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STRATEGIC CONTROL ALGORITHM DEVELOPMENT
Volume IIA: Technical Report

R. L. Erwin
M. J. Omoth
W. H. Galer
D. Hartnell
A. L. Yarrington et al.

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16. Abstract

The technical report presents a detailed description of the strategic control functional objectives, followed by a presentation of the basic strategic control algorithm and how it evolved. Contained in this discussion are results of analyses that constrain the design and operation of the strategic control algorithm and a description of the model developed to simulate strategic terminal area operation in order to develop and evaluate the algorithm. The data processing sizing requirements and the application of the strategic control algorithm in terms of time periods and airspace to be served are presented with an overall summary of the benefits of the system. Finally, a proposed research, development, test, and evaluation plan is detailed for developing the strategic control system capabilities for implementation as the primary air traffic management technique for high-density air routes and terminal areas.

Volume IIA includes sections 1 through 5 inclusive. Volume IIB includes sections 6 through 9 inclusive.

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PREFACE

The Strategic Control Algorithm Development program is a first study in the evolution of the strategic control concept. Previous work accomplished during the concept formulation stage of the Advanced Air Traffic Management System (AATMS) indicated that this technique held potential benefit for accommodating high traffic demands projected for the 1990's and beyond. The present effort explored the feasibility of basic strategic arrival control via analysis and fast-time simulation. This work included the design of a basic arrival control algorithm which accomplished sequencing, scheduling and generation of conflict-free four-dimensional flight paths for assignment to each arrival in the demand scenario.

In addition to the basic algorithm design and testing, tasks were accomplished to determine potential airports for application of strategic control; assess the resulting benefits; make a preliminary estimate of data processing requirements; and refine the concept. A Research, Development, Test and Evaluation (RDT&E) program was also developed.

In accomplishing this study it was necessary to provide an integration of technologies in the study team. As strategic control is primarily designed for automatic operation, it is necessary to understand airplane performance capability, wind and temperature effect, avionics capability, and computing technology, as well as comprehensive understanding of the Air Traffic Control environment. Successful integration of these technologies resulted in considerable insight into the requirements imposed on strategic flight path generation.

In the future, the evolution of the strategic control concept will require studies designed to establish the feasibility, requirements, and algorithms for strategic departure and en route airplanes. Further refinement of the basic arrival strategy and means of accommodating system perturbations will need to be accomplished. Real-time simulations, including those using strategically equipped airplane(s) will provide a logical test-bed for concept demonstration and testing.

The work of the following personnel is acknowledged: A.F. Norwood, Chief, ATC and Electronics, representing the executive level and ensuring full company support to the program and coordination with other Boeing ATC-related activities; E.A. Delanty, algorithm design; R.W. Schwab, evaluation model design; S.G. Datar, evaluation model design; R.O. Barnes, terminal and airspace requirements; E.A. Olmstead, data processing requirements; J.T. Burghart, benefits analysis; J.M. Bedregal, programming and analysis; W.L. Chu, programming and analysis; H.F. Lee, programming and analysis; E.D. Ramer, programming and analysis; J.M. Sherwin, programming and analysis supervision; R.L. Swanson, programming and analysis; J. Yonekawa, engineering support.

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1.0 INTRODUCTION

The technical report of the study presents a detailed description of the work performed in the study. The report is organized according to the specific tasks performed. Figure 1-1 shows the study plan. A summary of the study including significant results, conclusions, and an overview is given in volume I—Summary Report. The analyses, results, and data for all of the tasks are fully described in this volume. Each individual task is described separately. The description is self-contained and does not require reference to other areas of the report. Tasks are described sequentially by task number and not in time order. The details of the strategic algorithm and the evaluation model computer programs are discussed in volumes III and IV.

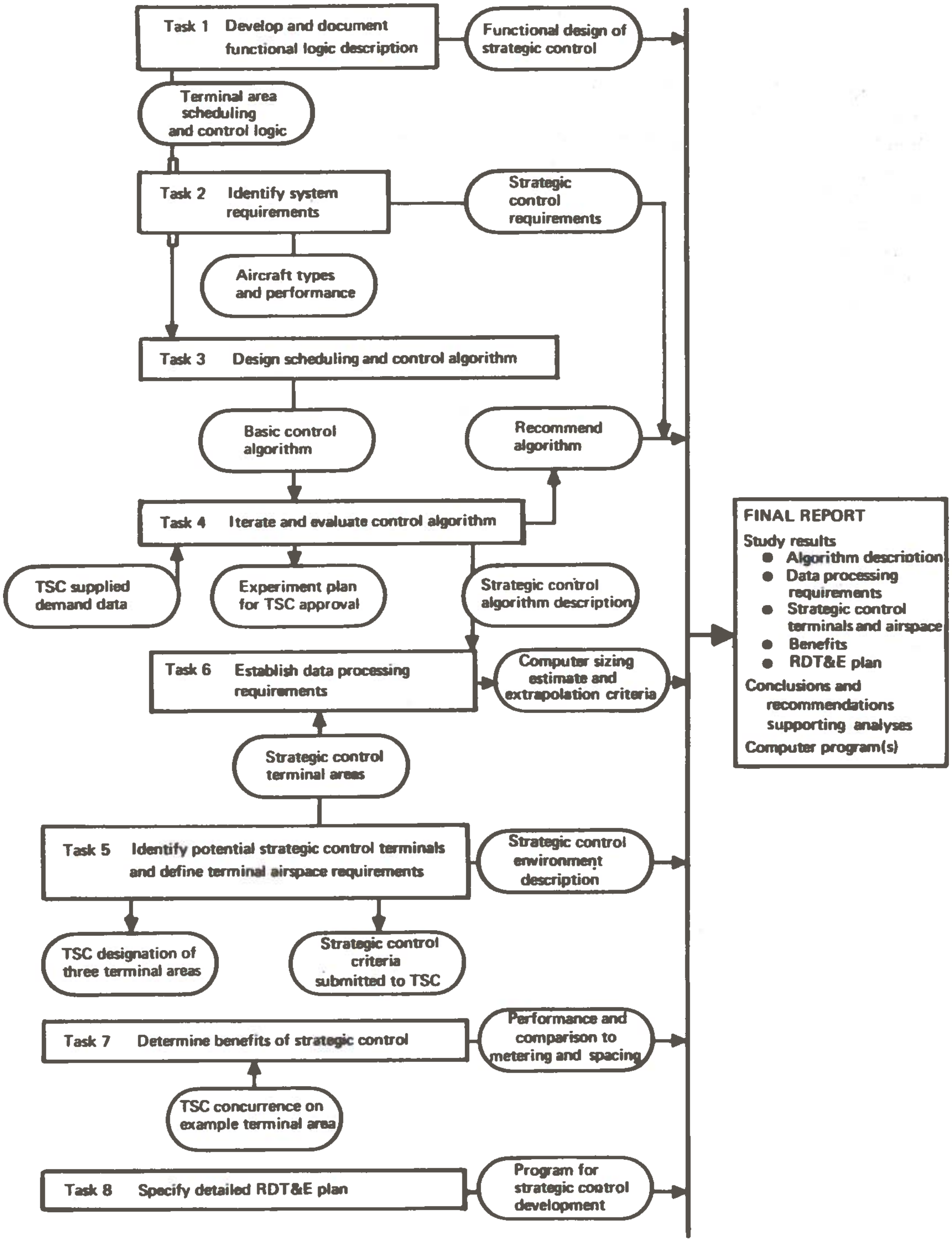


FIGURE 1-1.—STUDY PLAN OVERVIEW

2.0 STRATEGIC CONTROL FUNCTIONAL ANALYSIS

As discussed in the summary (vol. I), strategic control is the preplanning of flightpaths for conflict-free flight. The pilot has the responsibility to maintain adherence to a detailed route-time profile (RTP) and has an airplane with airborne equipment to make this possible. The air traffic controller acts in a surveillance and advisory capacity when the pilot maintains conformance to the route-time profile and has the equipment necessary to quickly generate new route-time profiles for airplanes, rescheduling them when necessary.

There is justification for departure, en route, and oceanic strategic control in addition to the strategic approach control program. All strategic control programs have the following in common:

1) A route-time profile is developed and assigned by the ATC system.

2) The route-time profile is transmitted to the airplane.

3) Both the airplane and ATC measure present position.

4) Both the airplane and ATC compare required and present position.

5) The pilot flies his airplane to achieve required position.

6) The ATC system initiates a route-time profile modification as required.

Figure 2-1 shows a block diagram of the basic functions common to all strategic control systems.

2.1 STRATEGIC CONTROL FUNCTIONAL DESCRIPTION

The primary operating mode for strategic control provides a fully automated system for that portion of the flight under strategic control with the controller serving as a monitor of the Air Traffic Management system. Automated computer routines work the problem of clearing and maintaining the flight plans. This will expedite traffic flow, respond to traffic density, provide for the airplane mix, and ensure safe separation.

On a first iteration basis, problems are resolved when the flight plan is filed. The system will reiterate the flight plan and assess planned versus actual progress of the flight. When the strategic controlled portion of the flight is initiated, the automated system, the pilot, and the controllers initiate surveillance to maintain integrity of the flight plan, to preclude problems, and to respond to unpredicted events.

The initial step in undertaking a strategic controlled flight is the generation and filing of a flight plan by the system user. Proposed strategic control flight plans will enter the ATC data base through the originating ARTCC for error/legality checking and correction. A

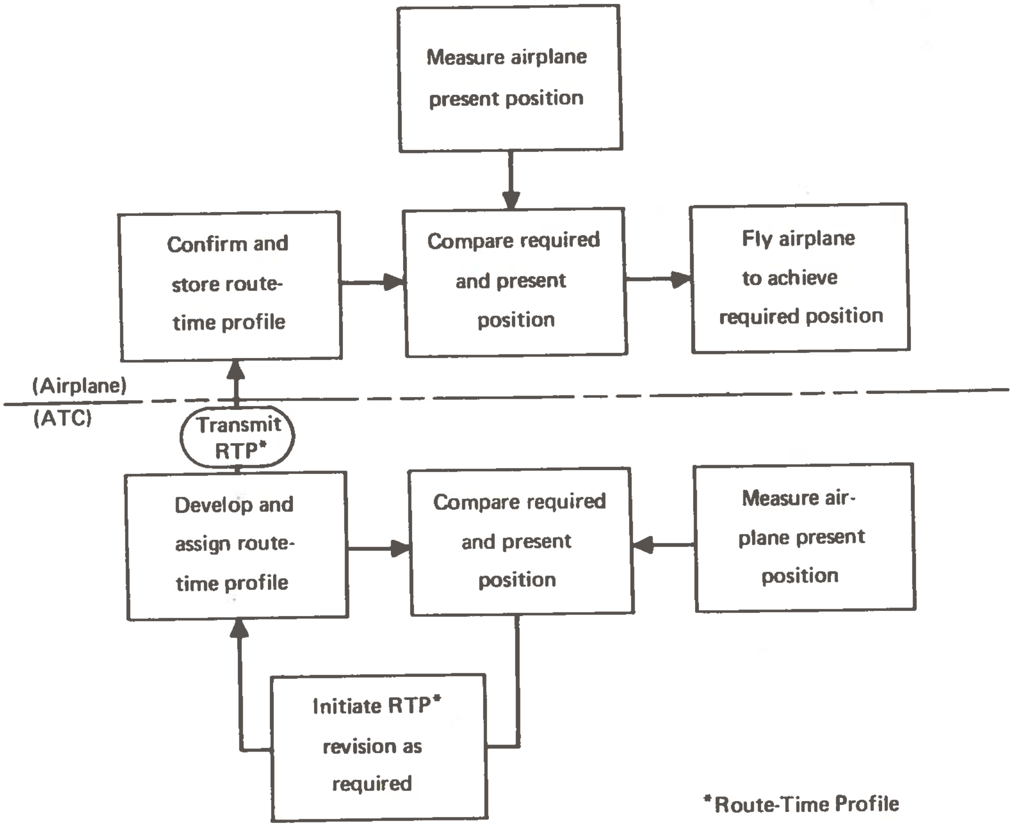


FIGURE 2-1.—BASIC STRATEGIC CONTROL FUNCTIONS

majority of the strategic control flight plans will be provided as bulk-stored flight plans for scheduled air carrier flights.

Preferred routing and reservation of a departure time and a landing time, a route-time profile for the flight, and pertinent data on the airplane are included in the flight plan. The proposed flight plan is automatically read into the ARTCC main core storage, modified to conform with current procedures, preferred routes, and restrictions known to the program.

Essential detailed departure flight data is forwarded to the originating TRACON and/or tower.

The filed and approved flight plan, assuming pilot acceptance, is input to the airplane's computer system by some form of information storage such as a carry-on magnetic tape cartridge, or by data link and manual or automatic input to the computer. The flight plan is verified by the crew by visually checking waypoint coordinate data.

If conflicts, system changes, or schedule slippages do not occur, the flight would proceed as filed. As a practical matter these perturbating influences will occasionally occur and hence require resolution during the flight and at a time when the nature of the perturbation is known. The benefit of strategic control is that this preplanning and use of airplanes equipped to perform accurate path/time compliance removes variables that otherwise introduce considerable randomness into ATC operation.

As an airplane proceeds through departure, en route, and through the transition area to the terminal area to the runway, the pilot makes good the route-time profile given him. He is monitored from the ground to check his position and to watch for intruders. The position data are used to check on route-time profile conformance and to obtain information to update the short-term wind model.

At each passing of a route-time profile waypoint the airplane position is checked against the cleared position. If the airplane is on course and on time there is no need for communication and the airplane proceeds toward the next route-time profile fix.

As the airplane proceeds inbound from the approach entry fix the allowable along-track deviation is tightened. The process described is illustrated functionally in figure 2-2.

The weather data bank shown in figure 2-2 will provide a technique whereby a computer estimates the speed of the wind on the various flightpaths by use of radar-derived coordinates of airplanes. The basic data available to the computer would be the radar(DABS)-derived X,Y coordinates, beacon altitude, groundspeed, and identity. A sufficiently accurate estimate of the on-course wind component can be derived by applying flight profile airspeed on the track data. It should be noted that this will not render the actual wind vector, since the heading of the airplane is required. However, in computing flying time estimates, it is usually necessary only to know the effective component of the wind along a given path. By averaging over several airplanes the weather data bank will dynamically smooth and predict winds aloft at different altitude levels along each route.

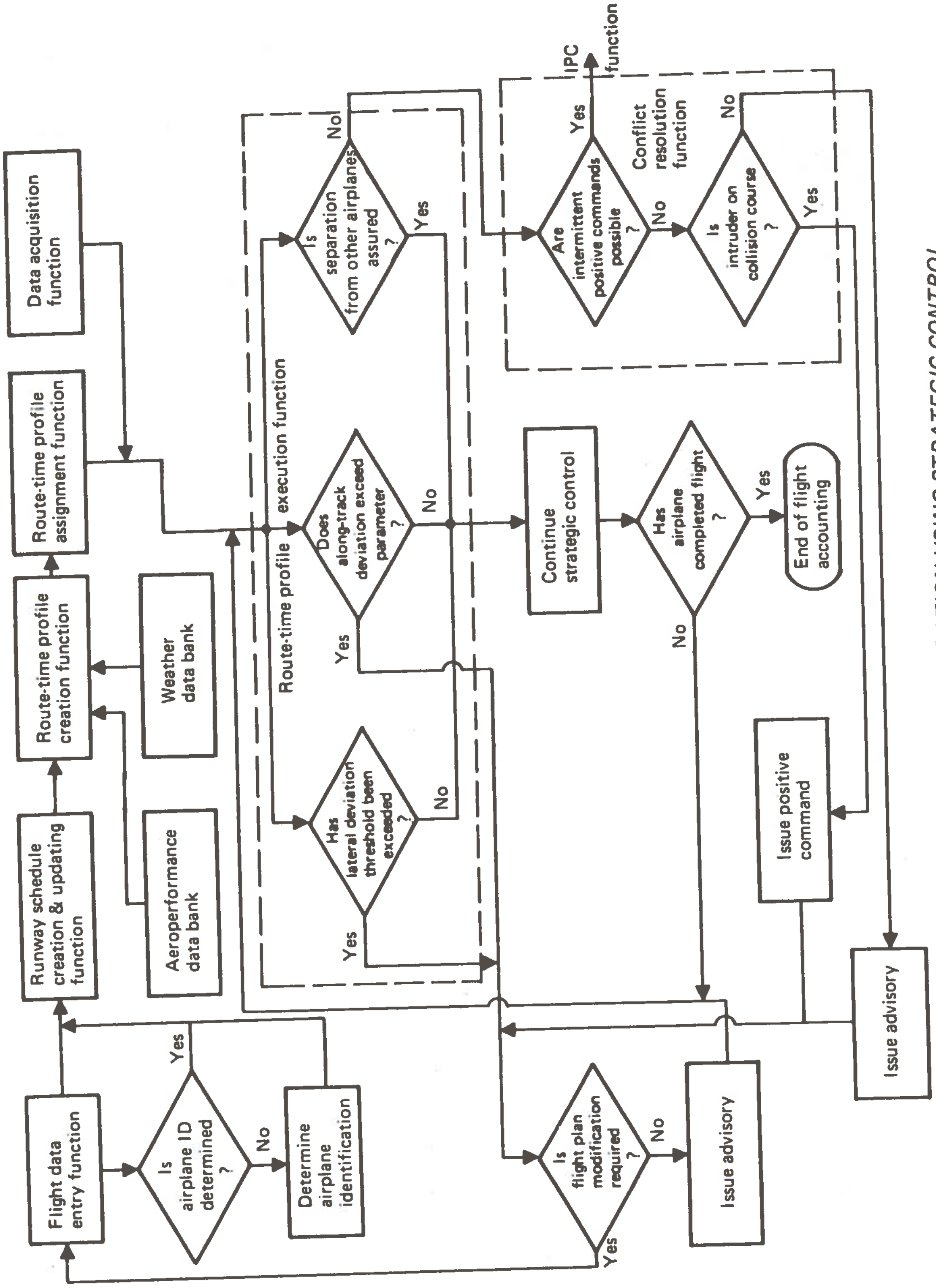


FIGURE 2-2.—ATC FUNCTIONAL OPERATION USING STRATEGIC CONTROL

Whenever the winds shift to the extent that a change in runway is required, the runway change program in conjunction with the weather data bank accepts inputs to reorganize the traffic for the new runway direction. In a metroplex area like New York there is considerable interairport interaction. Therefore. the arrival and departure routes for several airports are defined as a group for each wind direction, and the landing/departure patterns are shifted simultaneously for the group of airports.

The weather data bank must aid in redefining arrival and departure routes when severe weather moves through the area.

The data acquisition and surveillance function shown in figure 2-2 is not a part of the strategic control algorithm but is a very necessary part of the environment that will allow strategic control to work.

For control of air traffic, positive identification of all airplanes is necessary. The most useful tool for preventing air collision is the use of computers to extrapolate the velocity vector of an airplane and determine if the predicted vector of any airplane intersects the predicted vector of any other airplane on a time-space basis. That is, in addition to course and speed, altitude must be considered in the computation. When such an intersection of predicted vectors occurs, a collision is imminent. When presented with this situation, the controller does not have time then to initiate identification procedures and ascertain the communication frequencies used by each airplane. To provide the control measures desired of the system, it is imperative that the controller be able to establish contact with any airplane in the area, and thus he must have positive, continuous identification of all airplanes and their operating radio frequencies. To provide this positive, continuous identification capability, standardization of required information is necessary. Each controller must have the capability to provide identification inputs to the system, and must also, in turn, be able to have access to any identification data already in the system.

Coordination is necessary to tie together the functions of detection, identification, and communication. These functions must be available to the controllers for them to carry out their assignments. Primary requirement of the coordination function is the logical display of all available information and ready access to communication links necessary to the function. It is essential that any data inputs to the system that may be initiated by any single controller be made available to the other controllers. This necessitates a system whereby each controller must be able to initiate data inputs and monitor all other data inputs also.

As indicated in figure 2-2, if separation from other airplanes cannot be ensured (i.e., an intruder not under positive control has entered the airspace), the question of ability to identify and communicate with the intruder must be addressed. If the intruder can be communicated with, resolution of the potential conflict is possible so that the airplane under strategic control is able to proceed without the necessity of rescheduling at the runway. The necessity for revising the flight plan will depend on the airplane being able to meet its next fix on schedule.

2.1.1 Preflight Planning Analysis

Strategic control begins with the filing of a flight plan. Critical parameters are completeness and availability of information in the data base. The destination must be selected and tentative routes and altitudes with waypoints must be detailed. The estimated departure and arrival times should be stated.

The pilot wishing to establish a strategic flight plan must assess the operational, environmental, and regulatory factors in order to identify and assess the constraints that will be imposed on the proposed flight plan. The weather over the proposed route, traffic, ground equipment capability, rules, and procedural constraints should be considered.

The parts of the flight that will require strategic clearance should be included in the data provided. Although the flight plan is normally filed with the ARTCC in the departing area, the strategic flight plan is required at the departure airport if the departure is to be strategically controlled. With the en route strategic control route-time profile being generated by the ARTCC and the oceanic portion, if required, generated by the Oceanic Center, communication coordination is required. The destination terminal must receive the strategic flight plan in order to make up a tentative approach sequence list and tentative runway schedule.

