spacing between successive aircraft

The normal variation in true airspeed during descent at a constant indicated airspeed is intensified by the use of high approach altitudes This factor makes prediction and spacing operations extremely difficult for the radar controller Simulation tests show that all of these problems can be reduced by having aircraft leave the holding fix at low altitudes where normally they already will be slowed almost to approach speed

To conserve fuel during unusually long delays, such as those due to communications failure, lost aircraft, a blocked runway, or weather temporarily below landing limits, it still

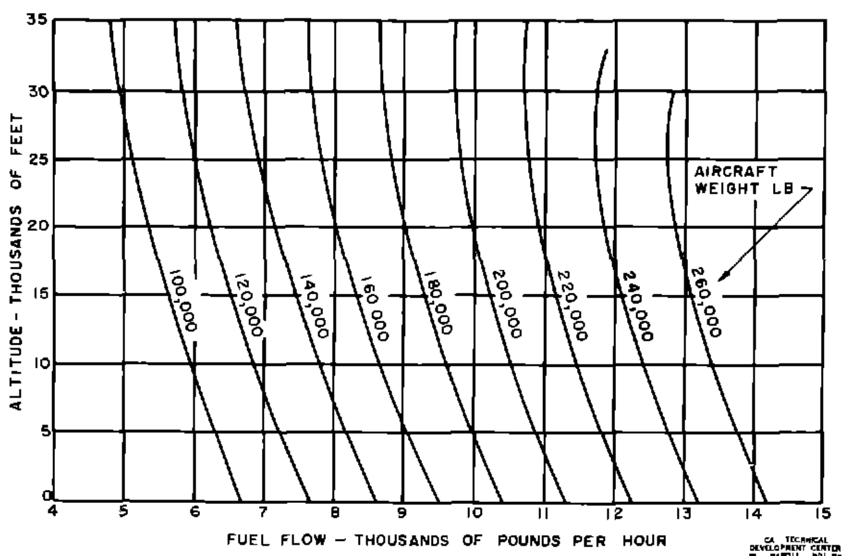


Fig. 20 Effect of Altitude and Weight on Fuel Consumption of a Typical Jet Transport, Holding in Clean Configuration (Gear and Flaps Up)

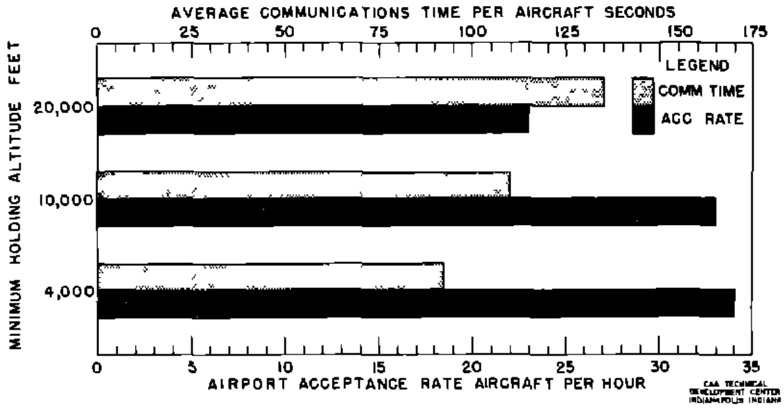


Fig 21 Effect of Jet Holding Altitude on Communications and Traffic Flow

will be advantageous to hold jet aircraft at high altitudes, preferably at fixes about 50 miles away from the destination airport To maintain a high acceptance rate when normal operations are resumed, such aircraft should be recleared to the feeder fix and descended en route to enter the terminal area at about the same altitude as other types of civil transport aircraft In most cases, the use of en route descent procedures will require radar coverage of the descent area

Figure 23 shows the importance of a relatively small change in airport acceptance rate on aircraft delays under saturated traffic conditions Under heavy traffic conditions, the decreased delays made possible by reducing the holding altitude of jet aircraft will more than compensate for the increased fuel consumption of such aircraft while at lower altitudes

A potential disadvantage of low-altitude holding is the additional fuel cost (or loss in range) in case the aircraft gets down to low altitude and then has to divert to its alternate airport. Typical penalties caused by diversions from different altitudes are compared in Fig 24 If diversion becomes necessary, it will be advantageous for the pilot to make his decision as early as possible, and to cruise as high as possible to his alternate airport However, high-altitude holding does not eliminate the risk of a possible low-altitude diversion, since the weather still can go below landing limits during the 8 minutes or so which is required to make an unrestricted descent from 20,000 feet.

In Fig 23, the number of aircraft which are being delayed at any time can be determined by counting the number of horizontal delay bars which are crossed by a vertical

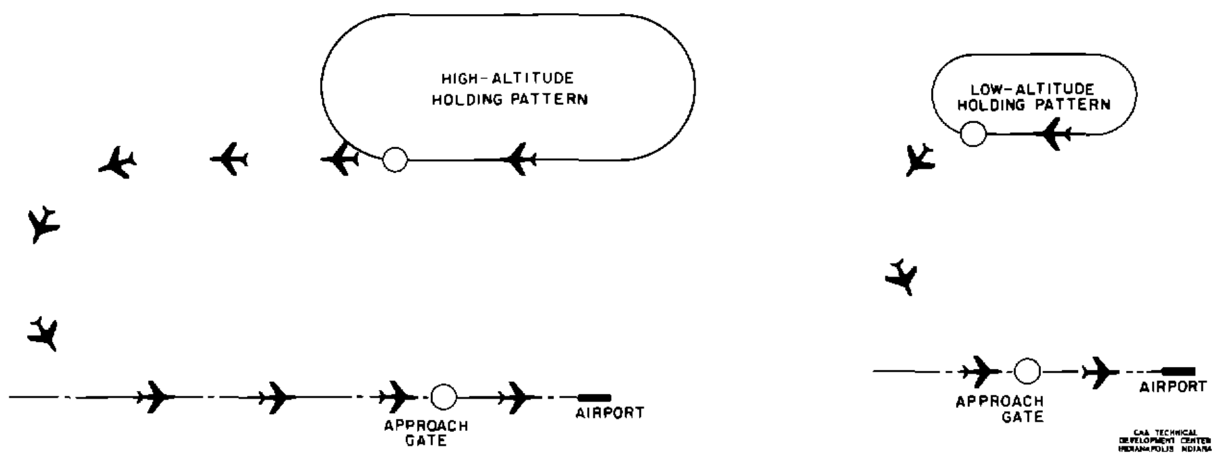


Fig 22 Effect of Holding Altitude on Size and Population of Radar Approach Pattern