The capability of the airplane is of primary importance in the formulation of a strategic control flight plan. The speed, range, cruise altitude, etc., should be specified or must be available in the Air Traffic Management system data base. The type and status of on-board equipment must be specified so that the capability of the airplane to perform a strategic control flight plan can be assessed.

With the above information available a strategic control flight plan can be compiled. After generating the flight plan it must be reviewed for completeness and then transmitted to the Air Traffic Management system. The present point of reception and assessment is the ARTCC in the originating area. Because of the sophistication of the strategic flight plan it may be necessary for an iteration to take place before a strategic control clearance is approved.

Many of the strategic control flight plans will be stored or prefiled flight plans. Prefiled flight plans are repetitive and predictable and are stored in a bulk storage medium. They are transferred automatically to core storage as required by the computer program for processing and use. Bulk storage of flight data is treated as an extension of core storage in terms of access to amend and cancel for a local current day. Since there is no pilot involved in the input function, the prefiled strategic flight plan is read from bulk storage at the appropriate time and enters the computer for processing.

The preflight phase of a strategic departure requires that the runway schedule routine get preliminary information on departure of an airplane before the airplane leaves the gate and the airplane must receive its route-time profile immediately upon leaving the gate. This will be discussed in greater detail in section 2.1.3.

2.1.2 Strategic Approach Control Functional Description

The strategic approach control program provides control from an entry fix at some distance, perhaps 175 miles, from touchdown at the runway. The airplane may or may not have been under strategic control at the time of entry.

In the case where an airplane has departed an airport within 175 miles of the arrival airport the entry fix for arrival might be the first four-dimensional fix after takeoff, the departure being under strategic departure control. This would permit the maximum time and distance for working the airplane into the arrival stream and yet ensure that the airplane had, in fact, departed the airport.

The strategic approach control of individual airplanes begins prior to the entry fix. In the nominal case, which will prevail most of the time, an arriving airplane is given a scheduled time of arrival at the runway that is equal to its estimated time of arrival at the runway as filed in the flight plan. In other words, the arriving airplane is cleared to exit the entry fix, enter the transition area, enter the terminal area, and land. The approach path fixes and times are specified and must be adhered to in order to remain on schedule.

The metering function as used in strategic control is implicit in the scheduling function and is covered in more detail in the description of the scheduling function. The term metering is defined as a measured rate of flow. The controlling function is performed by the scheduling process. Basically, metering is performed when the scheduled arrival time at the runway is prepared for each airplane. The scheduled arrival time, in turn, implies a certain clearance time through the entry fix. This effectively meters aircraft into the transition and sequencing area. This approach results in more precise metering than is possible using average rates as the controlling element.

Another aspect of metering that is implicit in the scheduling process is the equitable distribution between arrivals and departures. The arrival/departure ratio provided by the strategic control computer program is used to ensure the inclusion of departure gaps between arrivals. During periods of high arrival rate, additional time spacing is provided. The scheduling process, which inserts departures, is flexible enough to permit uneven distributions between arrivals and departures.

Tenative scheduling, not a part of strategic control, is done using airplane flight plan data. These data are received at some random time normally minutes prior to the airplane's approach to the entry fix. When this function is performed the flight plan and any previous affected plans are processed.

As long as the airplane is not being tracked, either by the ARTCC or the TRACON, it is scheduled based on the calculated runway time. Flight plan information and nominal time to fly to the runway are used to establish a sequence of arrival airplanes. The time-to-fly calculation is made for a general path from the entry fix to the runway using airplane maximum speed or nominal route-profile speed, whichever is smaller, and the pilot-specified final approach speed. Using the flight plan ETA at the entry fix, the tentative schedule routine checks the route-time profile files and runway schedule files for an approach path and runway vacancy. If no space is available a tentative en route hold request is issued. The time generated represents at this time nothing more than a number to use in establishing a first-come-first-served sequence list. The actual runway schedule time is provided by the runway schedule subroutine.

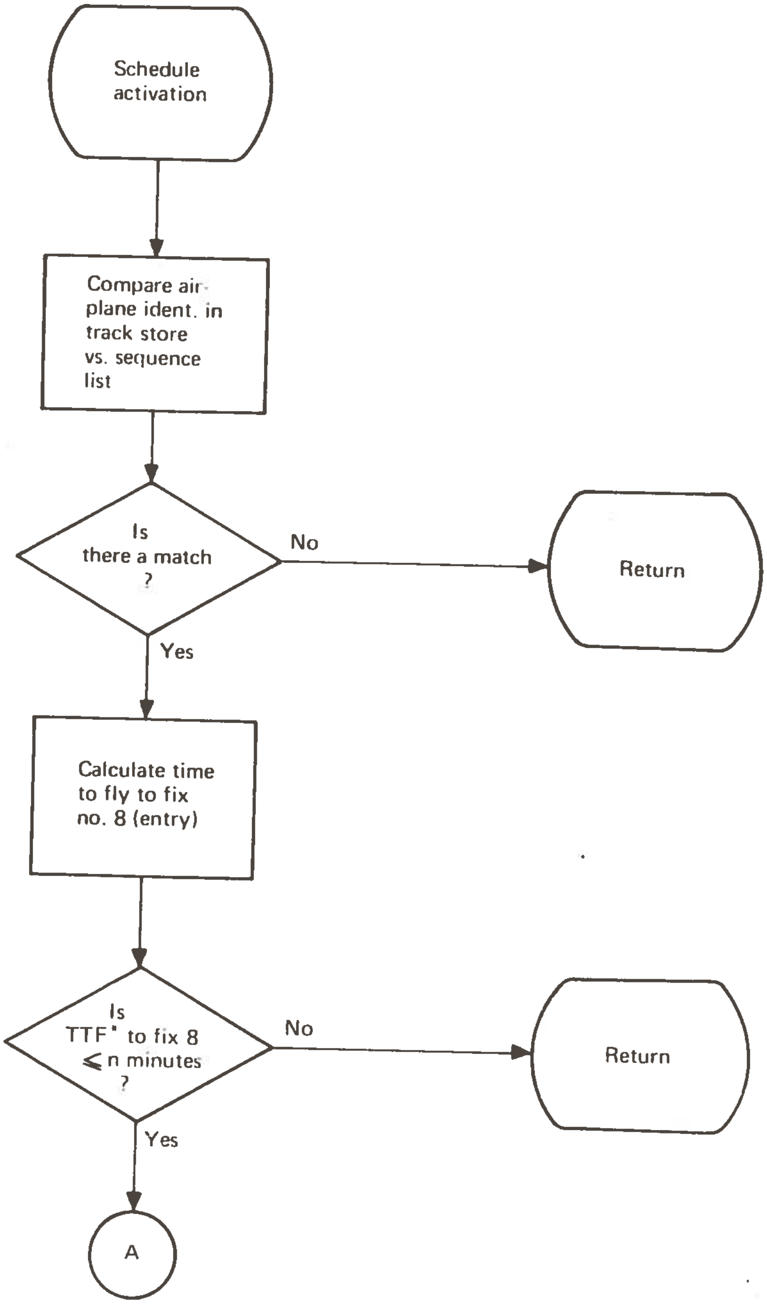
The strategic control scheduling program has been divided into four basic modules, each performing one of the separate functions required to schedule an airplane from the entry fix to the runway. The first of these is the schedule activation module. After the airplane becomes an active track within the radar range and as it approaches within 175 miles or so of the runway, calculations can be made for a scheduled time at the runway. The design premise for the schedule activation module is that the airplane is being tracked and any information obtained from tracking is better than the estimates received from the flight plan. The scheduling can now be accomplished on a firmer basis and a reasonable route-time profile can be generated.

With the airplane under radar track, the original tentative estimates of time to the runway can be updated. Using the airplane's present position, a time to fly to the entry fix is calculated and added to the current time, to provide an actual time of arrival at the entry fix. If the time to fly to the entry fix is greater at some specified time, control is returned to the executive program as the airplane is still too far from the entry fix, as indicated in figure 2-3. When the airplane gets to within a fixed limit of the entry fix the status of the airplane in the active track file decreases from 9 to 8, as indicated in figure 2-4. If it is less than or equal to the time limit, the actual time of arrival is compared to the flight plan estimated time of arrival at the entry fix.

When the actual time of arrival = ETA ±n minutes, the tentative, previously planned sequence and schedule at the runway are satisfactory and the airplane requires only the details of the route-time profile to be followed to make good the scheduled time at the runway, as indicated in figure 2-4.

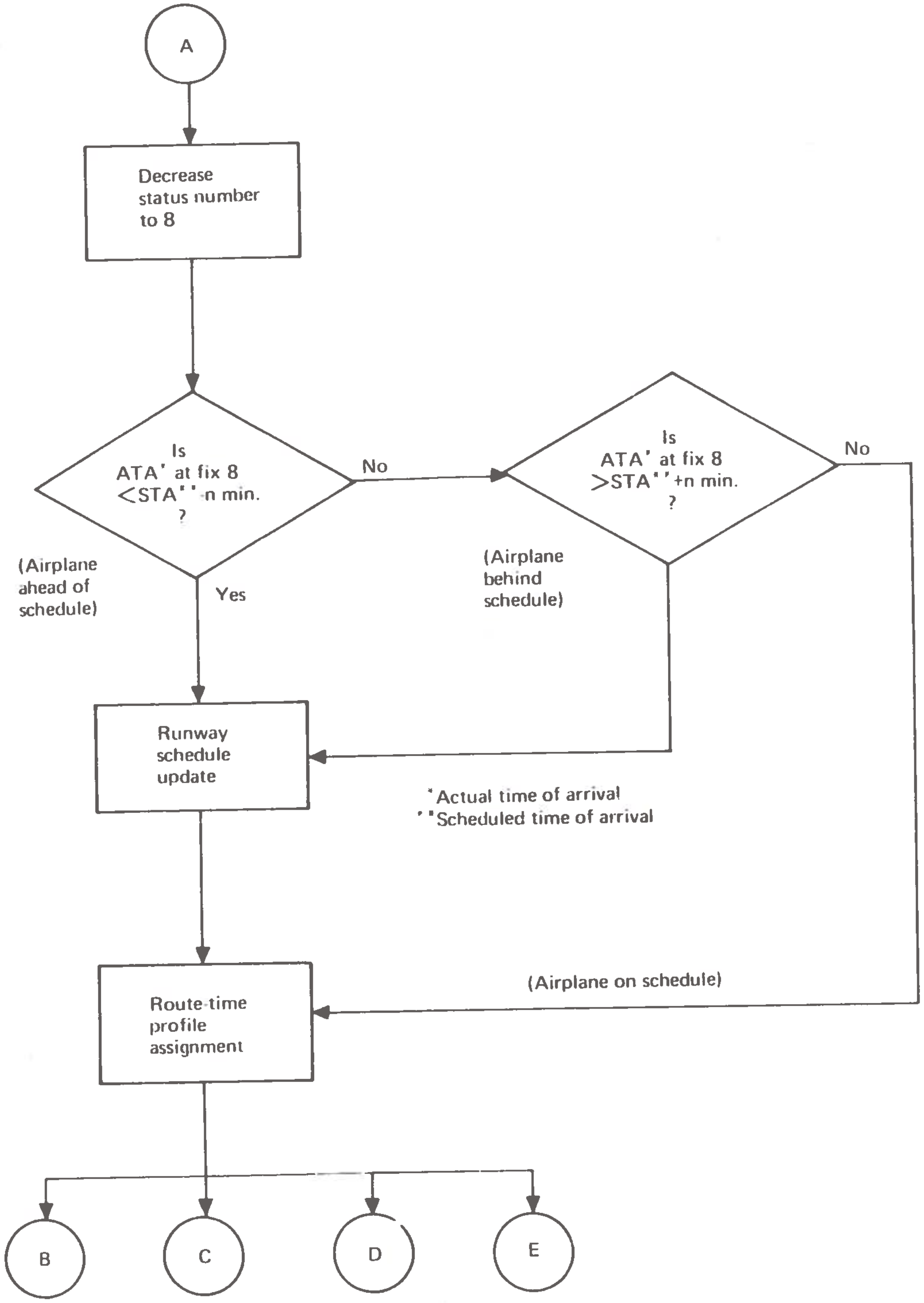
As the airplane proceeds toward the entry fix it is continuously tracked. The position data are used as checks on performance and to update the short-term wind model for that portion of airspace, a part of the weather data bank. The airplane receives its detailed route-time profile from the entry fix to touchdown at a time just prior to arriving at the entry fix. This detailed clearance is generated in the second of the strategic control schedule modules, the runway schedule routine. If the airplane is ahead of schedule at the entry fix, an attempt is made to resequence and move the ETA at the runway forward in time to accommodate the airplane. If, on the other hand, it is behind schedule a new time at the runway must be planned.

The runway schedule routine (the second of the four modules) generates a route-time profile that will accommodate the particular airplane proceeding inbound from the entry fix and that will be compatible with the flight profiles of the other airplanes in the sequence—the one ahead in landing time and the one behind.



*Time to fly

FIGURE 2-3.–APPROACH TO ENTRY FIX



*Actual time of arrival
**Scheduled time of arrival

FIGURE 2-4.–DECREASE OF AIRPLANE STATUS TO 8

The data are stored (fig. 2-5) in the sequence file to be used in comparing the actual route-time profile made good with that profile assigned by the runway schedule routine.

The route-time profile message will normally be transmitted (fig. 2-6) to the airplane by data link. The four-dimensional coordinates to be flown will normally be inserted automatically in the navigation computer to reduce cockpit workload. Acceptance by the airborne unit would be an indication that the route-time profile assigned is an aerodynamically acceptable solution.

The flight plan stored in the sequence file becomes available for display by the controller as indicated in figure 2-7. At each specific fix, deviation in excess of along-track or cross-track tolerances will be visually displayed along with status number and priority symbol.

The pilot, aided by on-board navigation, computer, and flight management equipment, works the problem of on-time arrival at the first fix inbound from entry fix 7. The ground system checks identity and computer distance to fix 7 as indicated in figure 2-8.

The airplane's position is checked as fix 7 is approached, both in the air and on the ground. The ground surveillance system is providing intruder protection, a check on airplane performance, and updating of the short-term wind model for that area and altitude.

The third part of the scheduling routine, the position update module, keeps track of the location, increases the priority, decreases the status number from 8 to 7, and tightens the allowable tolerances on position and time at the fix as indicated in figure 2-9. At fix 7 a representative allowable along-track deviation might be ±3 to 5 miles. If the airplane is on course and on time there is no need for communications and the airplane proceeds inbound to the next fix, fix 6.

The airplane proceeds inbound with the position update module keeping track of position, increasing priority, decreasing status number, and tightening tolerances. The airplane proceeds through arrival transition (status 5 and 6), arrival (status 4 and 3), approach (status 2), and to landing (status 1).

If the airplane cannot make good its schedule to a fix, the problem is resolved in the position update module and the runway schedule module. A new route-time profile will be generated that will accommodate the airplane. This may require the resequencing of adjacent airplanes scheduled for specific times at the runway. The new information generated is placed in the sequence list, the new route-time profiles are transmitted to the affected airplanes, and displayed to the controller to apprise him of the situation.

The identity of the airplane is checked by comparing the data in track store with that in the sequence list. As the airplane approaches the runway the four-dimensional position and the time to touchdown are computed. If it is still too far from touchdown, the surveillance system ignores the airplane except to provide intruder protection and to acquire data for the short-term wind model. When the time to fly to touchdown becomes less than a specified time, the position update module receives the position information and these data are also displayed to the controller.

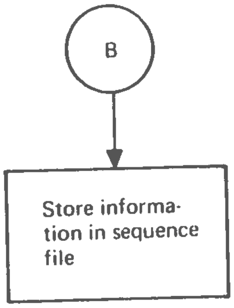


FIGURE 2-5.–STORE INFORMATION IN SEQUENCE LIST

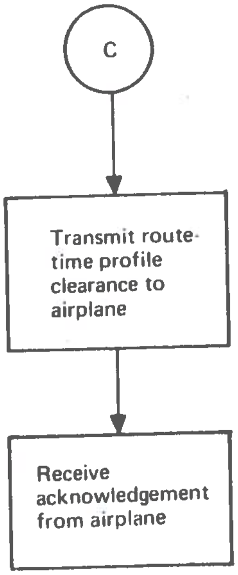


FIGURE 2-6.–TRANSMIT CLEARANCE TO AIRPLANE

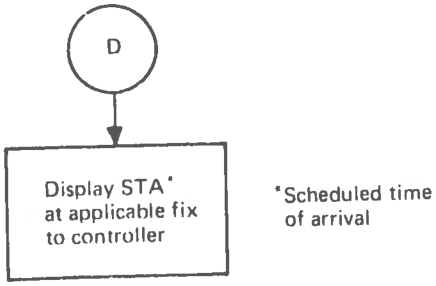


FIGURE 2-7. –DISPLAY STA* AT APPLICABLE FIX

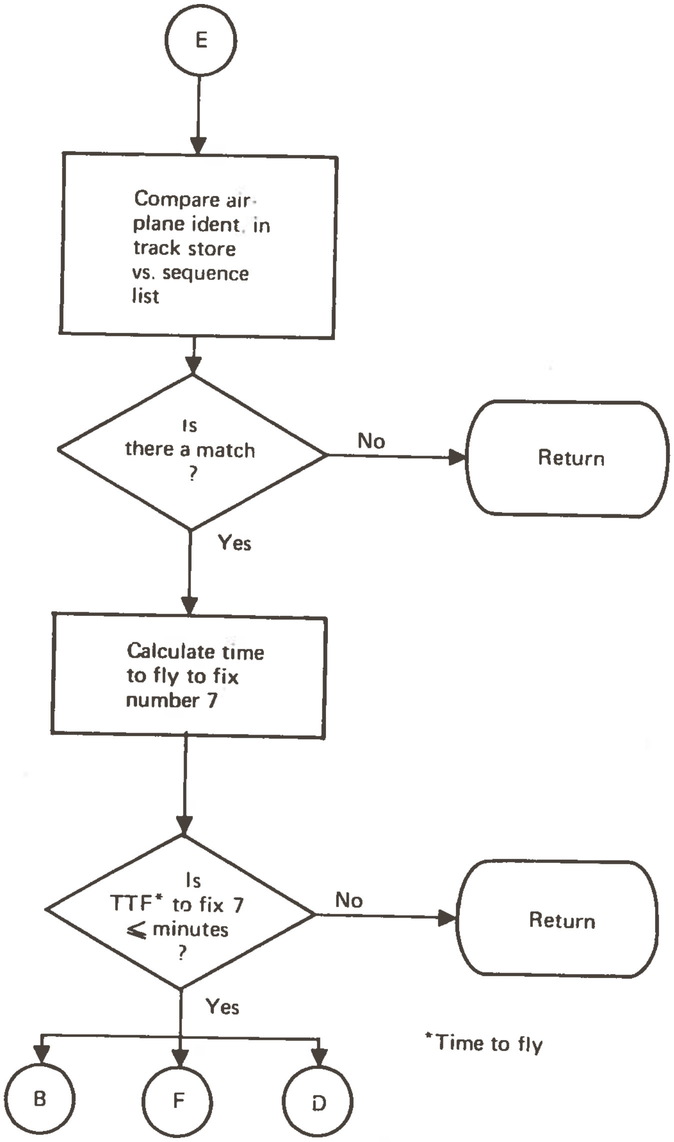


FIGURE 2-8.—APPROACH TO FIX NO. 7

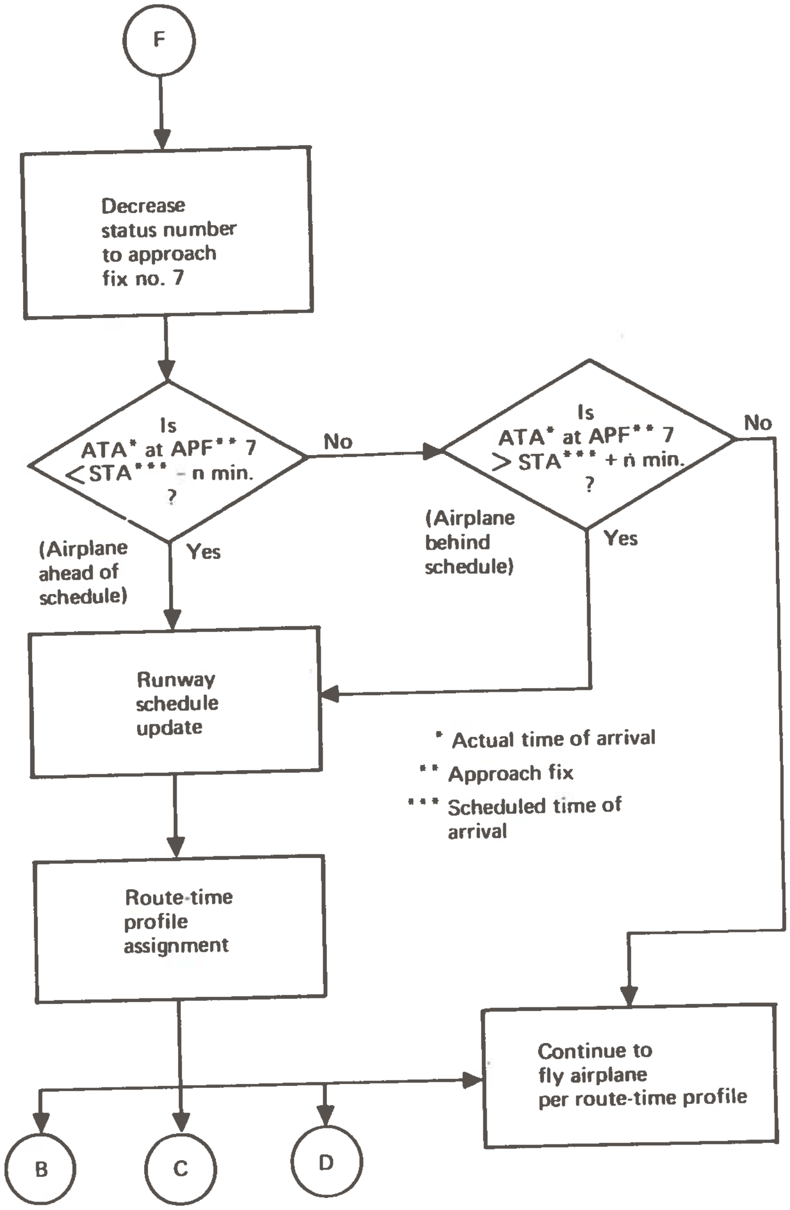


FIGURE 2-9.—CHECK ON ROUTE-TIME PROFILE STATUS

When the airplane turns onto final approach, the status number is reduced to 1, as shown in figure 2-10. The airplane location is checked to see if it is within tolerance. The airplane permissible along-track tolerance might be ±0.1 to 0.2 mile as final begins, with touchdown tolerance to be within ±0.05 to 0.1 mile. If the airplane is not within these tolerances, a modification is made in the flight plan if possible. If necessary, the airplane must be handled by the missed approach routine, as shown in figure 2-11.