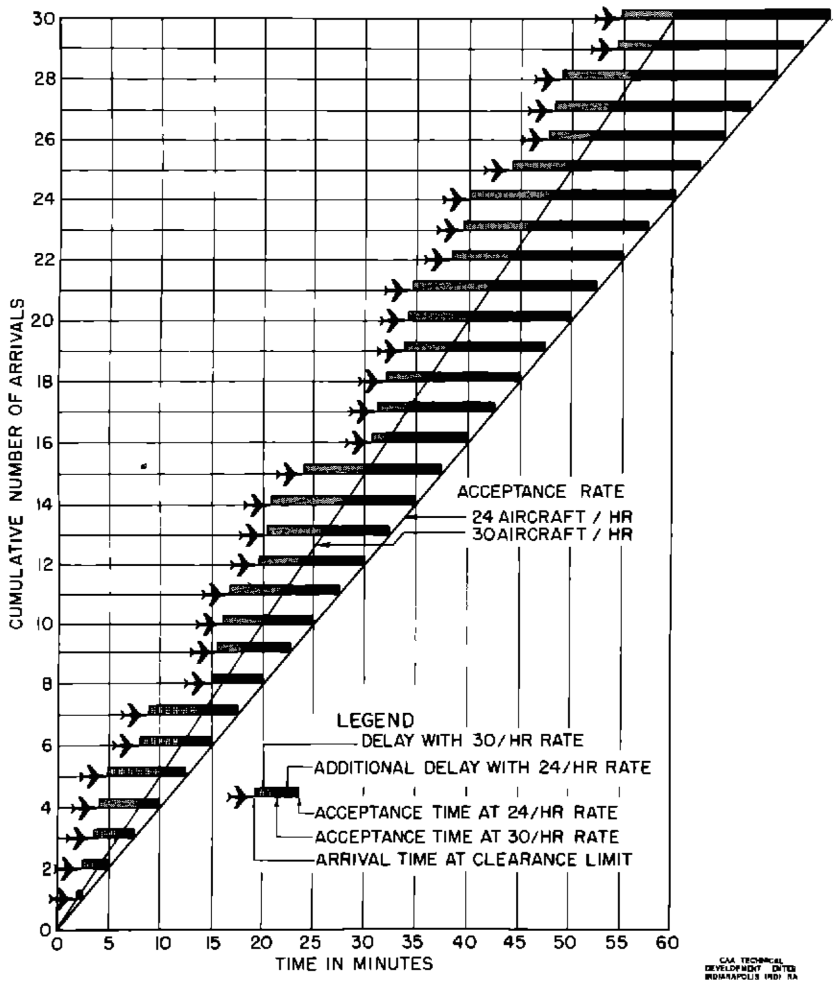


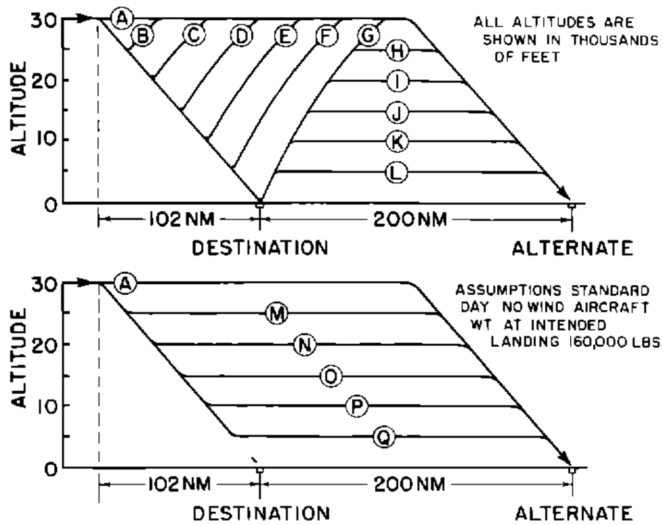
Fig. 23 Buildup of Delays to Random Arrivals Under Saturated Traffic Conditions

line at any particular time in question This feature makes it possible to analyze the effects of a sudden closing of the airport on the various aircraft involved

Suppose, for example, that 30 aircraft, including a goodly proportion of jets, expect to arrive at the airport within the next hour The weather conditions are deteriorating, and are forecast to go below authorized landing limits within the hour Should the jets be held at high altitude, restricting the acceptance rate to about 24 aircraft per hour, or should they be descended en route to feed off the holding patterns at low altitude and thus maintain a high acceptance rate?

Assume that the airport finally goes below limits at 47 minutes after the hour, and that all aircraft which have not landed by that time must be diverted to their alternate airports The effects of this situation on the aircraft concerned are listed in Table I

In any case, the pilot should decide, before he leaves 20,000 feet, whether or not he has enough fuel to risk a possible diversion from low altitude in case the weather closes in before his landing If the low-altitude holding procedure is in use, this decision must be made 10 to 15 minutes earlier than necessary with the high-altitude procedure However, once the decision to descend below 20,000 feet is made, the probability of holding in vain and then having to divert is greatly reduced if the low-altitude procedure is adopted Therefore, this strategy appears much more desirable from the probability of successful flight completion, as well as for purely economic reasons in minimizing delays to all aircraft using the approach system



PRO-CEDURE	PROFILE	ALTITUDE AT WHICH DIVERSION STARTED	CRUISING ALTITUDE TO ALTERNATE	PENALTY COMPARED TO PROFILE 'A"	
				FUEL POUNDS	TIME MINUTES
-	A	30	30	-	-
CLIMB BACK TO CRUISING ALT	B	25	30	40	1 2
	C	20	30	180	1 9
	D	15	30	290	3 2
	E	10	30	550	4 5
	F	5	30	900	6 4
CLIMBOUT AFTER MISSED APPROACH	G	0	30	1260	10 4
	H	0	25	1500	7 6
	I	0	20	1930	6 6
	J	0	15	2310	7 4
	K	0	10	3510	7 4
	L	0	5	3810	9 9
NO CLIMB	M	25	25	790	-0 4
	N	20	20	1510	0 3
	O	15	15	2290	2 5
	P	10	10	3090	4 9
	Q	5	5	3740	7 9

Fig 24 Typical Diversion Profiles Showing Effects of Altitude and Procedure on Time and Fuel Required

TABLE I

AIRCRAFT DELAYS AND DIVERSIONS
(See Fig 23)

		Jet Holding Procedure High Altitude	Jet Holding Procedure Low Altitude
A	Acceptance rate, aircraft/hour	24	30
B	Number of aircraft landed before 47	18	23
C	Number of aircraft diverted to alternate airport	12	7
D	Total delay to all aircraft before 47, minutes	199	96
E	Number of aircraft which held but did not complete approach	7	2
F	Total holding time of aircraft in line E, minutes	65	10
G.	Maximum delay to any aircraft in line E, minutes	13	7

Path-Stretching

The technique of controlling the length of a flight path, through the issuance of heading instructions to the aircraft, is known as path-stretching Used in conjunction with a properly arranged feeding system, this useful radar technique permits the controller to adjust the spacing between successive aircraft with a high degree of precision

Figure 25 shows a few of the approach system configurations which have been tested during the jet simulation study The overhead pattern shown on the left is an improvement over the conventional military jet teardrop penetration pattern Although the teardrop pattern works satisfactorily for isolated aircraft, it is poorly adapted to high-density approach operations, since it provides no room for adjusting the spacing of a jet aircraft behind a

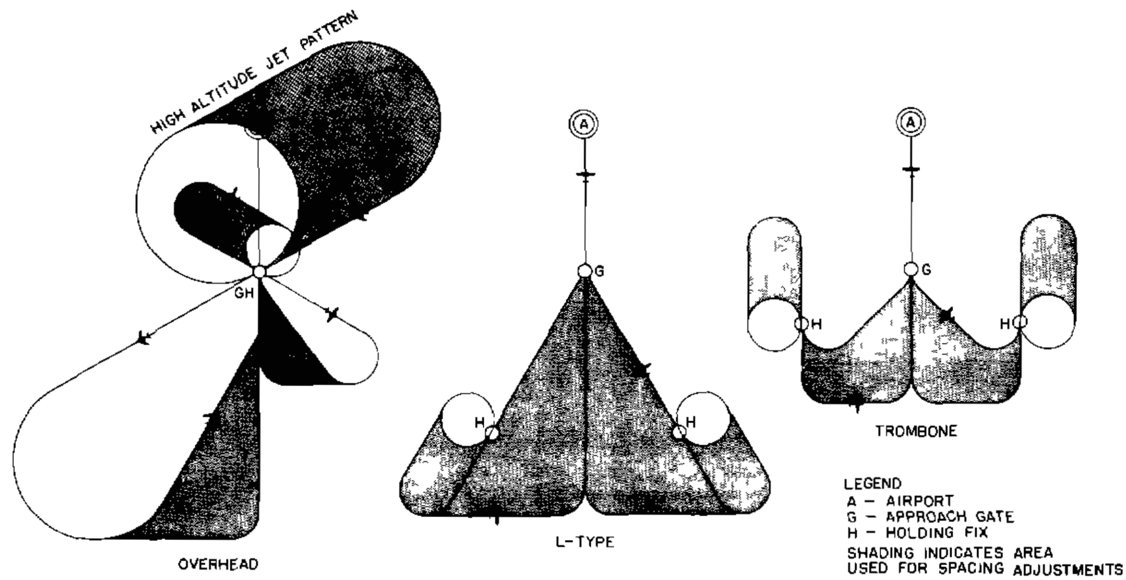


Fig 25 Types of Twin-Feed Approach Systems

preceding aircraft Simulation tests show conclusively that the provision of a base leg (a segment of the approach path approximately 90° from the final approach) is essential for the attainment of precision in manual radar approach-spacing operations.

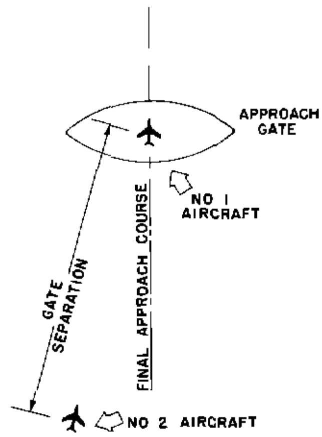
The double overhead pattern shown in Fig 25 permits the segregation of jet and piston-engine approaches on opposite sides of the final approach course This feature simplifies control operations somewhat by minimizing overtaking problems in the maneuvering area. However, the double-L and the trombone patterns shown in Fig. 25 have been developed to a higher degree of refinement during the past several years of simulation, and have been found to be well adapted for the control of jet aircraft

In general, simulation tests have shown that holding fixes and approach paths should be so arranged as to permit easy transition to the final approach course, adequate room for descent, and space for a base leg for precise path-stretching operations To reduce the effects of speed differences between successive aircraft, the final approach path should be as short as possible, consistent with the ease of obtaining proper alignment of the aircraft on the final approach course The use of a twin-feed arrangement permits the workload to be shared by two radar controllers and also cuts delays due to aircraft descent time

During the course of the simulation program, spacing tables, such as that shown in Fig 26, have been developed as a guide to the radar controller in path-stretching operations These tables show the amount of separation which must be provided at the beginning of the final approach path to insure a positive separation of 3 miles all the way down the final approach The table compensates for the effect of deviations in speed between aircraft of the same type, as well as differences in speed between aircraft of different types Figure 27 shows how the desired separation can be achieved by path-stretching techniques, using a series of circular reference lines marked on the radar display