A missed approach effectively places another airplane into the system at a point where the tolerances placed upon incoming airplanes are small. A means must be provided for rescheduling this airplane at the gate for another approach. It may require a priority to make the second attempt. For each landing runway in use there is a standard missed approach procedure that provides the pilot with a route-time profile to a holding/rescheduling point until further clearance is issued.

At the first recognition of a missed approach, the subroutine looks for a slot in the landing sequence into which the airplane can be fitted. A vacant slot or a separation in the arrival schedule planned to accommodate departures could be used by sacrificing the departure slot. When the missed approach subroutine is used the status number drops to zero as indicated.

If a runway change is in progress, the time to fly from the present position to the reentry fix is computed. With these data available the question now is whether a landing slot exists that the missed approach airplane can use. If a slot exists this slot is assigned to that airplane. If no slot exists then the question is whether a departure slot or slots can be used to land the missed approach airplane. If such a slot or slots exist these are assigned to the airplane to land.

If no departure slots are available then an arrival time of a strategic controlled airplane that is in the approach pattern must be used. This landing time is assigned to the missed approach airplane. This will necessitate the assignment of a new runway schedule time to the airplane that gave up its landing time. The runway assignment routine reschedules the airplanes affected and new route-time profiles for affected airplanes are generated. This may require resequencing of arriving airplanes.

2.1.3 Strategic Departure Control Functional Description

The strategic departure control program provides control from the gate to the point where the airplane exits the last strategic departure control fix. In most cases this will be at the point where the airplane enters the en route portion of the system. The airplane may or may not continue under strategic control in the en route portion of the flight.

In the case where the departure airport is approximately 200 miles from the arrival airport the first fix outbound from the runway, departure fix 6, might be the arrival entry fix for the strategic approach control program. The route-time profile for approach might be sent to the airplane just prior to arrival at that point. Strategic departure control in this case will amount to getting the airplane from departure gate to runway to the first outbound fix.

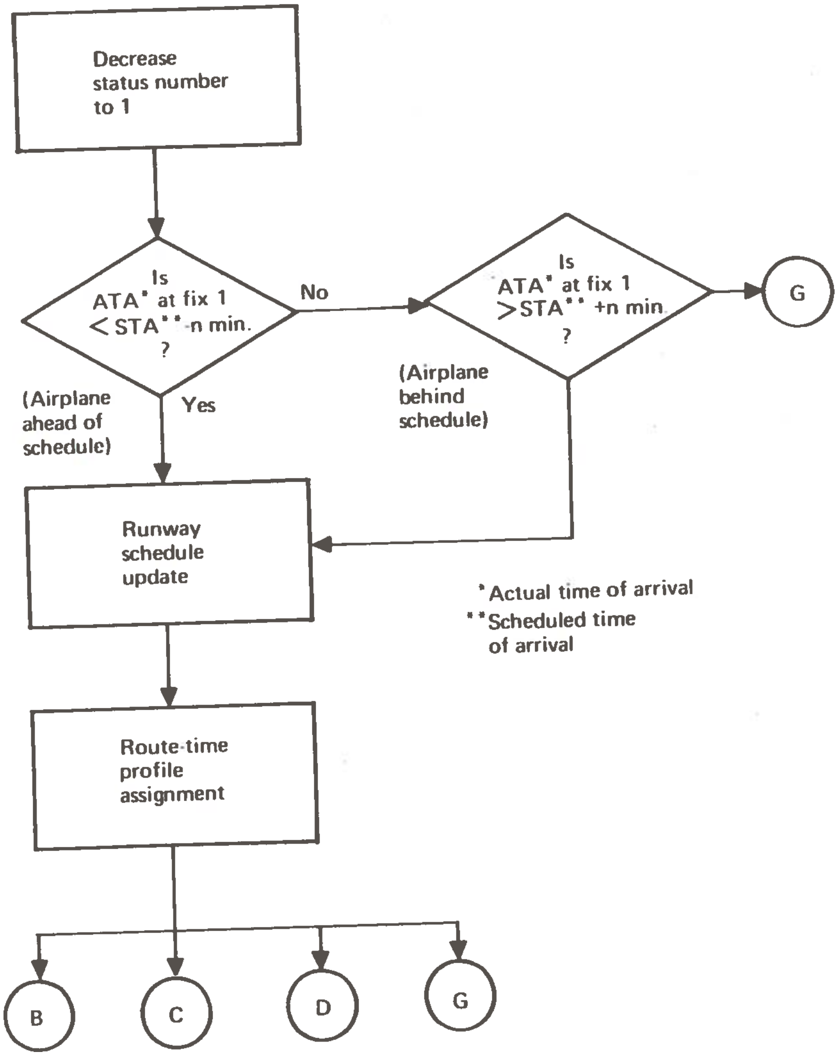


FIGURE 2-10.—DECREASE OF AIRPLANE STATUS TO 1

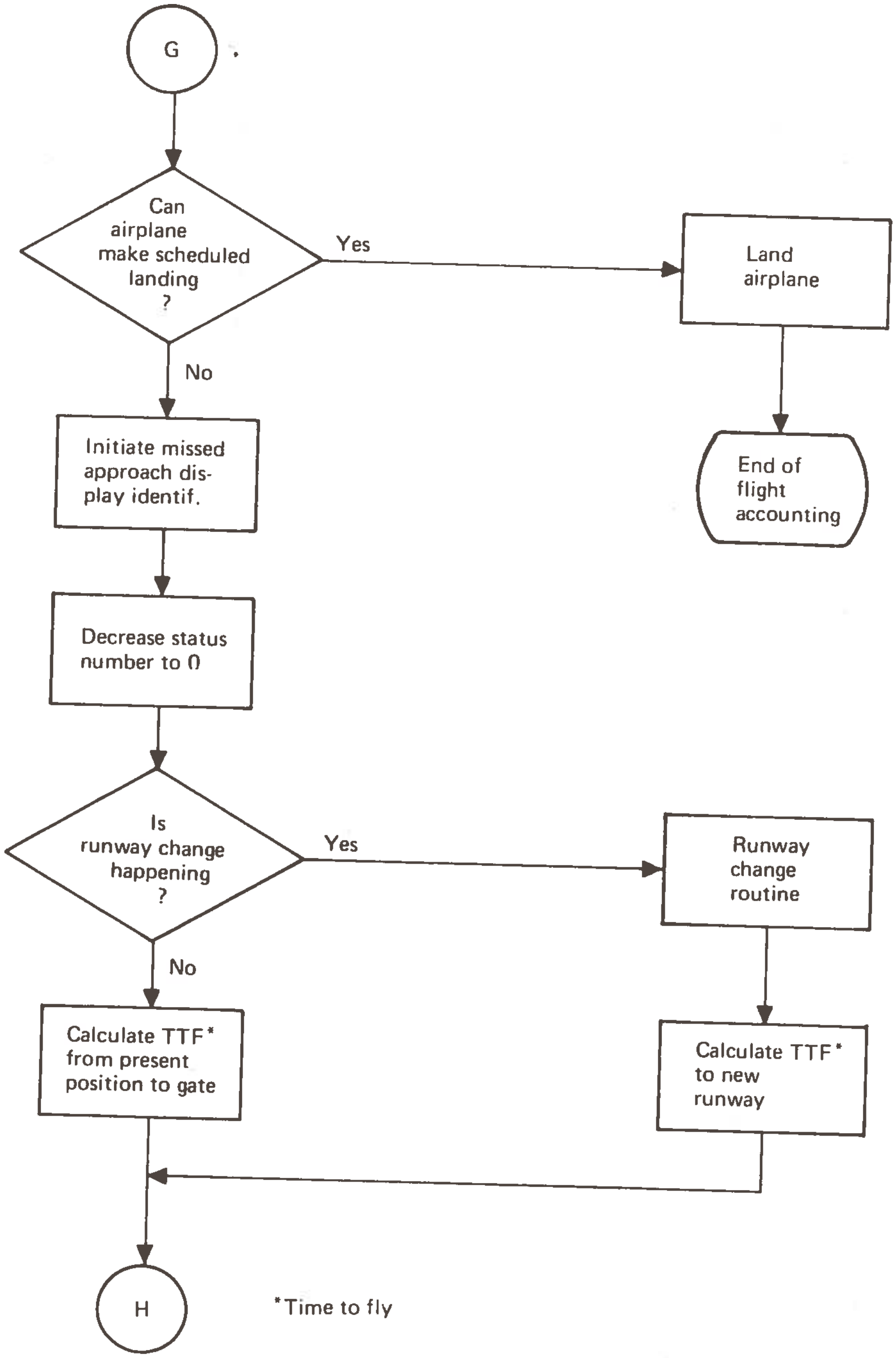


FIGURE 2-11.–MISSED APPROACH ROUTINE

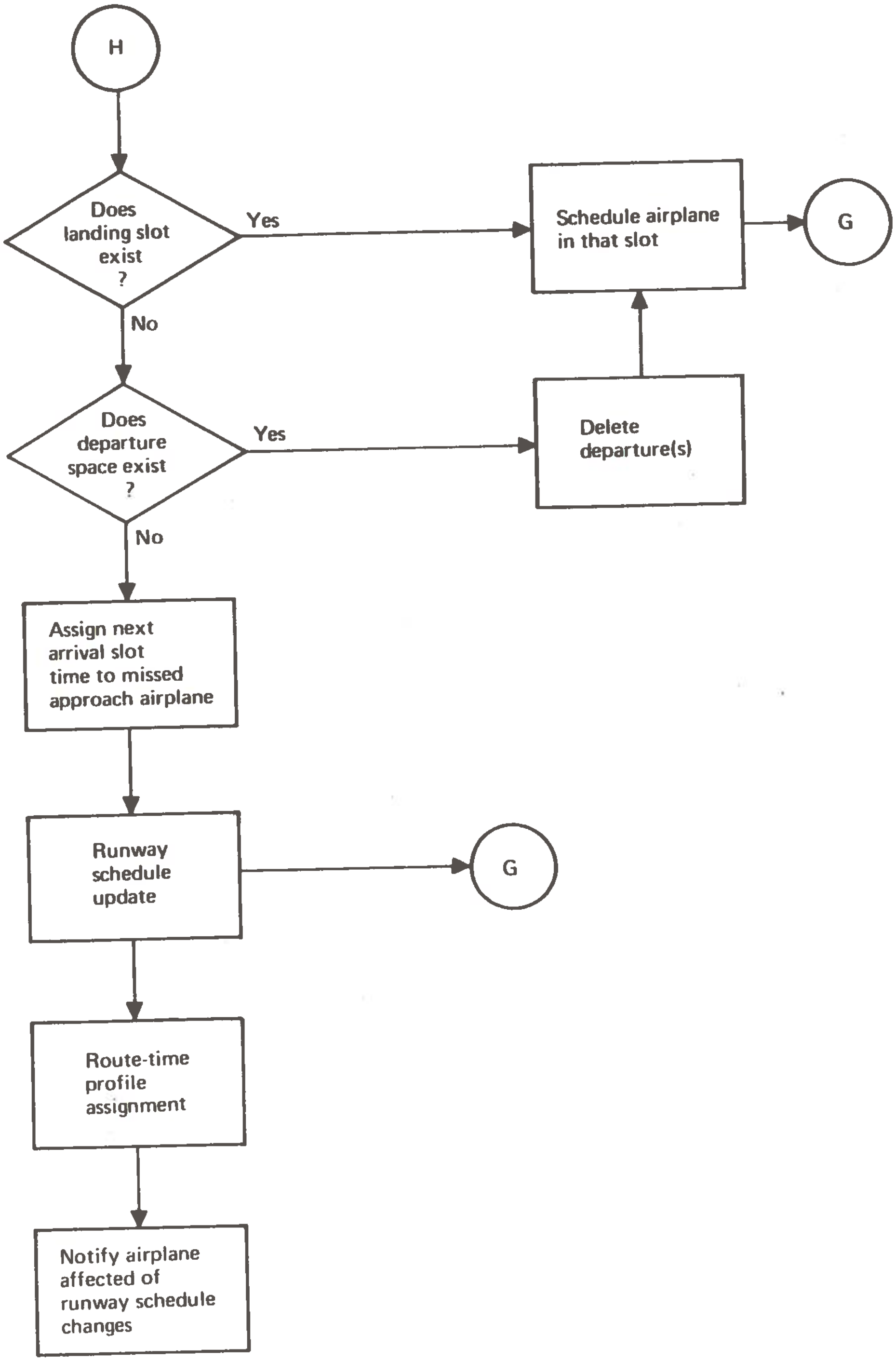


FIGURE 2-11.—CONCLUDED

The strategic departure control of individual airplanes begins prior to departure from gate. A departing airplane is given an estimated departure time, which is equal to its estimated time of departure as filed in the flight plan. The departing airplane is cleared to taxi out, take off, climb out, and depart from the terminal area. Metering is performed when the scheduled departure time from the gate is prepared for each airplane. The scheduled departure time, in turn, implies a certain clearance time through the departure exit fix. This effectively meters airplanes into the en route portion of the Air Traffic Management system.

Tentative departure scheduling is performed using the flight plan estimated time of departure from the runway. The tentative schedule routine checks the route-time profile files and runway schedule files from a runway vacancy. If no space is available a tentative hold request is issued. The departure list represents at this time nothing more than a number to use in establishing a first-come-first-served departure sequence list. The actual runway schedule departure time is provided by the runway schedule subroutine, which is common to both the approach and departure routines, and determines the time-to-fly calculation for a general path from the runway to the departure exit fix.

The strategic control scheduling program has been divided into four basic modules, each performing one of the separate functions required to schedule an airplane from the gate to the departure exit fix. The first of these is the schedule activation module. Before the airplane departs from the gate for the runway, calculations can be made for a scheduled departure time. The assumption is made that the airplane will soon depart the gate; at this time the scheduling can be accomplished on a firmer basis.

The original tentative estimates of departure time are updated with the airplane's expected time to depart the gate and a time to taxi to the runway. If the time to depart the gate is too large, control is returned to the executive program (fig. 2-12) and the airplane remains in status 9. When the airplane departs the gate and taxies out, the status of the airplane in the departure position update file decreases from 9 to 8.

The strategic departure control runway schedule assignment and route-time profile assignment has to be generated after the airplane leaves the gate. Because the strategic departure mode has no priority over arrivals in general and aborted landings in particular, the routine must, on a continuing basis, check to see that the departing airplane can, in fact, use a departure time slot. Of course, a runway reversal could also cancel a departure time slot. Figure 2-13 shows the iterative process exercised in the runway schedule module as the airplane proceeds from the departure gate to the runway for takeoff.

As shown in figure 2-14 the actual time of departure from the gate is compared to the flight plan scheduled time of departure from the gate. If the actual time of departure = scheduled time of departure ±n minutes, the tentative previously planned sequence and schedule from the gate are satisfactory.

The airplane receives its detailed route-time profile from the runway to the departure exit fix at a time just after departing from the gate. This detailed clearance is generated in the second of the strategic control schedule modules, the runway schedule routine. If the airplane is ahead of schedule at the departure gate an attempt is made to resequence and move the scheduled departure time forward in time to accommodate the airplane. If, on the

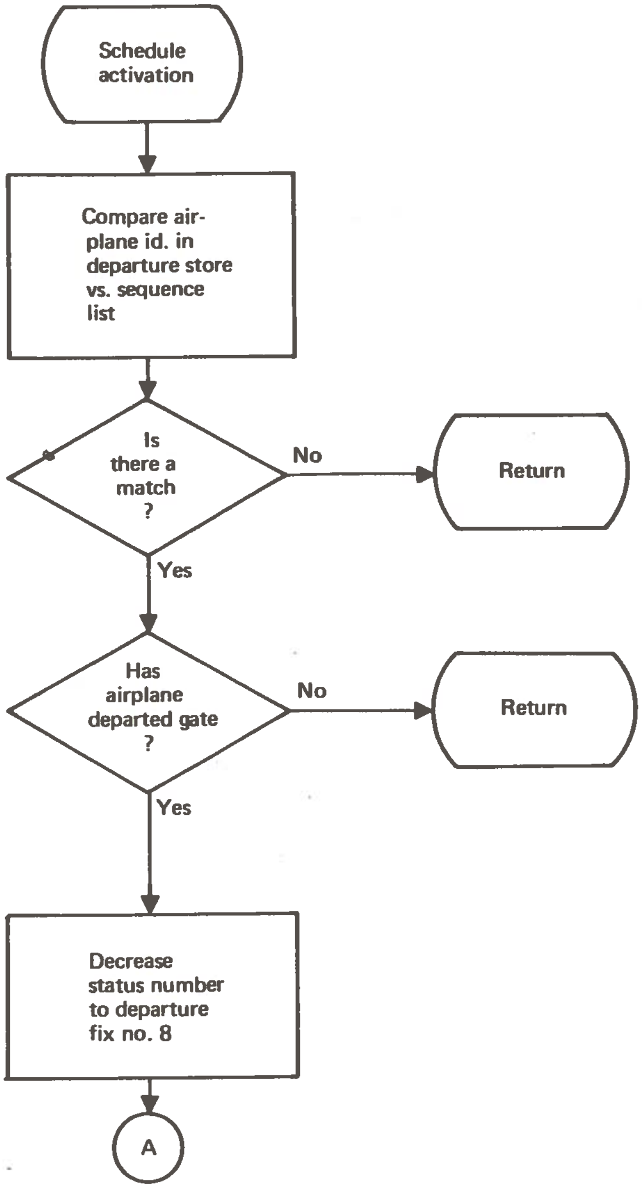


FIGURE 2-12.—STRATEGIC DEPARTURE CONTROL ACTIVATION AND AIRPLANE DEPARTURE FROM GATE

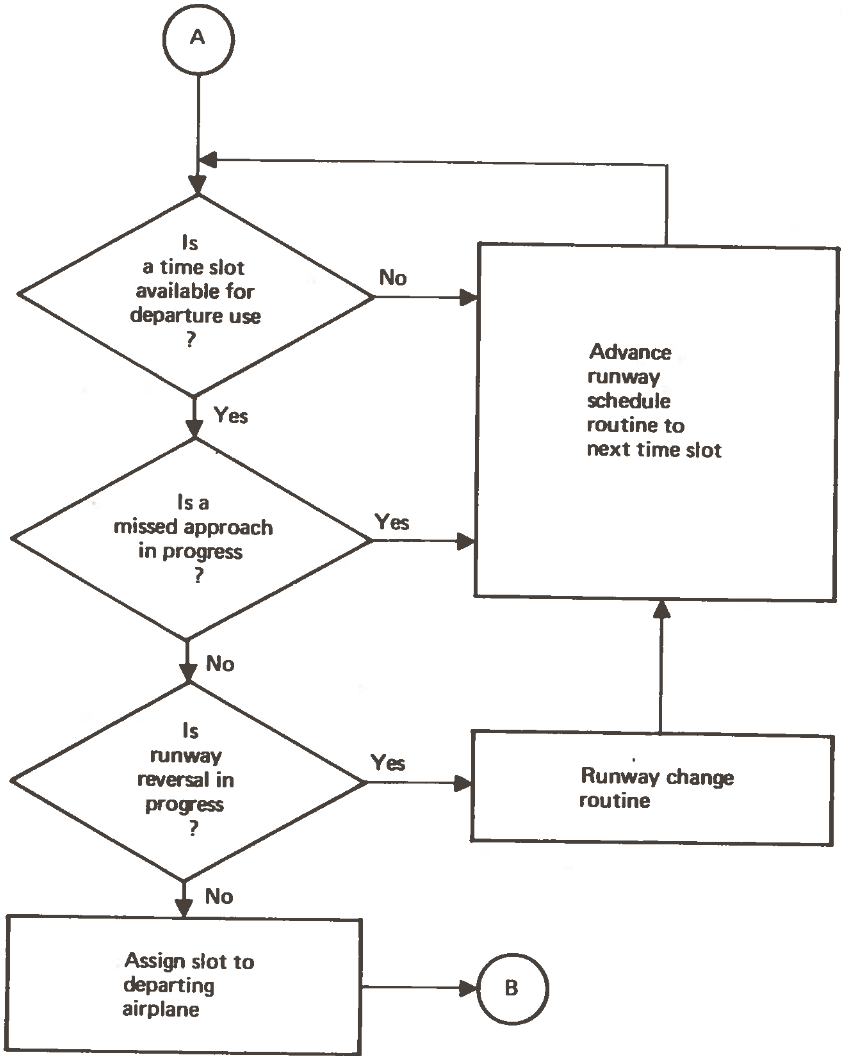


FIGURE 2-13.—RUNWAY DEPARTURE TIME SLOT ASSIGNED TO AIRPLANE

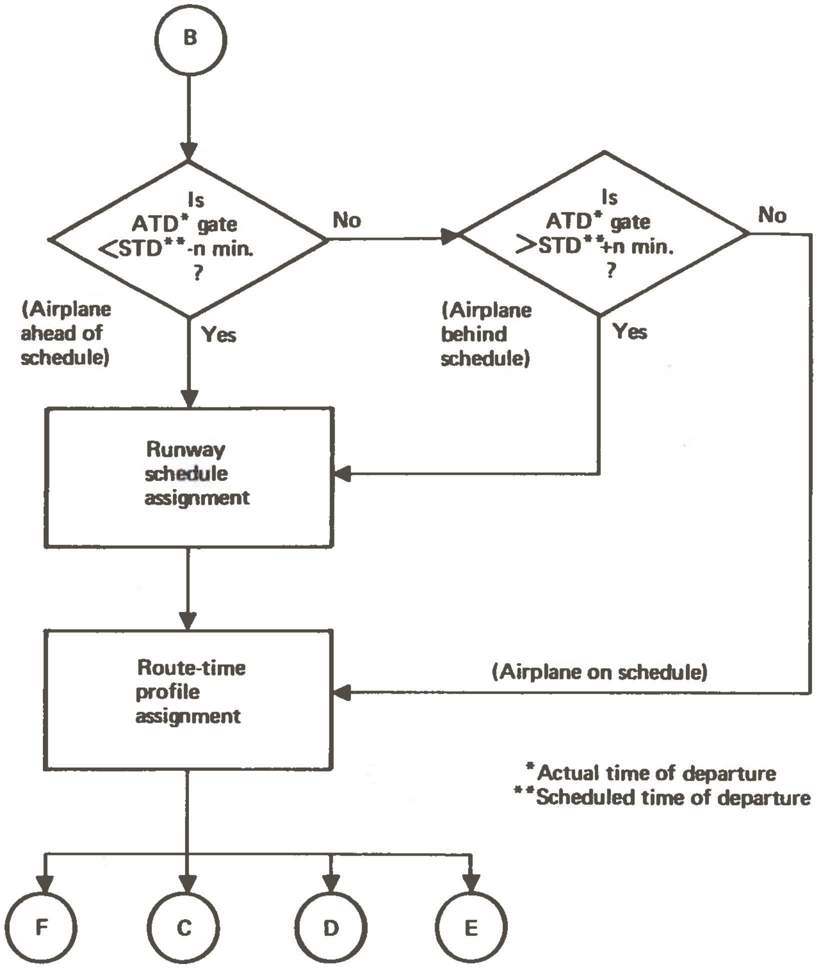


FIGURE 2-14.—ROUTE-TIME PROFILE ASSIGNED TO AIRPLANE

other hand, it is behind schedule, a new, later scheduled departure time must be planned. The runway schedule for departure does not have priority over arrivals on arrival aborts, hence must await a departure slot.

The runway schedule routine generates a route-time profile that will accommodate the particular airplane proceeding outbound from the departure gate and that will be compatible with the other flight profiles.

The data are stored in the sequence file to be used in comparing the actual route-time profile made good with that profile assigned by the departure schedule routine as indicated in figure 2-15.

The route-time profile message is transmitted to the airplane by data link and stored for display as shown in figures 2-16 and 2-17.

The pilot proceeds to the runway and, if no approaching airplane has acquired priority use of the runway, he is already cleared to depart the runway. Status of the airplane is reduced from 8 to 7 in the position update module as shown in figure 2-18 upon takeoff from the runway.

Upon departure from the runway the time of departure is checked against the scheduled time of departure (fig. 2-19). If the airplane is not within tolerance a new route-time profile must be generated. This revised route-time profile is sent to the airplane and displayed to the controller.

The pilot works the problem of on-time arrival at the first fix outbound from the runway, departure fix 6. The ground system checks identity and computes distance to departure fix 6 as indicated in figure 2-20.

If the airplane is proceeding to an airport capable of strategic approach control and within 200 miles of the departure airport, it would receive the strategic approach control route-time profile at this time. This would allow the maximum time and space to fit the airplane into the arrival schedule. The departure fix 6 would become the approach entry fix.

The airplane's position is checked as departure fix 6 is approached both in the air and on the ground. The ground surveillance system is providing intruder protection, a check on airplane performance, and updating of the short-term wind model for that area and altitude.

The third part of the scheduling routine, the position update module (fig. 2-21), keeps track of the location and decreases the status number from 7 to 6. If the airplane is on course and on time there is no need for communications and the airplane proceeds outbound to the next fixes, departures 5, 4, 3, and 2, etc.

If the airplane cannot make good its schedule to departure fix 6, the problem is resolved in the position update module and the departure schedule module. A new route-time profile will be generated that will accommodate the airplane. This may require the resequencing of adjacent airplanes scheduled for specific times at the departure exit fix.

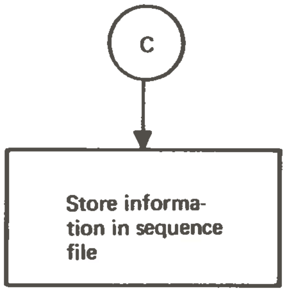


FIGURE 2-15.—STORE INFORMATION IN SEQUENCE LIST

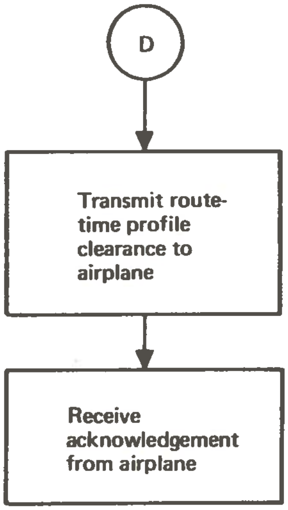
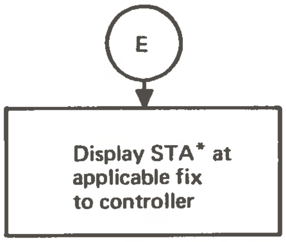


FIGURE 2-16.—TRANSMIT CLEARANCE TO AIRPLANE



*Scheduled time of arrival

FIGURE 2-17.—DISPLAY STA* AT APPLICABLE FIX

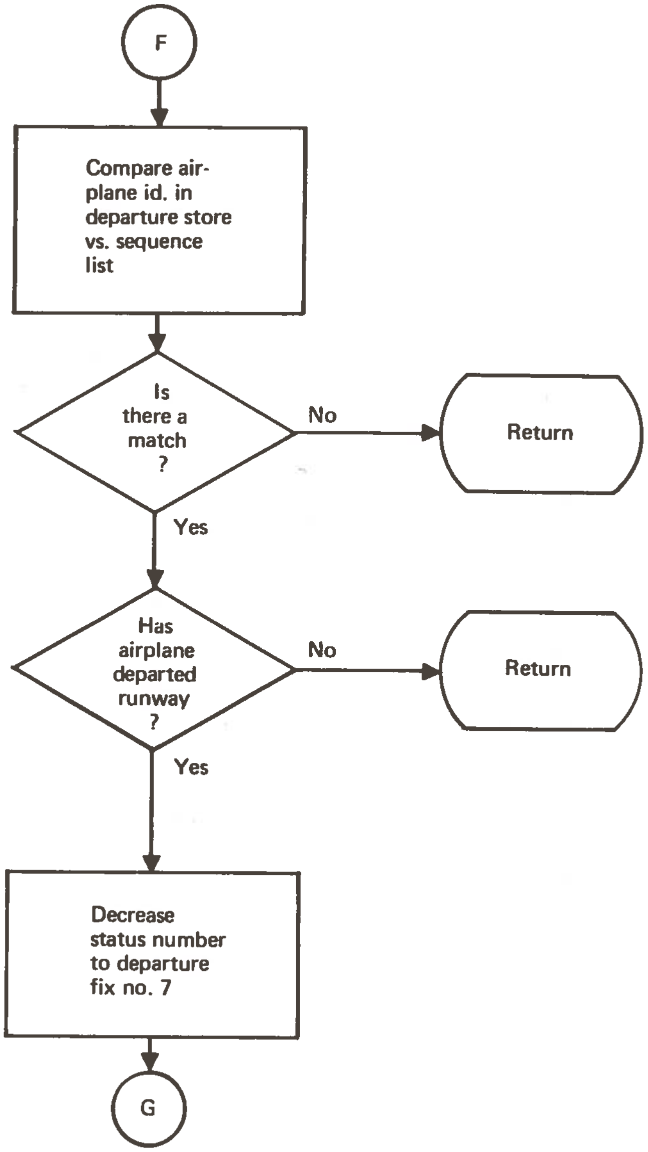
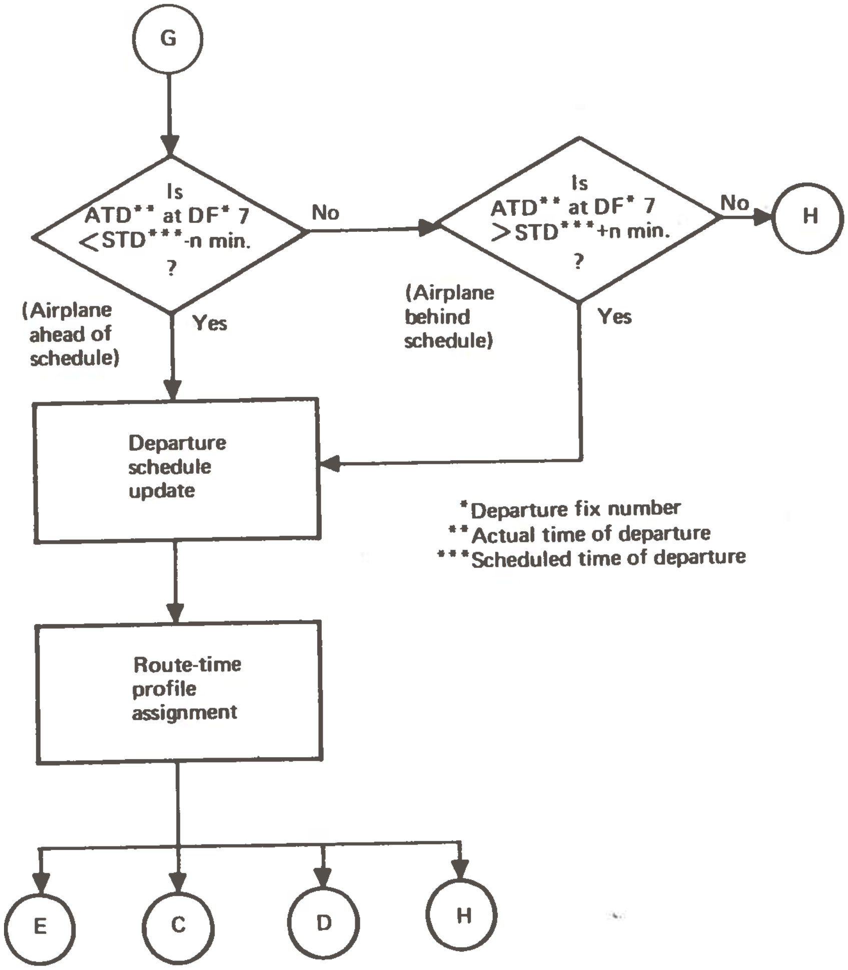


FIGURE 2-18.—AIRPLANE STRATEGIC CONTROL DEPARTURE FROM RUNWAY



*Departure fix number
**Actual time of departure
***Scheduled time of departure

FIGURE 2-19.—AIRPLANE ACTUAL RUNWAY TAKEOFF TIME VS. RUNWAY ASSIGNMENT TIME

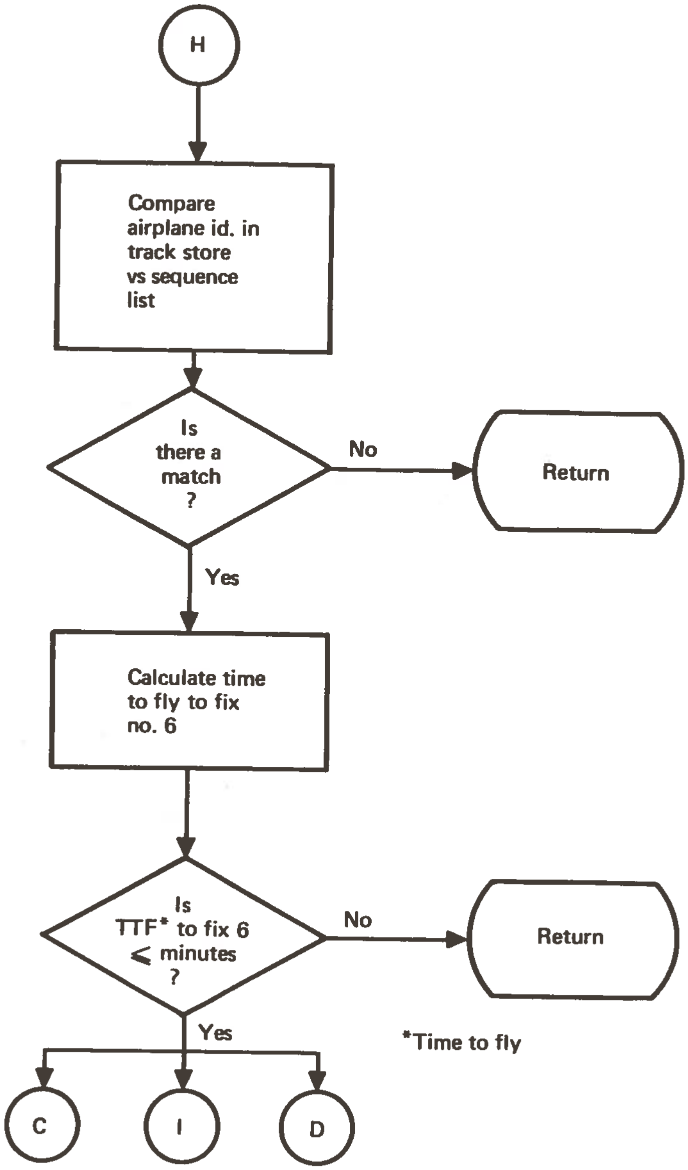


FIGURE 2-20.–APPROACH TO DEPARTURE FIX NO. 6

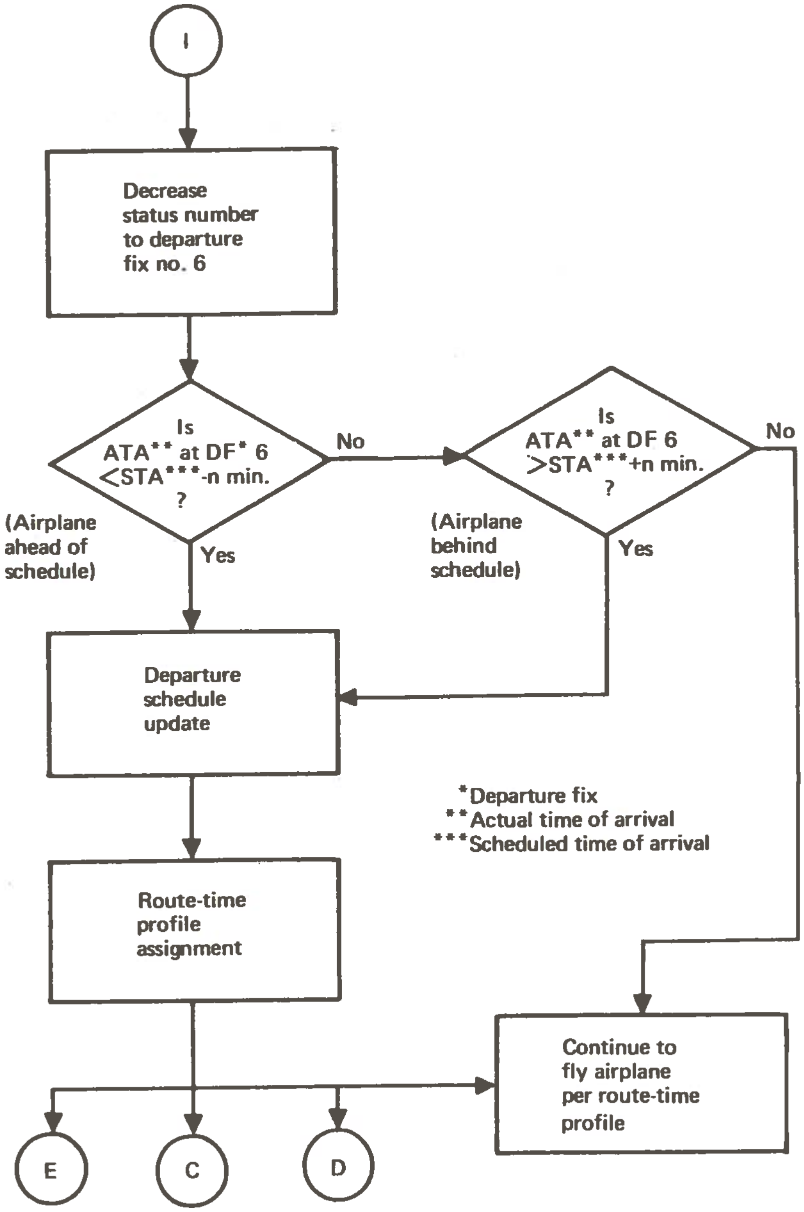


FIGURE 2-21.—CHECK OF AIRPLANE RTP STATUS AT DEPARTURE FIX NO. 6

The airplane proceeds outbound with the position update module keeping track of position, decreasing status number, and relaxing tolerances, as indicated in figure 2-22.

2.1.4 Strategic En Route Control Functional Description

The strategic en route control of individual airplanes begins just prior to the en route entry fix. An arriving airplane is given an estimated time of arrival at the en route exit fix that is equal to its estimated time of arrival at the en route exit fix as filed in the flight plan. In other words, the arriving airplane is cleared to pass the en route entry fix, enter the en route area, and exit the en route exit fix. The en route path fixes and times are specified.

Metering is performed when the scheduled arrival time at the en route exit fix is prepared for each airplane. The en route area is used to adjust for errors in actual versus predicted performance and to help schedule and space a stream of airplanes to aid the strategic approach control program.

Tentative scheduling is done for a general path from the en route entry fix to the en route exit fix using airplane maximum speed or nominal route-profile speed, whichever is smaller. A final en route schedule time is provided by the en route schedule subroutine.

The strategic control scheduling program has been divided into three basic modules, each performing one of the separate functions required to schedule an airplane from the en route entry fix to the en route exit fix. The first of these is the schedule activation module. After the airplane becomes an active track within the radar range and as it approaches within 50 miles or so of the en route entry fix, calculations can be made for a scheduled time at the en route entry fix. The design premise for the schedule activation module is that the airplane is being tracked and any information obtained from tracking is better than the estimates received from the flight plan.

With the airplane under radar track the original tentative estimates of time to the en route entry fix can be updated. Using the airplane's present position, a time to fly to the en route entry fix is calculated and added to the current time to provide an actual time of arrival at the entry fix. If the time to fly to the en route entry fix is too great, control is returned to the executive program (fig. 2-23). When the airplane gets to within the predetermined limit of the en route entry fix, the status of the airplane in the active track file decreases from 9 to 8, as indicated in figure 2-24. When the previously planned sequence and schedule at the en route entry fix are satisfactory, the route-time profile is assigned (fig. 2-24).

The en route schedule routine generates a route-time profile that will accommodate the particular airplane proceeding en route from the en route entry fix, and that will be compatible with the other flight profiles of the other airplanes in the sequence—the one ahead in time and the one behind.

The route-time profile data are stored, transmitted, and made available for display (figs. 2-25, 2-26, and 2-27).