Simulation tests indicate that the use of 1.5°-per-second (half-rate) turns by jet aircraft in the approach pattern has a detrimental effect on path-stretching operations The relative lack of maneuverability of aircraft turning at this rate forces the controller to use much more space for path-stretching operations, and forces him to peel aircraft off the holding pattern earlier to make sure they will be in a position for radar spacing operations at the proper time This forces the controller to use much more space for path-stretching operations and also requires him to commit himself earlier on every decision he has to make

In addition, the increased length of the approach pattern requires more aircraft to be in the pattern simultaneously in order to keep the final approach path operating at full capacity The additional aircraft increase the radar vectoring and communications workload and



OPTIMUM AIRCRAFT SPACING

DISTANCE APPROACH GATE TO TOUCHDOWN, 5 MILES

AIRCRAFT SEQUENCE NO 1	NO 2	GATE SEPARATION (MILES)
S	M	5 1
S	F	5 5
S	J	6 6
M	S	3 1
M	F	4 5
M	J	5 8
F	S	3 0
F	M	3 5
F	J	5 2
J	S M F	3 0
SAME TYPE		4 0

AIRCRAFT CATEGORY		APPROX APPROACH SPEED MPH	KT
S	SLOW	120	104
M	MEDIUM	140	122
F	FAST	150	130
J	JET	180	156

Fig 26 Spacing Table Used in Approach Control Operations

divide his attention further As a result, the spacing accuracy possible with path-stretching techniques is reduced, and the acceptance rate suffers accordingly

Tests show that the entire approach-spacing operation can be simplified immensely if the aircraft in the approach pattern can be slowed to a speed at which they can make standard-rate, 3°-per-second turns

Future Approach Techniques

Velocity Control

Whenever the traffic input exceeds the acceptance rate, delay is inevitable From the ATC standpoint, holding stacks form a convenient reservoir of excess aircraft requiring no

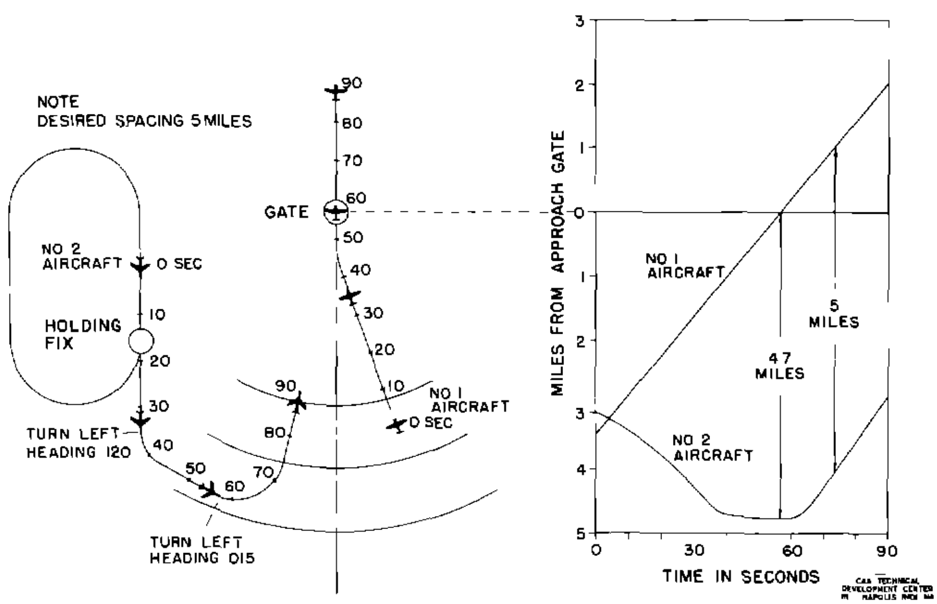


Fig 27 Example of Approach Spacing Procedure

navigational guidance by the controller, and very little controller effort to maintain separation from each other However, holding stacks sometimes tie up valuable airspace within the terminal area, particularly in cases where the holding airspace extends outside the boundary of the associated airway. As a possible means of minimizing low-altitude holding in congested terminal areas, considerable simulation work has been devoted recently to an approach system incorporating preassigned landing reservations, and utilizing velocity control during the last 100 miles or so of the flight to absorb most of the delay.