The pilot, aided by on-board navigation, computer, and flight management equipment, works the problem of on-time arrival at the first fix en route from en route entry fix 7. The

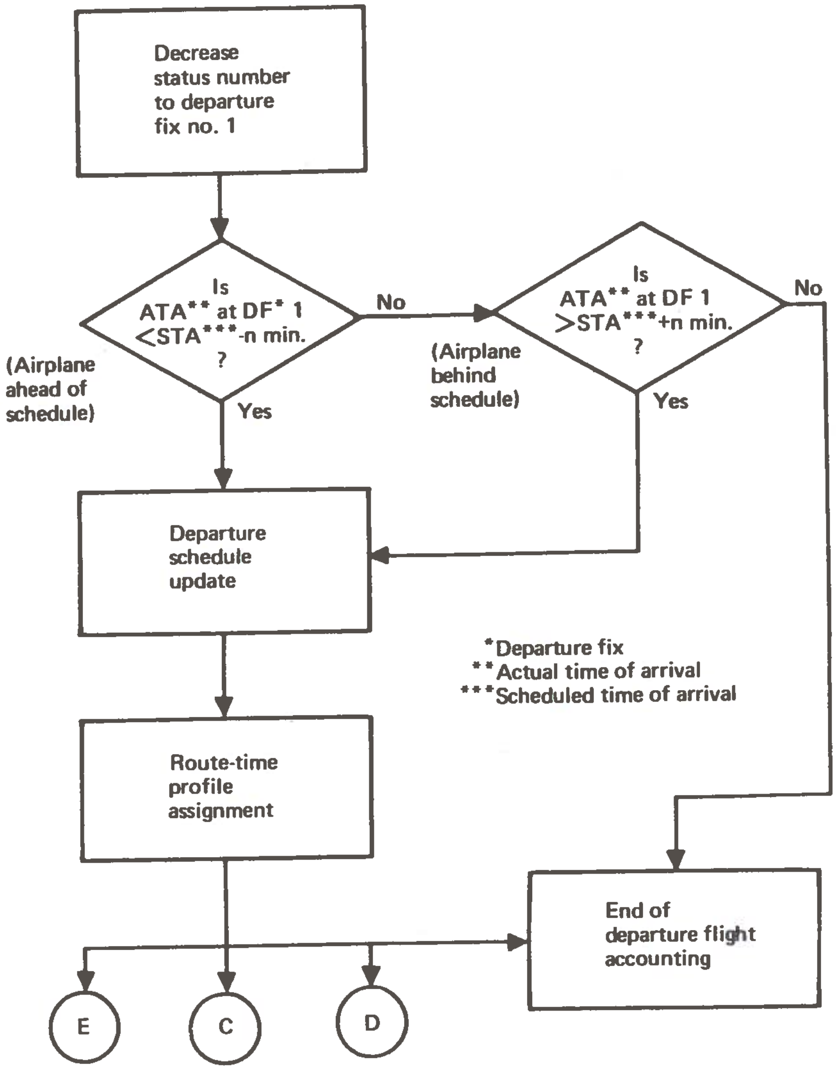


FIGURE 2-22.–END OF STRATEGIC DEPARTURE CONTROL FLIGHT

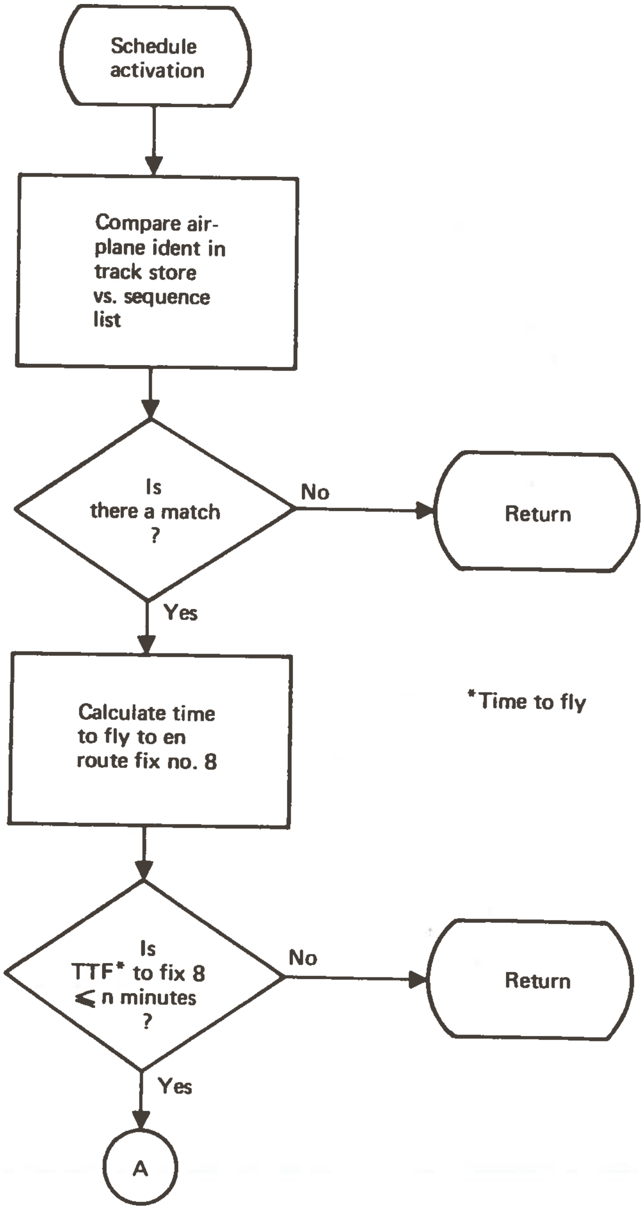


FIGURE 2-23.—APPROACH TO ENTRY FIX

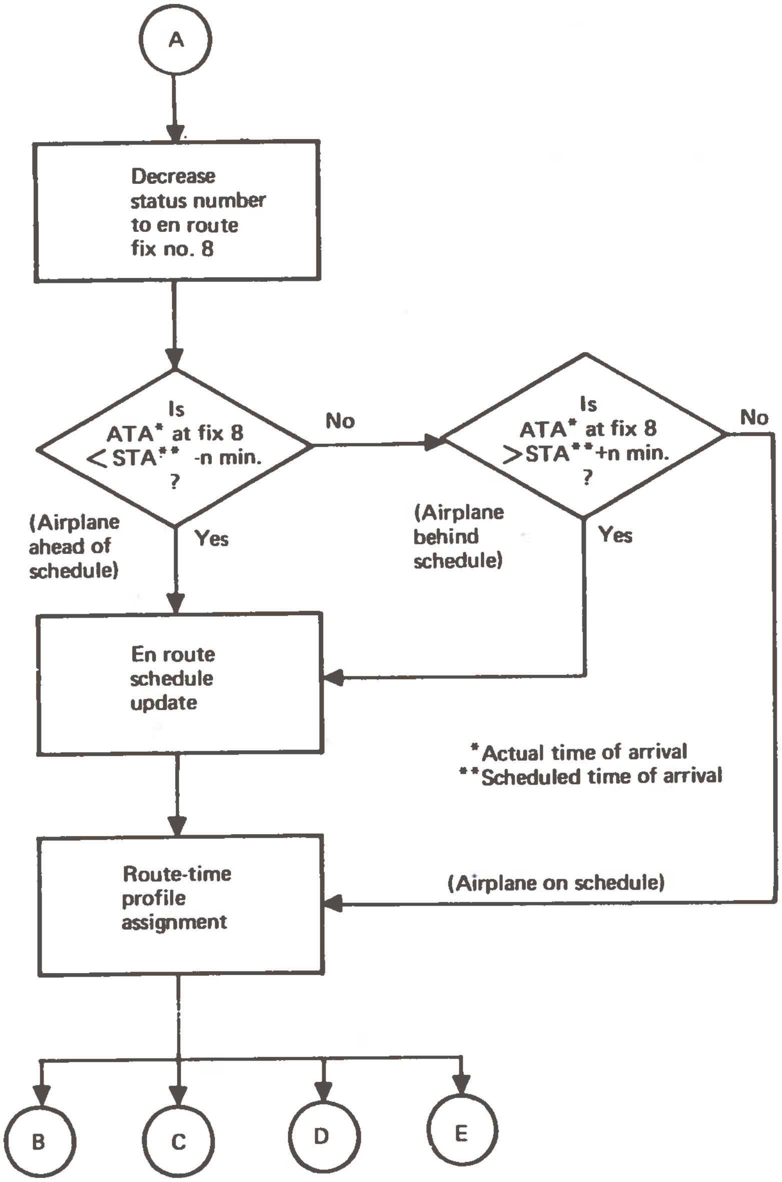


FIGURE 2-24.—DECREASE OF AIRPLANE STATUS TO EN ROUTE ENTRY FIX

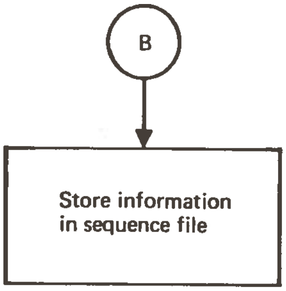


FIGURE 2-25.—STORE INFORMATION IN SEQUENCE LIST

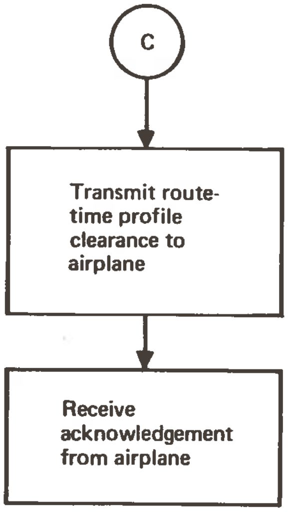
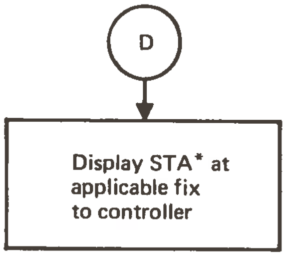


FIGURE 2-26.—TRANSMIT CLEARANCE TO AIRPLANE



*Scheduled time of arrival

FIGURE 2-27.—DISPLAY STA* AT APPLICABLE FIX ground system checks identity and computer distance to en route fix 7, as indicated in figure 2-28.

The airplane's position is checked as fix 7 is approached both in the air and on the ground. The ground surveillance system is providing intruder protection, a check on airplane performance, and updating of the short-term wind model for that area and altitude.

The third part of the scheduling routine, the position update module, keeps track of the location, decreases the status number from 8 to 7, and checks the allowable tolerances on position and time at the fix indicated in figure 2-29. The airplane proceeds through the assigned fixes of the en route system until completion of the en route portion of the flight.

If the airplane cannot make good its schedule to any en route fix, the problem is resolved in the position update module and the en route schedule module. A new route-time profile will be generated that will accommodate the airplane. This may require the resequencing of adjacent airplanes scheduled for specific times at the en route exit fix.

As the last en route fix is approached the identity of the airplanes are checked by comparing the data in track store with that in the sequence list. Those airplanes not under strategic control are sorted out as indicated in figure 2-30. The four-dimensional position of the airplanes and their time from en route exit fix are computed. If they are still too far from the en route exit fix, the surveillance system ignores them except to provide intruder protection and to acquire data for the short-term wind model. When the time to fly to the fix becomes less than a specified time the position update module receives the position information and these data are also displayed to the controller.

When the airplane approaches the en route exit fix the status number is reduced to 1 as shown on figure 2-31 and from 9 to 8 in the approach strategic control or oceanic strategic control programs. The new route-time profile is received and stored by the airplane. The transition from the strategic en route control programs to the strategic approach control or strategic oceanic control program takes place at the en route exit fix.

2.1.5 Strategic Oceanic Control Functional Description

The strategic oceanic control program provides control from the oceanic entry fix to the oceanic exit fix. It provides a means of orderly control of airplanes as they enter the en route areas or terminal areas and will make easier the strategic control of the airplanes in those areas.

The strategic oceanic control program also provides control during the ocean crossing, keeping a check on the position to see that the route-time profile is maintained.

The strategic control of individual airplanes begins prior to the oceanic entry fix. An arriving airplane is given an estimated time of arrival at the oceanic entry fix that is equal to its estimated time of arrival at the entry fix as filed in the flight plan. In other words, the arriving airplane is cleared to enter the entry fix, enter the oceanic area, and depart the oceanic area. The oceanic path fixes and times are specified.

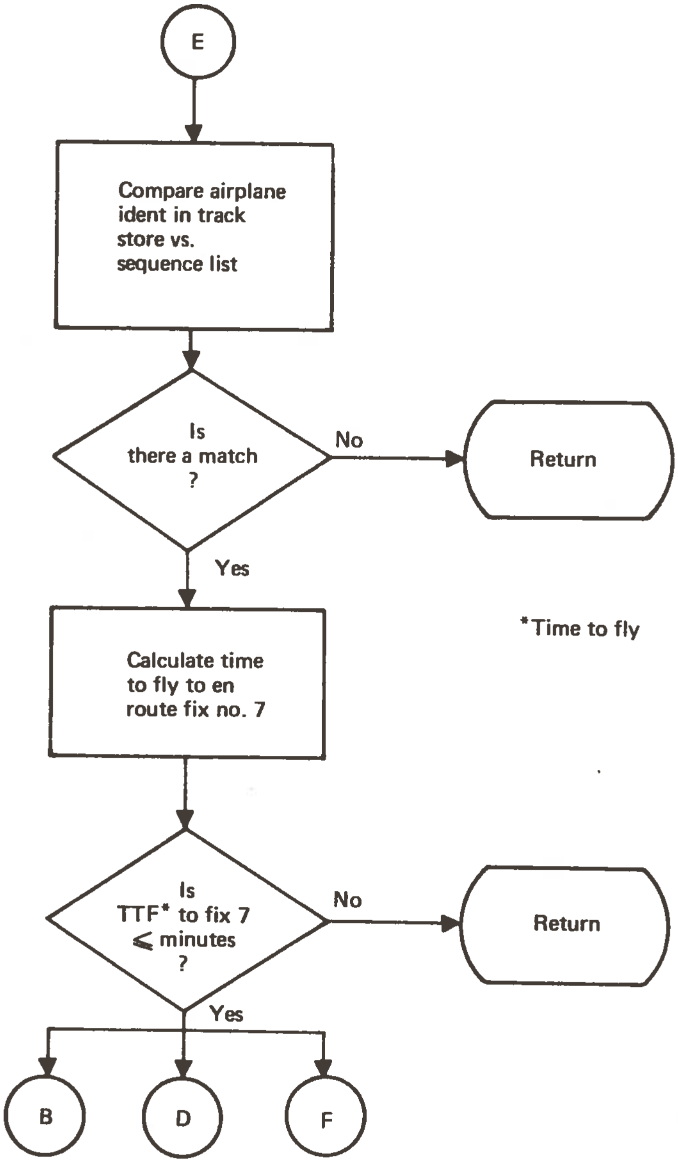


FIGURE 2-28.—APPROACH TO EN ROUTE FIX NO. 7

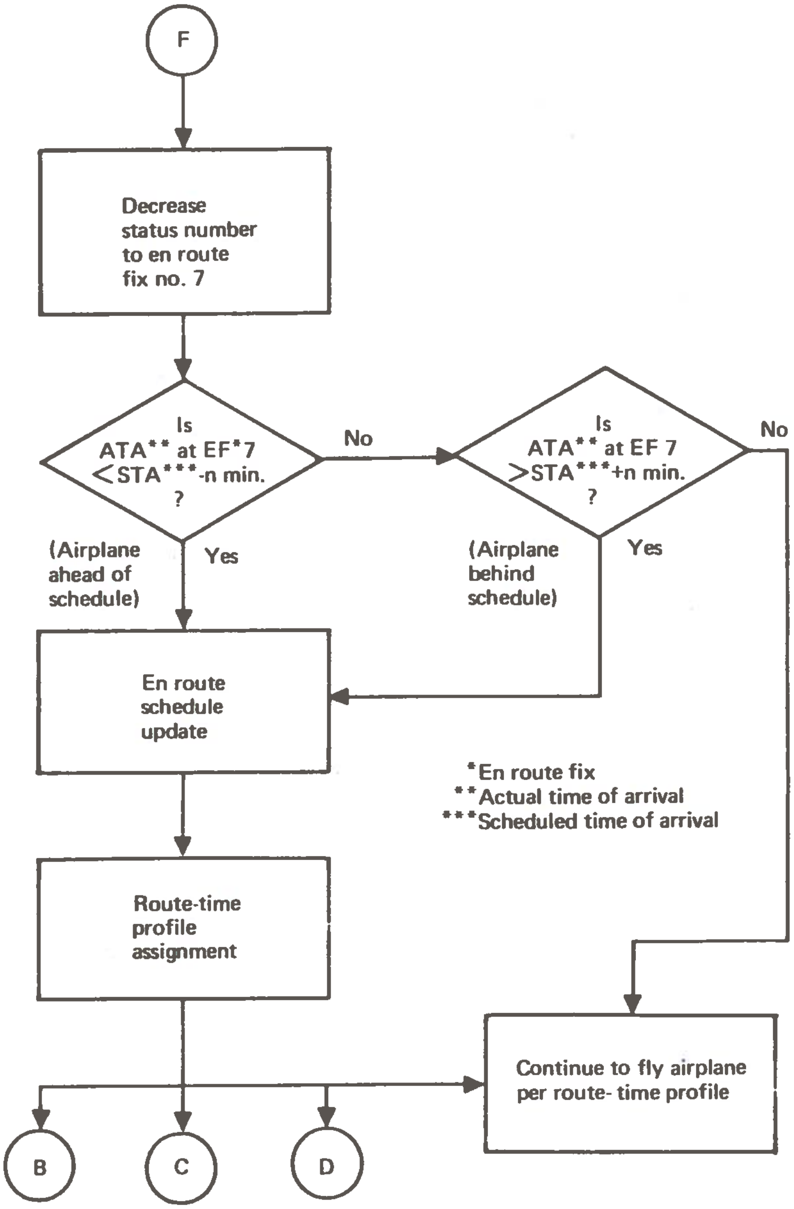
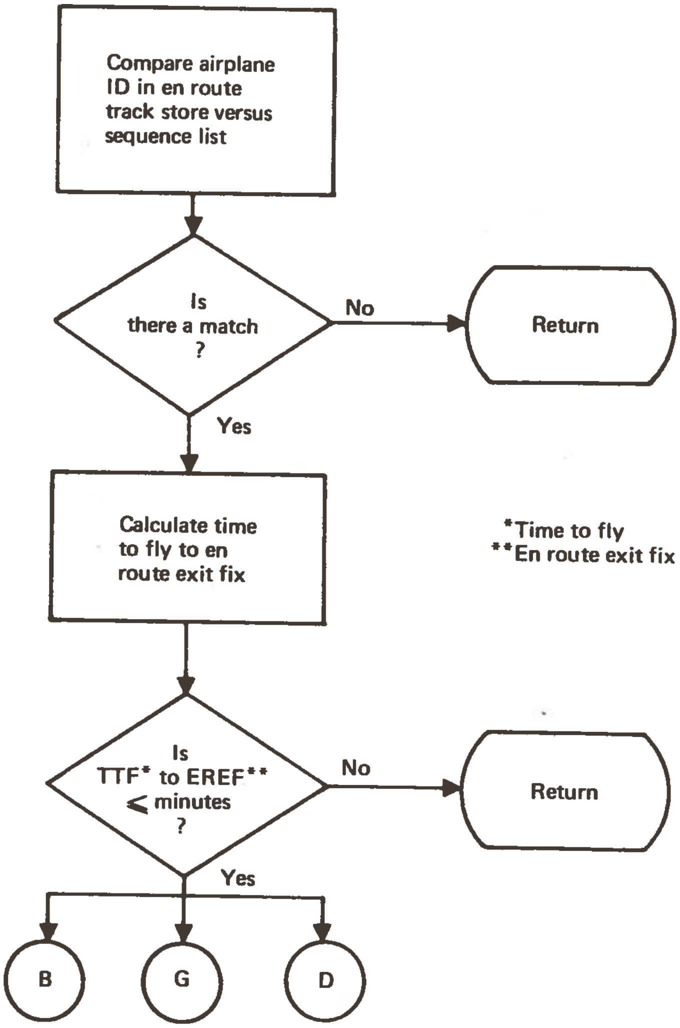


FIGURE 2-29.—CHECK OF EN ROUTE AIRPLANE ROUTE-TIME PROFILE STATUS



*Time to fly
**En route exit fix

FIGURE 2-30.—APPROACH TO EN ROUTE EXIT FIX

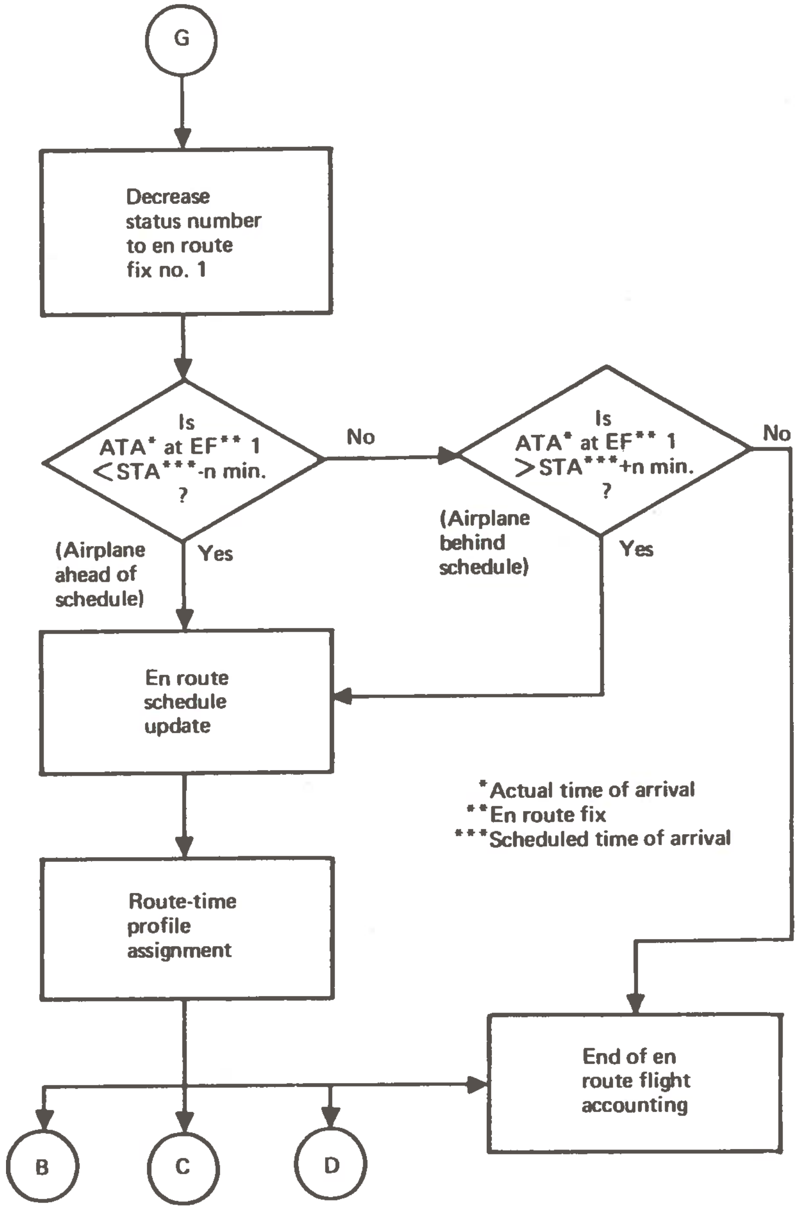


FIGURE 2-31.—END OF STRATEGIC EN ROUTE FLIGHT

Metering is performed when the scheduled arrival time at the oceanic exit fix is prepared for each airplane. The oceanic areas are used to adjust errors in actual versus predicted performance and to schedule and space a stream of airplanes to aid the strategic approach control program. Tentative scheduling is done with a general path from the oceanic entry fix to the oceanic exit fix using airplane maximum speed or nominal route-profile speed, whichever is smaller. The tentative schedule routine checks the route-time profile files and oceanic schedule files for a suitable path.

The strategic control scheduling program has been divided into three basic modules, each performing one of the separate functions required to schedule an airplane from the oceanic entry fix to the oceanic exit fix. The first of these is the schedule activation module. After the airplane becomes an active track within the radar range and as it approaches within 20 miles or so of the oceanic entry fix, calculations can be made for a scheduled time at the oceanic exit fix. The original tentative estimates of time to the oceanic exit fix are updated. Using the airplane's present position, a time to fly to the oceanic entry fix is calculated and added to the current time, to provide an actual time of arrival at the entry fix (fig. 2-32). When the previously planned sequence and schedule to the oceanic exit fix are satisfactory, the airplane requires the details of the route-time profile to be followed to make good the scheduled time to the oceanic exit fix (fig. 2-33).

As the airplane proceeds toward the oceanic entry fix it is continuously tracked. The route-time profile data are transmitted, stored, and made available for display (figs. 2-34, 2-35, and 2-36).

The pilot, aided by on-board navigation, computer, and flight management equipment, works the problem of on-time arrival at the first fix outbound from oceanic entry fix 7. The ground system checks identity and computer distance to fix 7 as indicated in figure 2-37.

The airplane's position is checked as oceanic fix 7 is approached both in the air and on the ground. The ground surveillance system is providing intruder protection, a check on airplane performance, and updating of the short-term wind model for that area and altitude.

The airplane proceeds outbound with the position update module keeping track of position, decreasing status number, and checking tolerances (fig. 2-38). The airplane proceeds through oceanic fixes (status 6, 5, 4, 3, 2) and to the oceanic exit fix 1 (status 1).

As the last oceanic fix is approached the identities of the airplanes are checked by comparing the data in the track store with those in the sequence list. Those airplanes not under strategic control are sorted out as indicated in figure 2-39. When the airplane approaches the oceanic exit fix the status number is reduced to 1 as shown in figure 2-40 and from 9 to 8 in the strategic approach control or strategic en route control program. The new route-time profile is received and stored by the airplane. The transition from the strategic oceanic control program to the strategic approach control or strategic en route control program takes place at the oceanic exit fix.

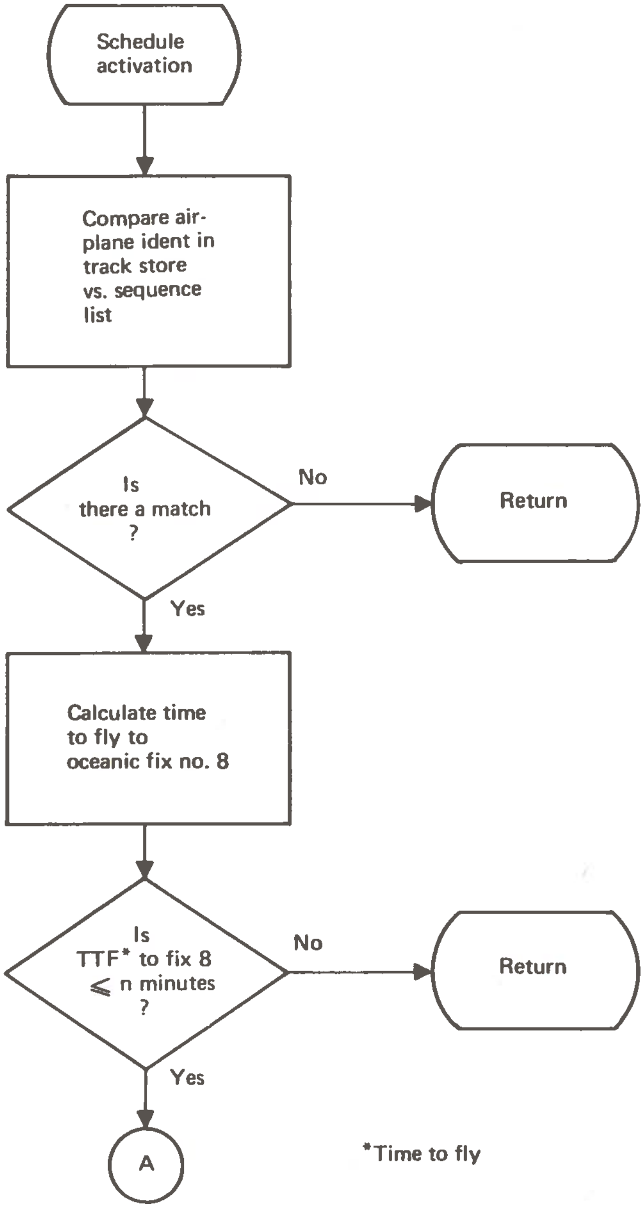


FIGURE 2-32.–APPROACH TO OCEANIC FIX NO. 8

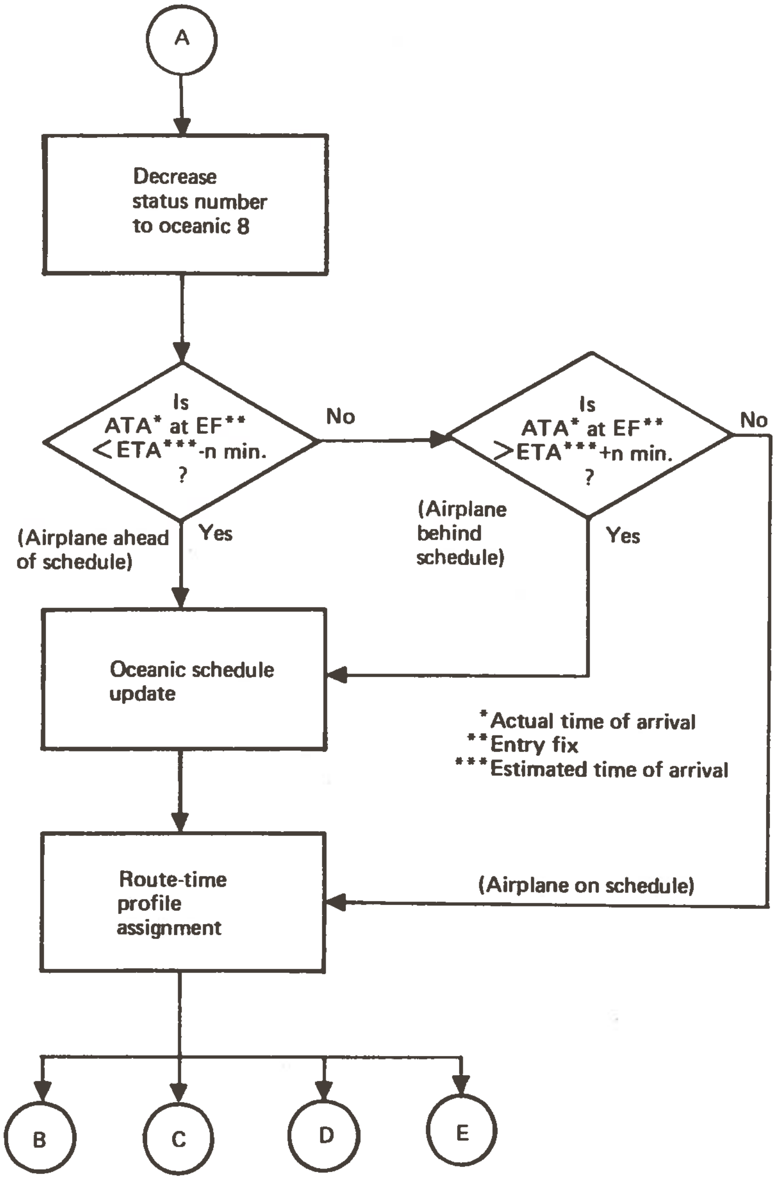


FIGURE 2-33.—DECREASE OF AIRPLANE STATUS TO OCEANIC 8

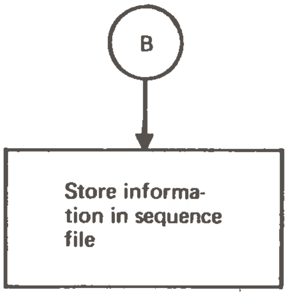


FIGURE 2-34.–STORE INFORMATION IN SEQUENCE LIST

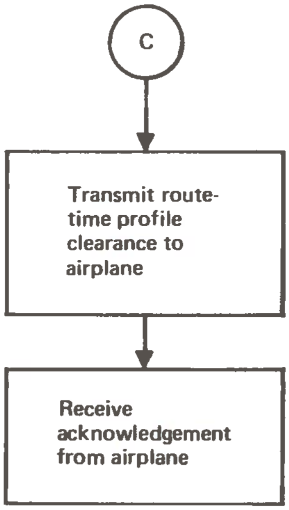


FIGURE 2-35.–TRANSMIT CLEARANCE TO AIRPLANE

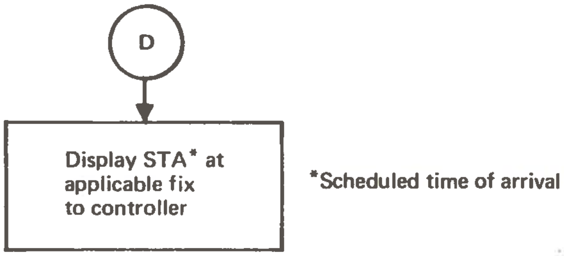
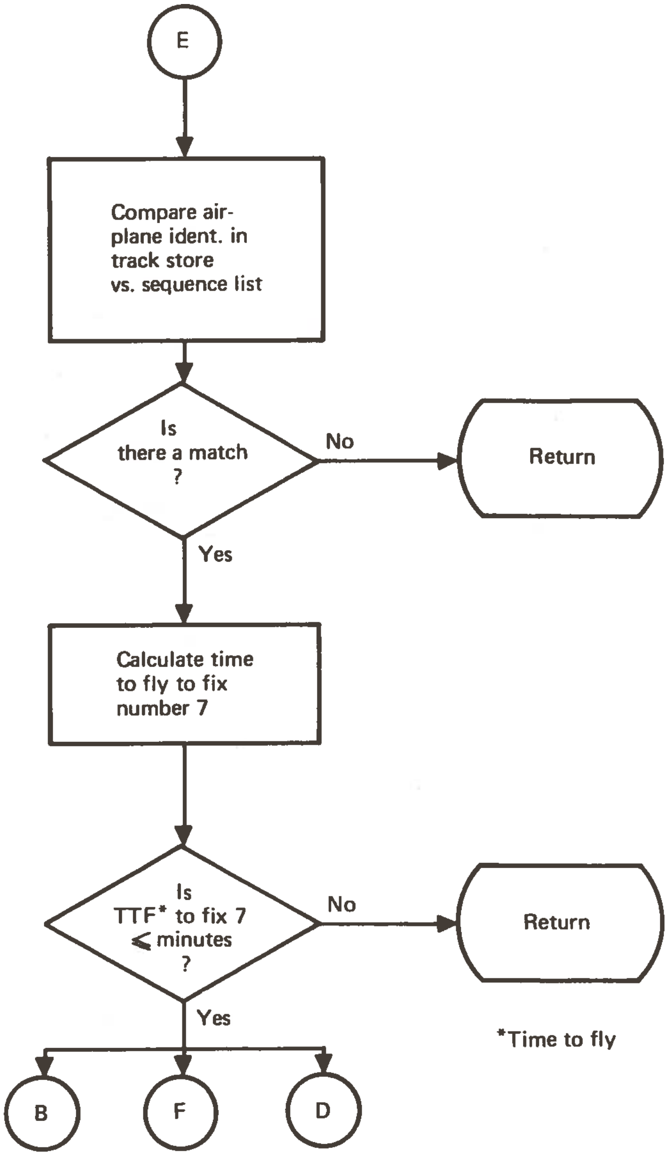


FIGURE 2-36.–DISPLAY STA* AT APPLICABLE FIX



*Time to fly

FIGURE 2-37.–APPROACH TO OCEANIC FIX NO. 7

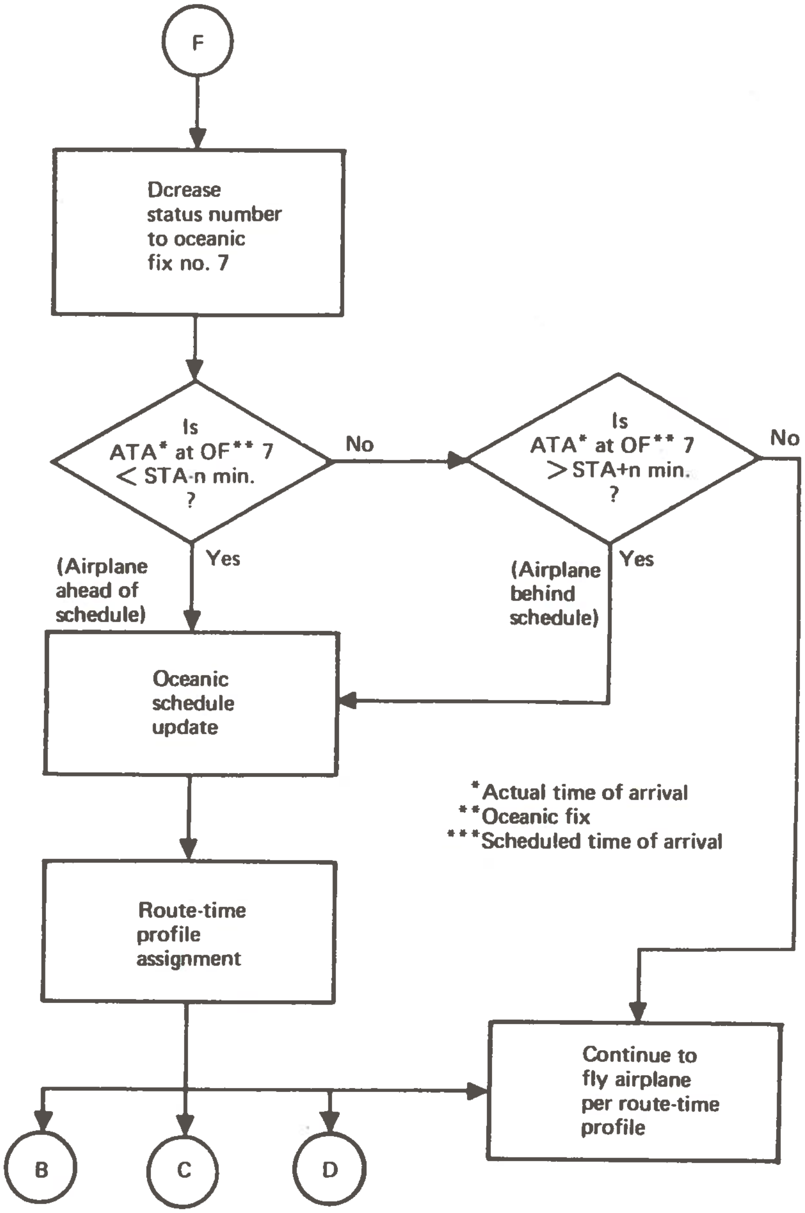


FIGURE 2-38.–STRATEGIC OCEANIC ROUTE-TIME PROFILE CHECK

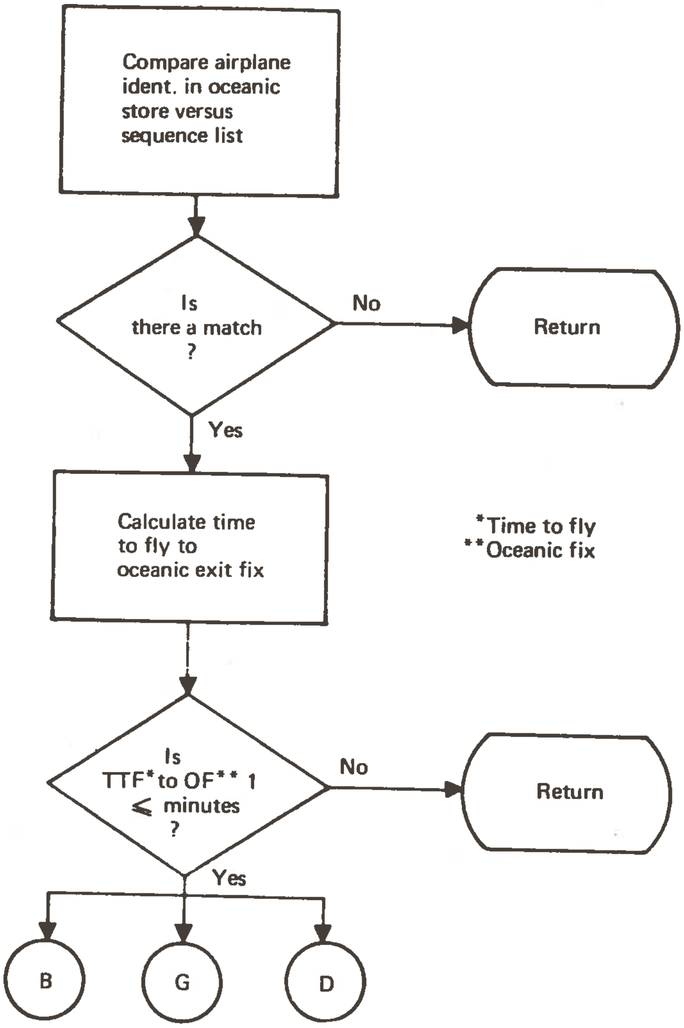


FIGURE 2-39.—APPROACH TO OCEANIC EXIT FIX

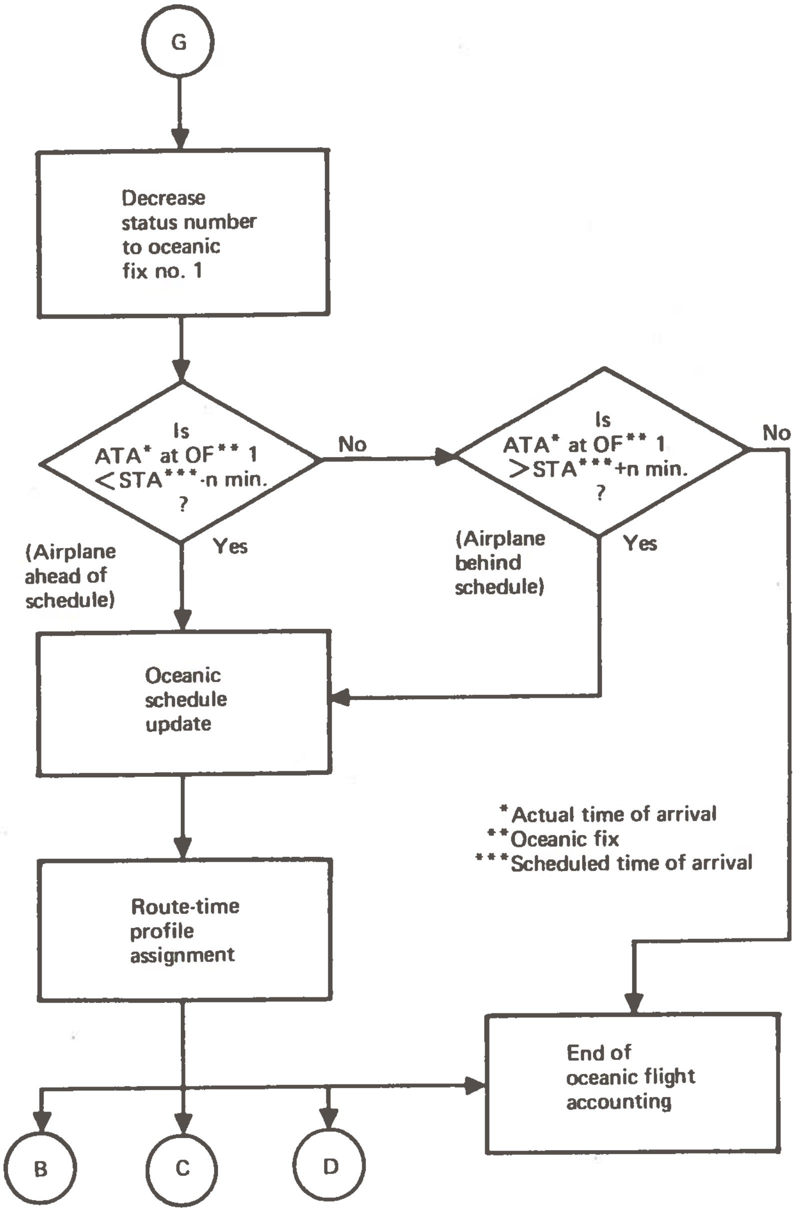


FIGURE 2-40.–END OF STRATEGIC OCEANIC CONTROL FLIGHT

2.1.6 London-to-Honolulu Strategic Flight Scenario

This scenario uses the logic flow descriptions developed in sections 2.1.1 through 2.1.5 to generate a scenario for a flight from London, to New York, to Los Angeles, to Hawaii. This scenario provides a means of comprehending the nature of the decisions and functions required to actually execute a strategically controlled flight through the system from planning through completion.