A special slide-rule computer known as ASCON (arrival scheduling control) is used in the simulation of this system Starting with the optimum speed and deceleration program for each aircraft, ASCON computes the time the aircraft would arrive if it were the only aircraft in the area In determining this theoretical arrival time, the computer also takes into consideration the altitude and allowable descent rate of the aircraft, in order to insure that it will have adequate time to descend to the airport Starting with the theoretical arrival time, the controller then checks the list of landing reservations and reserves the first available time slot. The computer then indicates what ground speed should be made good by the aircraft in order to arrive on its assigned schedule, taking into consideration the normal speed and descent capabilities of the aircraft

Further progress reports can be inserted into the computer to provide speed adjustments for greater precision In cases where the aircraft cannot fly slowly enough to absorb all the delay en route, the computer indicates the need for an en route delay maneuver, or determines the time at which the aircraft should leave any holding fix on the way in order to meet the assigned delivery time.

Simulation tests show that the establishment of a definite landing reservation for each aircraft does not, in itself, increase the airport acceptance rate However, it is apparent that the "derandomization" of arriving traffic simplifies the approach control operation immensely by metering the flow of arrivals to a steady rate which can be accommodated easily by the radar approach system

Tests indicate that the precision possible with velocity control alone is not as high as that attainable by path-stretching. This is because the effectiveness of velocity control decreases progressively as the aircraft approaches the destination, while the usefulness of path-stretching is maintained right up to the approach gate For this reason, it appears that the use of offset approach courses, with the ability to make last-minute path-stretching adjustments if necessary, still will be desirable even in a system which utilizes velocity control as a primary concept

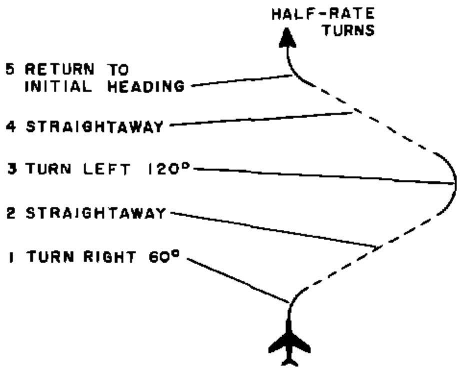
As previously discussed, the decrease of air density with altitude increases the true airspeed which is necessary to maintain a given equivalent speed This factor increases the minimum usable speed and thus reduces the range of speeds which can be employed for any aircraft at higher altitudes The decreased range of usable speeds reduces the effectiveness of velocity control by reducing the amount of delay which can be absorbed during high-altitude en route flight on any specific segment of the airway For example, slowing a jet aircraft down to its minimum operating speed at a high altitude, 80 miles from touchdown, delays its landing time only about 4 minutes

The shortest conventional holding pattern is a 360° turn which, if made at high altitude at the rate of 1 1/2° per second, delays the aircraft approximately 4 minutes To provide additional flexibility in adjusting the arrival times of jet aircraft, a series of delay patterns, shown in Fig 28, has been developed These patterns allow the aircraft to absorb various amounts of delay in 1/2-minute increments Normally, these patterns would be used only at minimum operating speed, to absorb small amounts of delay in excess of that which could be absorbed by slowdown alone The amount of excess delay in this case would be computed by the ASCON and issued to the pilot, who first would slow the aircraft and then fly the appropriate delay pattern

Normally, delay patterns would be made to the right unless otherwise advised by the controller If the excess delay were more than 3 1/2 minutes, some combination of 180° or 360° turns would be used instead to reduce the amount of airspace required for the delay maneuver Preliminary tests indicate that the delay patterns are easy to calculate and fly

Test results show that the use of preassigned landing reservations produces a very orderly flow of inbound traffic and drastically reduces the amount of holding operations within the terminal area In high-density simulation tests, many jets are able to make practically unrestricted descents from 20,000 feet, without degrading the acceptance rate of the approach system

It should be pointed out that these tests were made primarily to observe the concept of arrival scheduling control in operation and to determine the system requirements for such an



MINUTES	
DELAY	STRAIGHTAWAY
0 5	0
1	0 5
1 5	1
2	1 5
2 5	2
3	2 5
3 5	3
4	MAKE 360° TURN

Fig 28 Jet Delay Patterns

operation The actual design of an operational system with enough information-handling capacity to do this job properly will require additional research and development in the fields of automatic tracking, computers, and data links Meanwhile, the general idea looks very promising

Preassigned Departure Time

If the concept of setting up a definite landing reservation for each aircraft is considered, and the scheduling control is carried back farther and farther from the destination airport, ultimately the stage is reached where the departure time is controlled in order to make good a definite landing reservation

In view of the limited amount of information storage and processing capacity in the present manually controlled ATC system, the idea of preassigning departure times in order to mastermind the entire flow of traffic in advance may seem far-fetched at this time However, with a general trend toward shorter elapsed times and higher operating costs, the ability to absorb most traffic delay on the ground, prior to takeoff, someday may become a very attractive proposition for large jet aircraft with direct operating costs approaching 1,000 dollars per hour. The realization of such a concept would, of course, depend upon the development of a highly complex tracking, computing, and data-processing system

Sequencing Procedures.