The airplane is a Boeing 747 belonging to Air Columbia. The airplane's call sign is AC 1654. It flies a fixed schedule such that the flight plan is prefiled. Strategic control is available within the conterminous United States and AC 1654 is properly equipped to take advantage of this service.

2.1.6.1 London-to-New-York Flight Stage

AC 1654 has a prefiled flight plan. The flight plan is predictable and repetitive and is stored in a bulk storage medium at the London ATC Center. The flight plan is transferred automatically from bulk storage to core storage at the appropriate time and enters the computer for processing. AC 1654 operates every day between London, New York, Los Angeles, and Honolulu using predetermined routing equipment. Since the flight plan is stored at the London ATC Center, the carrier is only required to submit an amended flight plan for changes from the stored flight plan.

When the flight plan is center stored, the flight progress strips are printed during the night shift for the coming day and set aside. They are delivered by assistants half an hour before departure of AC 1654 to the required positions. This procedure results in time savings and reduces congestion during busy periods. The contiguous U.S. portion of the flight of AC 1654 will be under strategic control and the capability of the airplane is of primary importance in that airspace. The speed, range, cruise altitude, etc., of AC 1654 are available in the U.S. Air Traffic Management data base as are data on types and status of on-board equipment required for strategic controlled flight. A copy of the flight plan is sent by teletype to all points in the system concerned with AC 1654's flight.

When the pilot is ready to start the airplane's engines, he calls clearance delivery, "Air Columbia 747, AC 1654, requesting IFR clearance to Shanwick Oceanic." The clearance delivery controller will look for the clearance and replies, "Air Columbia 747 AC 1654." This is clearance delivery. IFR clearance ATC clears Air Columbia 747 AC 1654 to "Shanwick Oceanic, center stored flight plan, maintain flight level 270, takeoff runway 10 right, depart Heathrow UB 29 to Woodley, enter UG-1 at Woodley, enter Shannon UIR at Slaney, squawk 1101."

Upon departure the Heathrow tower controller depresses a button on his console that will automatically input departure time for AC 1654 into the computer at London ATC Center. The pilot follows the cleared departure route to leave the London area.

With the United Kingdom NATCS equipped with facilities for radar data processing, it is not necessary for AC 1654 to report its progress as it proceeds IFR toward Shannon. It maintains the same transponder code until landing in New York. The flight plan is forwarded to Shanwick Oceanic Center via landline teletype. The pertinent details of the flight plan are stored in the center for later use. When the flight takes off from Heathrow, the center is notified of the departure time. Based on the time of departure, filed airspeed, and forecast winds, planning and coordination strips are prepared by Shanwick Oceanic Center. These strips contain the estimated time that the flight will be over the last few Shannon fixes and the first oceanic fix at 53°N latitude, 15°W longitude. The oceanic planner examines the route, altitude, and fix times to tentatively determine if the flight will conflict with other flights.

As the flight approaches the boundary between the Shannon UIR and the Shanwick OCA, updated fix estimates are forwarded to the Shanwick Oceanic Center. These fix estimates are used to actively plan the airplane oceanic route. This planning consists of a check of the proposed route, altitude, and fix times against all other active tracks to determine if the requested flight path of the airplane will be conflict free. If the requested route (track X) is conflict free, it is assigned to the flight. If it is not conflict free, then the route, altitude, or time must be changed. Since the requested route was a track in the organized track system, then alternate flight levels and/or tracks are checked to determine a conflict-free route for the flight.

Once the conflict-free route has been developed, it is held at the clearance delivery position in the Shanwick Oceanic Center for delivery to the pilot when he calls in and requests clearance. He must make this call when still east of 2°W longitude. If the organized route has been changed from that requested by the pilot, he will need a few minutes to modify his request for clearance between Shannon VOR and the oceanic entry fix at 15°W longitude.

Before handoff from London ATC Center to Shannon ATC Center at Slaney, the pilot is in possession of his oceanic clearance. AC 1654 can now request clearance from Shannon ATC Center for a flight from Shannon VOR on a vector of 289° true to 15°W, 53°N, the oceanic entry fix for organized track "X." The handoff of the flight from Shannon ATC Center to Shanwick Oceanic is handled according to normal ATC procedures.

When AC 1654 enters the oceanic area, it is handed off to the appropriate oceanic high altitude controller. This controller monitors the airplane across the ocean and hands the flight plan to Gander Oceanic Center when AC 1654 passes the 40°W meridian. Reporting points for AC 1654 are at 15°, 20°, 30°, and 40°W, where the airplane is handed off.

After handoff from Shanwick Oceanic to Gander Oceanic, the control passes to the western side of the Atlantic Ocean. AC 1654 makes position reports at 50°W longitude and at position CYQX where track X terminates. At this point the oceanic high altitude controller at Gander hands off to the appropriate domestic high altitude controller at Gander, who monitors the flight as it transits Canadian airspace. The transponder code remains the same and ATC relays progress of the flight to New York Center.

After AC 1654 comes within range of New York radar and as it approaches within 200 miles or so of J. F. Kennedy Airport, calculations can be made for a scheduled time at the runway. The schedule activation module is alerted. This module withdraws from the data bank the flight plan for AC 1654 and the specific details of the airplane and its equipment.

With AC 1654 under radar track, the original tentative estimates of time to the runway can be updated. Using AC 1654's present position, a time to fly to the entry fix is calculated and added to the current time to provide an actual time of arrival at the entry fix. When AC 1654 gets near the entry fix, a comparison is made between flight plan estimated time of arrival at the entry fix and the actual time. If the two times are within allowable tolerance, the previously planned sequence and schedule at the runway are satisfactory and all AC 1654 requires is the details of the route-time profile to be followed in order to make good the scheduled time at the runway. AC 1654 receives its detailed route-time profile from entry fix to touchdown at a time just prior to arriving at the entry fix.

If AC 1654 is ahead of schedule at the entry fix, an attempt is made to resequence and move the scheduled time at the runway forward in time to accommodate it. If, on the other hand, it is behind schedule, a new later scheduled time at the runway must be planned.

The runway schedule routine generates a route-time profile that will accommodate AC 1654 proceeding inbound from the entry fix that will be compatible with other flight profiles of airplanes in the sequence—the one ahead in landing and the one behind.

The pilot, aided by on-board navigation, computer, and other flight management equipment, works the problem of on-time arrival at each of the fixes inbound from the entry fix. The ground system checks identity and position, provides intruder protection, and acquires wind data to update the short-term wind model for that area and altitude. If AC 1654 is on course and on time, there is no need for communications and the airplane proceeds inbound to J. F. Kennedy International Airport.

When AC 1654 turns onto final approach, the status number is reduced to 1 and the location is checked to see if it is within tolerance. The permissible along-track tolerance might be ±0.1 to 0.2 mile as final begins with touchdown tolerance to be within ±0.05 to 0.1 mile. If AC 1654 is not within these tolerances a modification to the route-time profile is made. The flight of AC 1654 is a routine flight and the pilot makes good his route-time profile, landing at J. F. Kennedy Airport within the time slot allocated to him.

2.1.6.2 New York-to-Los Angeles Flight Stage

The strategic departure control program provides control from the gate to a point where AC 1654 exits the last strategic departure control fix. At this point AC 1654 enters the en route portion of the system.

The strategic departure control of AC 1654 begins prior to departure from the gate. In the usual case, AC 1654 is given an estimated departure time from the runway that is equal to its estimated time of departure from the runway as filed in the flight plan. Using the flight plan estimated departure time from the runway, the tentative schedule routine checks the route-time profile files and runway schedule files for a runway departure vacancy. If no space is available, a tentative hold request is issued. Departure times are available so a tentative departure time is reserved for AC 1654. This departure time is equal to departure time from the gate plus taxi time to the runway.

When AC 1654 departs the gate the runway schedule assignment and route-time profile are computed. Because the strategic departure mode has no priority over arrivals in general and aborts in particular, AC 1654 may be called upon to hold at any time after leaving the gate.

When AC 1654 actually departs the gate, the departure time is compared to the estimated departure time. If the two times are within tolerance, the takeoff time previously set aside on a tentative basis is assigned to the airplane. AC 1654 departs the gate on schedule and its departure time slot from the runway is not commandeered by an arriving plane so it departs the runway on schedule. The route-time profile it receives by data link after departing the gate gives the four-dimensional fixes that will allow AC 1654 to make its way to the departure exit fix, which is the first en route fix of the strategic en route control program.

The pilot, aided by on-board navigation, computer, and other flight management equipment, works the problem of on-time arrival at the four-dimensional fixes. The ground ATC system checks altitude, identity, position, and time. The ground system also provides intruder protection and acquires data to update the short-term wind model for that area and altitude.

When AC 1654 gets within a short distance of the departure exit fix (the location also of en route entry fix), the route-time profile for the en route portion of the flight is received.

The route-time profile for the en route flight across the continent will aid the strategic approach control program in smoothing the flow of traffic into the Los Angeles terminal area.

The pilot, aided by on-board navigation, computer, and other flight management equipment, works the problem of on-time arrival at the en route fixes. AC 1654 is handed off from sector to sector and ARTCC to ARTCC but the disruption in the cockpit routine is minimal. The transponder code received before takeoff from J. F. Kennedy Airport is assigned for the flight to Los Angeles. Frequency changes and weather briefings are received by data link and acknowledged by a push of an acknowledge button.

Over Kansas a violent weather pattern has developed that requires AC 1654 to deviate from the original route-time profile assigned. The en route strategic control routine produces an alternate route that permits AC 1654 to avoid most of the violent weather. The new flight plan is transmitted to the airplane and to Los Angeles, where a new tentative runway time slot is reserved. The route-time profile is agreeable to the pilot and automatically inserted in the airborne computer.

After passing a point approximately midway between Boulder City VORTAC and Needles VORTAC, AC 1654 approaches the en route exit fix, which is also the strategic approach control entry fix for Los Angeles. AC 1654 has adhered to the route-time profile and is on time. The runway schedule time, previously tentatively reserved, is now assigned to AC 1654. The route-time profile routine generates a series of fixes that can be made by the airplane and these data are transmitted by data link just prior to arriving at the entry fix. These fixes are automatically inserted in the airborne guidance computer.

The pilot of AC 1654 now flies the route-time profile received. The allowable deviation at each fix is tightened as the airplane proceeds inbound. AC 1654 is on time and on course and there is no need for communications. The pilot has a clearance to land at Los Angeles International Airport if he can adhere to the schedule. AC 1654 turns onto final and lands well within the time slot allowed, thus terminating this portion of the flight. AC 1654 taxies in to the gate and shuts down engines.

2.1.6.3 Los Angeles-to-Honolulu Flight Stage

The Los Angeles strategic departure control program provides control for AC 1654 from the gate to Cypress fix where the airplane enters Oakland Oceanic CTA/FIR. AC 1654 is given an estimated departure time from the runway, which is the time as filed in the flight plan. The runway schedule assignment and route-time profile are generated when AC 1654 departs the gate. AC 1654 is late departing the gate so the tentative runway time slot cannot be utilized. AC 1654 has no priority over arrivals so it must await a departure time. A departure slot is found for AC 1654 and the route-time profile is generated for the airplane. No approaching airplane requires the departure time assigned to AC 1654 and it departs Los Angeles International with a route-time profile that will allow conflict-free flight to the departure exit fix called Cypress.

The pilot, aided by on-board navigation, computer, and other flight management equipment, works the problem of on-time arrival at the four-dimensional fixes of the route-time profile. AC 1654's position at the departure fixes is checked both in the air and on the ground. The ground surveillance system provides intruder protection, a check on airplane performance, and acquires data to update the short-term wind model for that area and altitude. Because AC 1654 is on course and on time, there is no need for communications.

As AC 1654 nears Cypress fix, it is handed off to Oakland Oceanic Center. It proceeds outbound across the Pacific Ocean on route BRAVO, reporting its position at the 130° and 140° meridians. At Ocean Station November at 140°W longitude, AC 1654 acquires an updated position fix and weather data. AC 1654 is handed off at this point from Oakland Oceanic to Honolulu Oceanic. At 150°W longitude, a position report is made to Honolulu Oceanic Center. At Banana fix at 154° 23'W longitude, 21° 01'N latitude, after a position report is made, the airplane passes from the Honolulu Oceanic CTA/FIR to Honolulu FIR and AC 1654 is handed off again. AC 1654 proceeds inbound on route BRAVO toward Maui VOR. Upon entering Honolulu FIR, the pilot makes use of the civil jet radar advisory service as the airplane is still above flight level 240. AC 1654 is cleared to proceed via Maui VOR, Molokai, and Koko Head and is cleared to land at Honolulu International Airport. AC 1654 lands, taxies in to the gate, and the flight ends.

2.2 SERVICES AND FUNCTIONS MODIFIED BY STRATEGIC CONTROL

One of the most important services modified by strategic control is the Airport/ Airspace Use Planning Service. This service (table 2-1) is the long-range control service concerned with the establishment and modification of plans for airspace and airport use. This service is related to both safety and efficiency, and involves an agreement between user

TABLE 2-1.—ATC SERVICES AND FUNCTIONS MODIFIED BY STRATEGIC CONTROL

Functions Services	Provide flight planning information	Control traffic flow	Prepare flight plan	Process flight plan	Issue clearances and clearance changes	Monitor aircraft progress	Maintain conformance with flight plan	Assure separation of aircraft	Control spacing of aircraft	Provide airborne landing and ground navigation capability	Provide aircraft guidance	Issue flight advisories and instructions	Handoff	Maintain system records	Provide ancillary and special services	Provide emergency services	Determine system capability and status
Planning																	
Flight plan filing			●											○			
Flight plan checking				●													
Flight plan processing				●													
Flight plan approval				●													
Flight plan distribution					●												
Scheduling				●													
Taxiway determination				●													
Runway determination				●													
Flight plan verification				●													
Close flight plan				○										○			
Traffic control																	
SID assignment				○													
Altitude assignment				●													
Vectoring								○									
Handoff													○				
Accept handoff													○				
Blunder determination																	
Flight progress determination						○											
Determine position, X, Y, Z, time																	
Conflict resolution									●								
Departure sequencing								●									
Flight plan conformance							●										
Departure clearance					●												
Flight progress observation																	
Arrival sequencing								●									

● Modified by strategic control ·

TABLE 2-1.—CONTINUED

Services / Functions	Provide flight planning information	Control traffic flow	Prepare flight plan	Process flight plan	Issue clearances and clearance changes	Monitor aircraft progress	Maintain conformance with flight plan	Assure separation of aircraft	Control spacing of aircraft	Provide airborne landing and ground navigation capability	Provide aircraft guidance	Issue flight advisories and instructions	Handoff	Maintain system records	Provide ancillary and special services	Provide emergency services	Determine system capability and status
Traffic control (continued)																	
Arrival clearance					●												
Merging									●								
Interleaving									●								
STAR assignment					●												
Approach clearance					●												
Metering								●									
Runway assignment					●												
Landing clearance					●												
Waveoff					●												
Missed approach coordination					○												
Separation assurance																	
Spacing									●								
Conflict determination									○								
Collision avoidance								○									
Relative position observation									●								
All weather landing																	
Approach track guidance											○						
Glide path guidance											○						
Airspace structure																	
Routes	●	○															
SIDs	●	○															
STARs	●	○															

● Modified by strategic control ·

TABLE 2-1.—CONTINUED

Functions / Services	Provide flight planning information	Control traffic flow	Prepare flight plan	Process flight plan	Issue clearances and clearance changes	Monitor aircraft progress	Maintain conformance with flight plan	Assure separation of aircraft	Control spacing of aircraft	Provide airborne landing and ground navigation capability	Provide aircraft guidance	Issue flight advisories and instructions	Handoff	Maintain system records	Provide ancillary and special services	Provide emergency services	Determine system capability and status
Weather services																	
Weather observation	○	○															
Weather prediction	●	○															
Weather reporting	○	○												○			
Weather advisories	○	○										○		○			
Pilot reports	○	○															
Ground control and guidance																	
Conflict resolution									●								
Hazard avoidance																	
Handoff													○				
Merging																	
Determine position, X, Y, Z, time																	
Runway assignment					○												
Surface guidance											○						
General field surveillance																	
Blunder determination						○											
Issue taxi instructions					○												
Runway guidance											○						
Metering																	
Flight plan conformance							●										
Takeoff clearance					○												
Taxi exit assignment					○												
Landing guidance											○						
Accept handoff													○				
Determine position, X, Y						○											

● Modified by strategic control

TABLE 2-1.—CONCLUDED

Services \ Functions	Provide flight planning information	Control traffic flow	Prepare flight plan	Process flight plan	Issue clearances and clearance changes	Monitor aircraft progress	Maintain conformance with flight plan	Assure separation of aircraft	Control spacing of aircraft	Provide airborne landing and ground navigation capability	Provide aircraft guidance	Issue flight advisories and instructions	Handoff	Maintain system records	Provide ancillary and special services	Provide emergency services	Determine system capability and status
General information																	
Pilot briefing															○		
General field conditions	○	○															
NOTAMs	○													○			
Emergency assistance																	
Emergency resolution																○	
Abort directive					○												
Facilities operations & maintenance																	
System status monitoring		○															●
System servicing		○															○
Operation & maintenance of:																	
Flow control facilities		○															○
Communication facilities		○															●
Nav & surveillance facil.		○				○		○		○							●
Planning facilities		○															○
Flight service stations																	○
Weather facilities		○															●
Failure resolution		○															●
Operational regulations																	
Regulation determination	○	○															
Standard departure procedures	○	○															
Standard approach procedures	●	○															
Standard landing procedures	●	○															

● Modified by strategic control ·

and control authority. It includes such things as the flight planning process, flow control (both national and local), conflict prevention by planning, promotion of efficiency by planning, and the clearance process.

The strategic control planning process becomes a matter of developing a conflict-free path through the airspace some time (about one-half hour) before the airplane actually penetrates that airspace and providing a clearance for that path.

Those services and functions modified by strategic control are identified by black dots on table 2-1.

2.3 AIR TRAFFIC MANAGEMENT SERVICES BY FLIGHT PHASE MODIFIED BY STRATEGIC CONTROL

In order to identify services that will change as a result of implementing strategic control in the Air Traffic Management system, table 2-2 is provided. Various services provided are identified as to phase of flight. Those services that will change as a result of strategic control are identified by black dots.

Some changes are more pronounced than others. For instance, the flight planning service will have major changes due to the changes in the flight plan generating process and the clearance process. The traffic control service, the long-range service that promotes implementation of the flight plans mentioned above, includes:

- Monitoring to deviation from plan
- Corrections back to the plan
- Modifications to the plan
- Monitoring of conflicts within the plan
- Resolution of these conflicts

Strategic control requires that the airplane adhere closely to the route-time profile provided in the planning process and this monitoring is conducted both in the air and on the ground. If airplane deviation occurs that is outside of the amount allowed, it may be necessary to select a new time at the runway and consequently a new route-time profile to get there.

Weather services, although not a part of strategic control, may require much more sophisticated data collection, analysis, and handling.

The Department of Transportation standardized list of flight phases, dated February 28, 1973, is used in this analysis.