In operating present radar approach systems without definite landing reservations, the sequencing or arrangement of the landing order of the individual aircraft is not planned very far in advance Instead, it is worked out by the approach controllers as required, usually on a first-come, first-served basis, depending on the positions of the various aircraft with respect to the approach gate Since the input to the terminal area in such systems is unscheduled, the flexibility provided by this arrangement is desirable, in that the controllers do not have to commit the aircraft to a definite landing order until the situation has developed to the point where the proper order is quite easy to determine and control

In simulating the operation of advanced approach systems utilizing a predetermined landing reservation for each aircraft, it was found that the procedure used in obtaining these reservations had a decided effect on the distribution of delays to the various types of aircraft using the system For this reason, a number of different methods of sequencing aircraft were explored, to determine their relative advantages as well as their applicability to future approach systems using digital computers Comparative tests were made of three widely different procedures in which landing reservations for individual aircraft were assigned on the following bases

1 First-come, first-served on arrival at outer check point.
2 First-come, first-served at touchdown, based on best possible estimated arrival time of each aircraft
3 Controlled priority

The significant differences in the operation of these procedures, and their effects on the distribution of aircraft delays, are detailed below Results are listed in Table II.

TABLE II

EFFECT OF VARIOUS SEQUENCING PROCEDURES
ON DISTRIBUTION OF AIRCRAFT DELAYS

	Sequencing Method	Per Cent of Total Delay by Class			
		Jet	Fast	Medium	Slow
1	First-come, first-served at 80 miles from touchdown	44	35	18	3
2	First-come, first-served at touchdown (based on ETA)	26	29	23	22
3.	Priority for jets, other aircraft first-come, first-served at touchdown (based on ETA).	2	35	33	30

Input - 30 aircraft per hour, total 200
Equal number in each speed class
Random distribution of entry times and speed classes

Note Total delay remained the same in each case

1. When aircraft were sequenced on the basis of first-come, first-served at reporting points about 80 miles from touchdown, there was a large disparity between the delay to various types of aircraft, with faster aircraft consistently receiving longer delays than the slower types Analysis showed that this was caused by the fact that slower aircraft checked into the system farther ahead of their estimated arrival time at the airport than did the faster aircraft Thus, many of the landing slots already were reserved when the faster aircraft checked in at the same check points, so that these aircraft received proportionately longer delays.

2 When the landing sequence was preplanned on the order of first-come, first-served at touchdown, based on the estimated arrival time of each aircraft, it was found that the delays were much more evenly distributed This procedure produced a much more democratic arrangement, much better for the jet aircraft than the results of procedure 1, and relatively straightforward and easy to program on an approach computer

3 Based on the premise that it may not always be in the best public interest to distribute delays equitably among all types of aircraft, another procedure was tried in which jet aircraft received first priority and all other aircraft were handled on the basis of first-come, first-served at touchdown This procedure expedited the arrival of the jet aircraft at the expense of somewhat longer delays to the other aircraft using the system

Dual-Lane Approach Systems

Figure 29 points up the extremely great increase in spacing accuracy which is required to increase the acceptance rate of an approach system This implies that the design of high-capacity systems can be simplified by the use of multiple approach lanes with relatively low spacing accuracy, rather than by the use of a single approach lane with extremely high accuracy.

To achieve an acceptance rate of 60 landings per hour, using one runway and a reduced separation standard of 2 miles, a system accuracy of plus or minus 4 seconds at the delivery point would be necessary Such accuracy is far beyond the capability of present manual approach systems, and probably would be extremely difficult to achieve in automatic or semiautomatic systems, inasmuch as it must embrace the errors of all the elements of the control loop shown in Fig 1

The addition of a second approach lane would enable the system to handle the total demand rate by landing 30 aircraft per hour on each runway. With the same separation standard, the system accuracy could be relaxed to plus or minus 33 seconds, a value well within the capability of human controllers By increasing the spacing between aircraft in the same approach lane, it also would tend to reduce the effects of turbulence behind large jet aircraft Although these effects are not clearly defined at the present time, recent studies

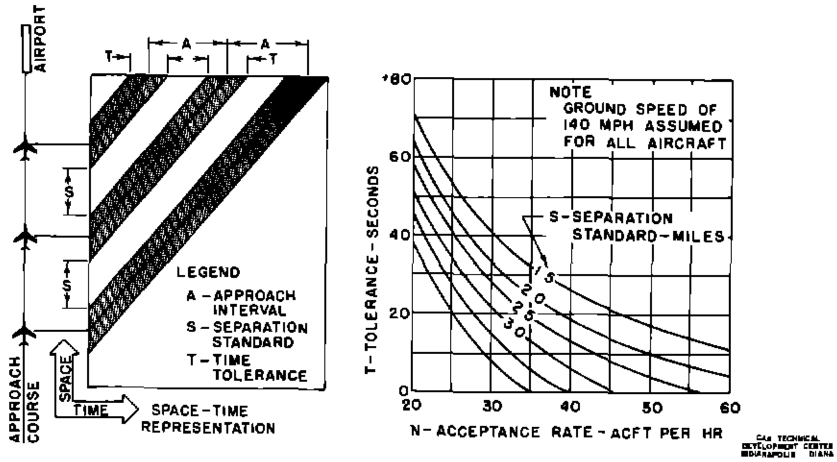


Fig 29 Relationships Between Acceptance Rates, Separation Standards, and Time Tolerances Required for Approach System

in England indicate that such turbulence persists over a period of at least 2 minutes and, under certain conditions, can form a hazard to the operation of smaller aircraft following closely in the same lane.

It is true that a dual approach system would require relatively high navigational accuracy to prevent interference between aircraft in opposite approach lanes However, extensive simulation tests of dual-approach systems, backed by flight tests of approaches into parallel lanes about 6,000 feet apart at Chicago O'Hare Airport, indicate that the turn-on is potentially the most hazardous part of the procedure, that once the aircraft are established on their respective ILS courses, with adequate monitoring by radar, there is little possibility of interference between aircraft in opposite lanes Tests indicated that any hazard due to over-shooting the turn-on can be eliminated by placing the turn-on points opposite to each other, and far enough away from the approach gate so that aircraft turning into opposite lanes can have altitude separation from each other until they are established on their respective ILS courses

CONCLUSIONS

During the past few years, the philosophy regarding the integration of civil jet aircraft into the ATC system has ranged all the way from the idea that jet aircraft should receive special priority to the idea that such aircraft should be handled in precisely the same manner as other aircraft Reviewing these philosophies in the light of TDC simulation studies up to this time, it appears that the civil turbojet transport can be handled most expeditiously, safely, and efficiently through the use of procedures similar to those now used in controlling other civil transport aircraft

In cases where jets cannot be cleared for unrestricted climbs on course, the use of tunnels should be preferable to detours. The higher and shorter the tunnel, the smaller the penalty in jet fuel and flight time

If it becomes necessary to conserve fuel while waiting out long delays, jets should hold at high altitudes However, the use of high-altitude holding patterns to feed present types of civil jet aircraft into an approach lane results in an extremely long, inefficient approach pattern Reducing jet holding altitudes at the feeding fix results in considerably shorter approach patterns, leading to higher acceptance rates In high-density approach operations, this reduces arrival delays to override the effects of increased low-altitude fuel flow, and thus produce an over-all saving in fuel

Many of the problems associated with high-altitude feeding systems could be alleviated by the development of jet aircraft with the ability to descend at extremely high vertical rates but relatively low forward speeds. This combination of flight characteristics would decrease the length of the approach path and enable the aircraft to make approach from high altitudes without reducing the over-all acceptance rate

The development of advanced approach systems using preassigned landing reservations will greatly reduce the amount of low-altitude holding by present types of jet aircraft without reducing the acceptance rate of the approach system.

Path-stretching is the most precise method of adjusting approach intervals, and probably still will be required in future types of approach systems which utilize velocity con trol as a primary concept The precision, and therefore the acceptance rate, of approach-spacing operations can be improved if the civil jets can be slowed to a speed at which they can make standard-rate turns

To insure the safe, efficient integration of civil jet aircraft into the present ATC system, it is desirable that operations personnel understand the special characteristics and limitations of such aircraft. Although the material in this report is correlated into the broad context of systems engineering, the authors have made a special effort to present these data in a form which can be used readily by operations personnel, as well as by persons engaged in systems design or other planning activities