TABLE 2-2.—AIR TRAFFIC FLOW PLANNING/CONTROL OPERATIONS

	Preflight	Departure Taxi	Takeoff	Departure	Departure Transition	En route Conus	En route Oceanic	Arrival Transition	Arrival	Approach	Landing	Arrival Taxi	Postflight
Planning													
Flight plan filing	●												
Flight plan checking	●												
Flight plan processing	●												
Flight plan approval	●												
Flight plan distribution	●												
Scheduling		●											
Taxiway determination		●											
Runway determination		●											
Flight plan verification		●											
Flight plan modification					●	●	●	●					
Close flight plan													●
Traffic control													
SID assignment			●										
Altitude assignment			●										
Vectoring			●										
Handoff			○										
Accept handoff			○										
Blunder determination			○										
Flight progress determination			●										
Determine position, X, Y, Z, time			●	●	●	●	●	●	●	●	●		
Conflict resolution				○	○	○	○	○	○	○	○		
Departure sequencing					●								
Flight plan conformance				●	●	●	●	●	●	●	●		
Departure clearance					●								
Flight progress observation					○	○	○	○	○	○	○		
Arrival sequencing								●					
Arrival clearance						●							
Merging						●		●					
Interleaving						●		●					
STAR assignment								●					
Approach clearance								●					

● Modified by strategic control

TABLE 2-2.—CONTINUED

	Preflight	Departure Taxi	Takeoff	Departure	Departure Transition	En route Conus	En route Oceanic	Arrival Transition	Arrival	Approach	Landing	Arrival Taxi	Postflight
Traffic control (continued)													
Metering								●					
Runway assignment											●		
Landing clearance											●		
Waveoff											●		
Missed approach coordination											●		
Separation assurance													
Spacing		●	●	●	●	●	●	●	●	●	●	●	
Conflict determination		●	●	●	●							●	
Collision avoidance		○	○	○	○							○	
Relative position observation		○	○	○	○							○	
All weather landing													
Approach track guidance										○			
Glide path guidance											○		
Airspace structure													
Routes						●	●						
SIDs				●	●								
STARs								●	●				
Weather services													
Weather observation	○	○	○	○	○	○	○	○	○	○	○		
Weather prediction	●	●		●	●	●	●	●	●				
Weather reporting	○												
Weather advisories		○	○	○	○	○	○	○	○	○	○		
Pilot reports				○	○	○	○	○	○				
Ground control and guidance													
Conflict resolution		●	●									●	
Hazard avoidance		○										○	
Handoff		○											

● Modified by strategic control

TABLE 2-2.—CONTINUED

	Preflight	Departure Taxi	Takeoff	Departure	Departure Transition	En route Conus	En route Oceanic	Arrival Transition	Arrival	Approach	Landing	Arrival Taxi	Postflight
Ground control and guidance(continued)													
Merging		●										●	
Determine position-X, Y, Z, time		●											
Runway assignment		●											
Surface guidance		○										○	
General field surveillance		○										○	
Blunder determination		○										○	
Issue taxi instructions		●										●	
Runway guidance			○								○		
Metering			○										
Flight plan conformance			○										
Takeoff clearance			●										
Taxi exit assignment											●		
Landing guidance											○		
Accept handoff												○	
Determine position-X, Y												○	
General information													
Pilot briefing	●												
General field conditions	○	○									○	○	
NOTAMs	○												
Emergency assistance													
Emergency resolution		○	○	○	○	○	○	○	○	○	○		
Abort directive			○								○		
Facilities operations & maintenance													
System status monitoring	●	●	●	●	●	●	●	●	●	●	●	●	
System servicing	○	○	○	○	○	○	○	○	○	○	○	○	
Operation & maintenance of:													
Flow control facilities	○												
Communication facilities	○	○	○	○	○	○	○	○	○	○	○	○	○

● Modified by strategic control

TABLE 2-2.—CONCLUDED

	Preflight	Departure Taxi	Takeoff	Departure	Departure Transition	En route Conus	En route Oceanic	Arrival Transition	Arrival	Approach	Landing	Arrival Taxi	Postflight
Operation and maintenance of:													
Nav & surveillance facil.	○	○	○	○	○	○	○	○	○	○	○	○	○
Planning facilities	●	●	●	●	●	●	●	●	●	●	●	○	○
Flight service stations	○	○	○	○	○	○	○	○	○	○	○	○	○
Weather facilities	●	●	●	●	●	●	●	●	●	●	●	○	○
Failure resolution	○	○	○	○	○	○	○	○	○	○	○	○	○
Operational regulations													
Regulation determination	○												
Standard departure procedures			●										
Standard approach procedures										●			
Standard landing procedures											●		
Statistical													
Record keeping	●	●	●	●	●	●	●	●	●	●	●	●	●
Flight plan storage	●												

● Modified by strategic control

3.0 SYSTEM REQUIREMENTS

This section presents the results of analyses in the areas that constrain the design and operation of the strategic control system algorithm. Analyses were conducted on the following:

- Airplane Performance. The impact of the aeroperformance capability of the airplanes expected to make use of the strategic control system is analyzed. The controlling parameters necessary to preplan a route-time profile that is consistent with airplane capabilities are identified.
- Runway Operations. The requirements on a strategic control algorithm design imposed by considerations and strategies for handling approach/departure ratios, longitudinal spacing criteria, and multiple runway configurations are determined.
- Perturbations. The requirements imposed on the strategic algorithm design necessary to accommodate system perturbations associated with weather, go-arounds, and emergencies are analyzed and the potential means of accommodation identified. A determination of the requirements for dynamic rescheduling is made.
- Communication Requirements. The requirements for the communication of strategic control instructions in terms of message types, content, and format are defined.
- Ground Versus Airborne Data Processing. The relative merits of storage and computation either on the ground or in the airplane are investigated.

3.1 AIRPLANE PERFORMANCE ANALYSIS

Airplane performance is probably the single most important criterion in the design of the terminal area descent profile. In order to plan a descent strategy from cruise altitude and velocity to runway threshold at approach speed (V_{ref}) a careful investigation of the aerodynamic capabilities exhibited by current commercial transports is essential. In the following paragraphs a general discussion of these capabilities shows how they affect the design of the descent track, and a description of the descent path as prescribed by these aerodynamic constraints is given. The manner in which speed envelopes for the descent are specified by the aerodynamic performance characteristics of the particular airplane is outlined.

3.1.1 General Design Overview

The first and basic design requirement for the descent track is that an airplane must be able to meet the descent requirements of the track profile in a clean configuration (no flaps, spoilers, etc.) with the exception of deceleration from high descent speeds to the 250-knot calibrated airspeed (KCAS) limit at 10,000 feet and below as set by the Federal Aviation

Administration. In addition, the level of passenger comfort in the descending airplane should be as good as that of current transport operations.

The following sections assume straight-in approaches and still air conditions for simplification purposes only. The effect of a headwind during terminal descent is to lower the requirements on an airplane flying the track slope and, as expected, a tailwind will increase the effective track slope and the aerodynamic requirements will correspondingly increase. An approach involving turns aids descent requirements due to the loss of lift associated with a banking angle.

Linear descent profiles are used in this study analysis. Current descent procedures do not result in a linear descent track; however, linear altitude-distance tracks are desirable from scheduling and guaranteed conflict-free airspace aspects, and investigations show that linear paths do not impose unrealistic demands on current transports. The descent track used in this study is graphically shown in figure 3-1.

3.1.2 Gradient Parameter

One of the most useful and significant parameters in reference to airplane descent and deceleration performance is gradient. This parameter makes possible a comparison between deceleration or descent maneuver requirements placed on an airplane and what the airplane is actually capable of accomplishing. It is particularly important in the design analysis of the descent track, and in order to illustrate this a discussion of this parameter is necessary.

When an airplane flies a gradually descending flight path such as the 2° to 3° slope that a landing descent requires and the airplane is not experiencing acceleration, then an analysis of the forces acting on the airplane in flight shows that gradient may be expressed as:

$$\gamma_D = \text{descent gradient} = \frac{\text{drag}}{\text{lift}} - \frac{\text{thrust}}{\text{weight}} \tag{1}$$

This nondimensional parameter is equal to the descent track slope:

$$\gamma_T = \text{descent track slope} = \frac{\text{vertical distance}}{\text{horizontal distance}} \tag{2}$$

When relating this parameter to the level decelerating flight of an airplane, summation of the forces acting on the airplane indicates that gradient may be used to express deceleration:

$$\gamma_D g = \text{deceleration} = \frac{\text{force}}{\text{mass}} \tag{3}$$

Airplanes using descent speeds other than constant true airspeed, such as constant Mach number or constant calibrated airspeed, involve acceleration. The linear segments of a descent track require constant gradient while any acceleration within these segments

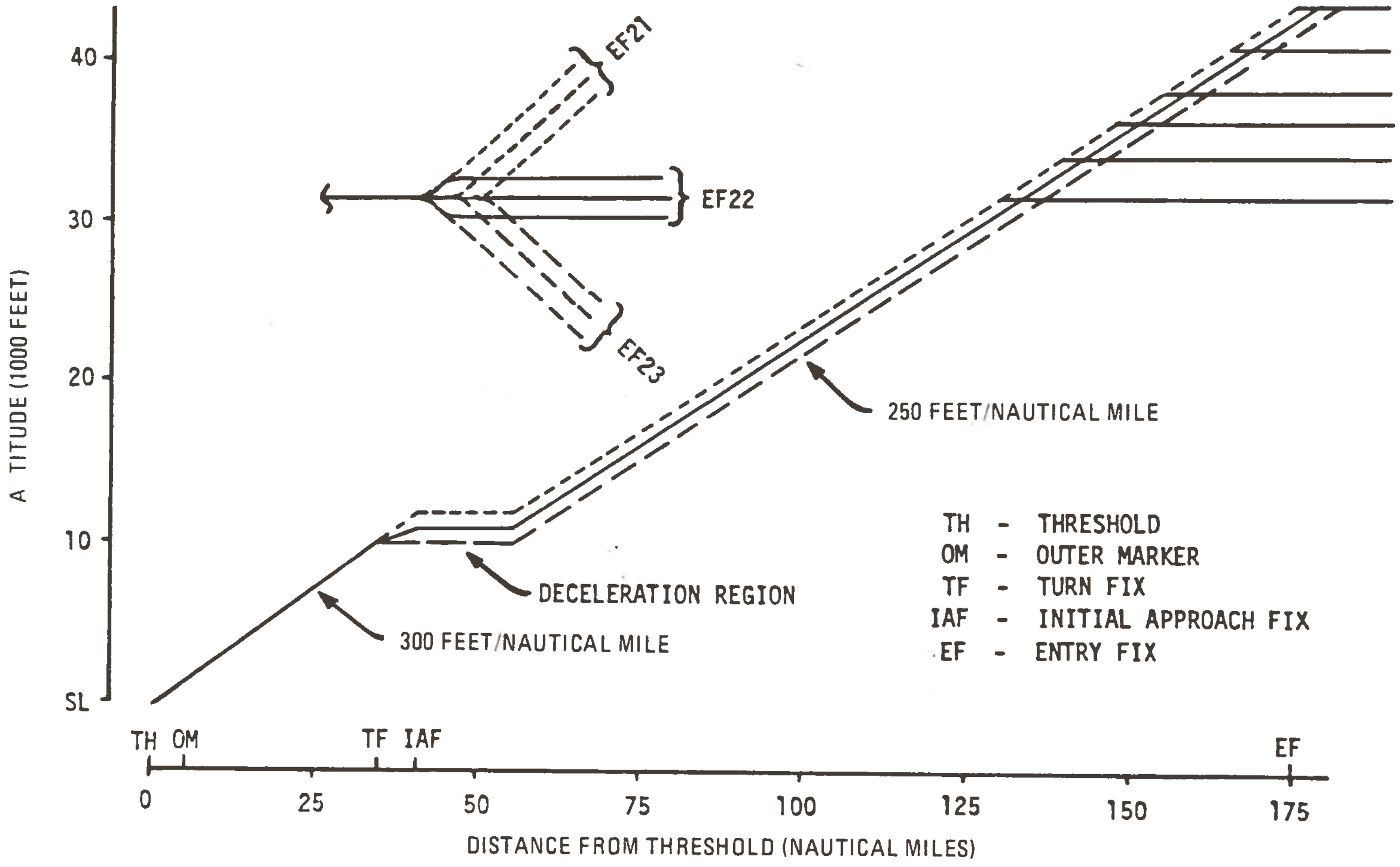


FIGURE 3-1.—STRATEGIC CONTROL DESCENT TRACK PROFILE

requires additional gradient that can be expressed in the form of an acceleration factor. This nondimensional factor, when written with respect to velocity and altitude, is expressed by:

$$a = \frac{dV}{dt} \qquad \text{since:} \quad dh = Vdt$$

$$\text{or:} \qquad 1 = \frac{Vdt}{dh}$$

Then:

$$a = V\frac{dV}{dt}\frac{dt}{dh} = V\frac{dV}{dh}$$

Therefore:

$$\text{Acceleration factor} = f_{acc} = \frac{V}{g}\frac{dV}{dh} \qquad (4)$$

With this in mind, the unaccelerated descent track gradient can be modified as follows to express the gradient required for an airplane in accelerated flight along the descent track:

$$\gamma_D = \gamma_T(1 + f_{acc})$$

$$\gamma_D = \text{gradient required} = \gamma_T(1 + \frac{V}{g}\frac{dV}{dh}) \qquad (5)$$

This final required gradient parameter is an indicator of the performance necessary for an airplane to execute the desired descent or deceleration operation. When this required gradient is compared to the gradient available to a particular airplane as shown by flight test data, it will be known whether the airplane is capable of handling the operation.

Speed variations affect an airplane's available descent gradient due to the manner in which speed is related to airplane drag. High Mach numbers, generally above 0.7 Mach for commercial transports, produce much higher drag due to the Mach number effect (fig. 3-2), and therefore an associated increase in gradient is available. Conversely, for Mach numbers below 0.7 Mach, the drag will be smaller and will reach a minimum at a certain speed (generally a low airspeed), at which point the drag-to-lift ratio will be a minimum (fig. 3-3). It is under this condition of minimum drag that an airplane in a clean configuration may not be able to meet the track slope requirements.

The velocities involved during descents outside the initial approach fix (IAF) and during the deceleration segment are generally beyond the speed placards of landing gear and flaps, and the majority of commercial transports are not equipped with flight thrust reversers. Therefore, additional gradient for descent control and deceleration must come from flight spoilers when engines are at minimum power settings. Varying engine thrust is the only method available for increasing gradient for a clean configuration. Spoiler effectiveness is a complex problem and is a function of airplane gross weight and equivalent

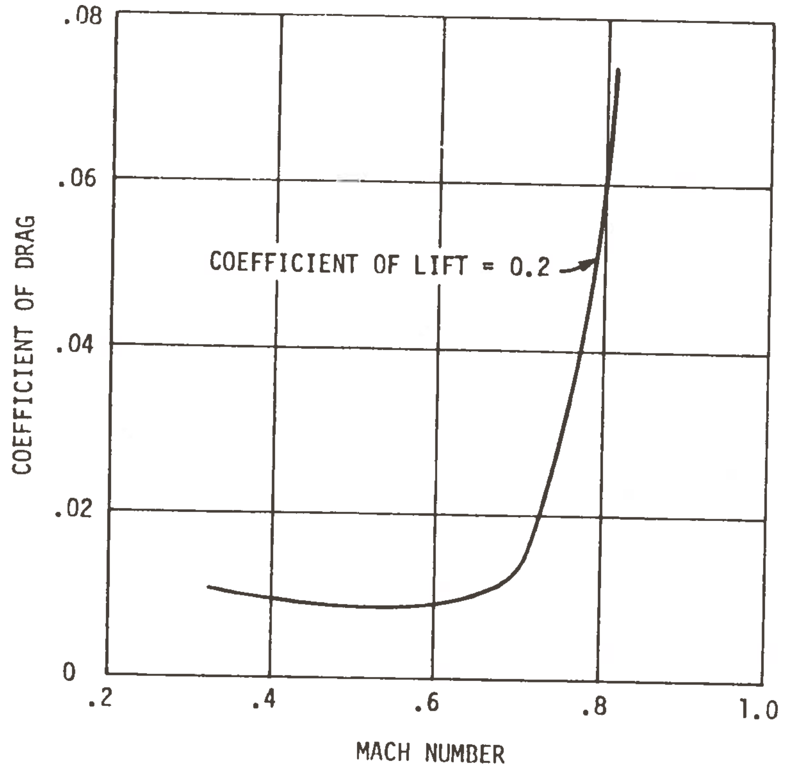


FIGURE 3-2.—EXAMPLE OF MACH NUMBER EFFECT ON DRAG COEFFICIENT OF A HIGH SPEED AIRFOIL

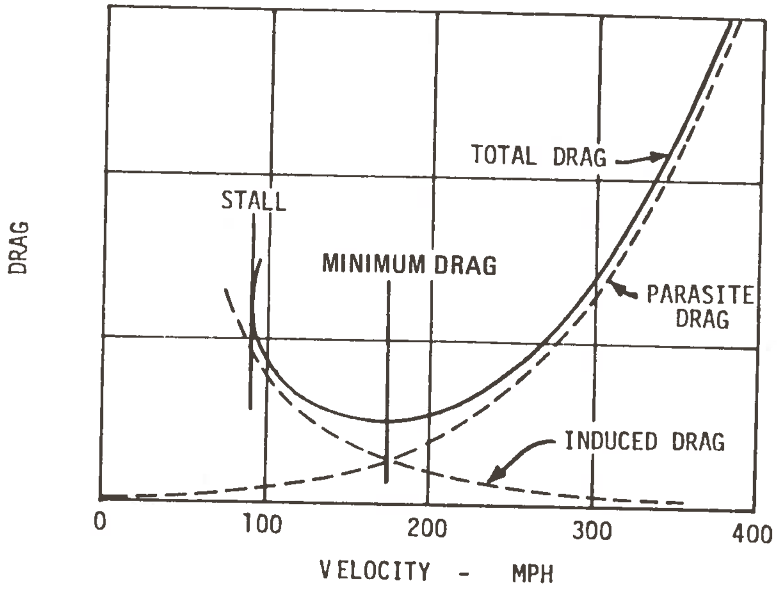


FIGURE 3-3.—EXAMPLE OF DRAG MINIMIZATION AT LOW AIRSPEED

airspeed. With spoiler operation, the available descent gradient will minimize at a lower velocity (generally below descent velocities) with spoilers deployed than with a clean configuration, and the magnitude of available gradient will be higher.

Thus deploying spoilers will effectively remove the restricted zone for descent speeds caused by the clean configuration drag minimization problem mentioned above.

Temperature effects on required and available gradient vary. Nonstandard temperatures do not affect lift, weight, or drag of the airplane flying at a particular calibrated airspeed or Mach number but do affect thrust. However, if the airplane is not thrust limited the available gradient will not be affected. Required gradient is affected by nonstandard temperatures through the acceleration factor. The effect on the dV/dh term in equation (5) is negligible but the temperature effect on the true airspeed, V, increases the required gradient with increasing temperature.

Other weather conditions such as icing or situations that necessitate bleeding engine power may require engine thrust increases that will decrease available gradient.

3.1.3 Airplane Passenger Environment Performance

An industry standard exists with respect to cabin pressurization that is intended to minimize passenger discomfort and may affect the operating capabilities of an airplane. This standard says that cabin pressure is not allowed to exceed the equivalent of 8000 feet in altitude and the maximum rate of change in cabin pressurization is set at 300 feet per minute, sea level equivalent. These values correspond to an approximate 3.8-psi pressure differential from sea level conditions and a rate of pressurization of 0.159 psi per minute. An 8000-foot cabin altitude would require a minimum of 23.8 minutes to repressurize to sea level conditions. It is possible that these values may control the earliest arrival time of an airplane traveling along the descent slope from the entry fix to the runway threshold.

Passenger acceptance levels for deceleration in flight are not specified as completely as cabin pressurization rates. Recent studies of braking deceleration acceptance indicate that 0.25-g deceleration during the braking action is generally acceptable. Using this as a guide, 0.125 g was chosen as an estimate of in-flight tolerance. This is equivalent to 143 knots true airspeed (KTAS) per minute deceleration and requires a deceleration gradient of 0.125 in level flight. A large number of the commercial transports flying have deceleration gradient capabilities in excess of this value. For example, the 727 and 737 airplanes will always have an available gradient of at least 0.136 and 0.150, respectively.

3.1.4 Descent Track Definition

Now that airplane descent and deceleration performance capabilities have been discussed from a general viewpoint, a more specific look will be taken at the effect gradient, aerodynamic performance, and passenger comfort have on the formulation of the descent track. As stated previously, the prime consideration in formulating the two-dimensional track definition is the capability of current transports to meet the track requirements while establishing a reasonable proximity between the entry fix point and the threshold. Descent segments of the track should be within clean configuration capabilities of current transports with flight spoilers used for deceleration and in flight zones where gradient available in the clean mode is less than required.

The descent track inside the initial approach fix utilizes FAA guidelines that recommend descent from 10,000 feet should be initiated between 30 and 40 nautical miles from the threshold. This recommendation can be met with a track slope of 300 feet per nautical mile and would place a 12,000-foot IAF 40 nautical miles from the threshold. Table 3-1 illustrates the capabilities of current transports to meet this descent slope at the velocity that requires the highest descent gradient. It should be noted that this track slope is slightly less demanding than a 3° glide slope (318 feet/nautical mile). Practical rates of descent below 10,000 feet are under 2000 feet/minute and are less than that approaching the outer marker. Table 3-2 illustrates the acceptability of the rates of descent associated with the track slope of figure 3-1 for a speed of 250 KCAS.

The deceleration segment of the descent path exists to facilitate transition from high-speed descent to speeds that are acceptable below 10,000 feet. Practices currently in use vary from deceleration along a descending path of reduced slope to level flight deceleration approaching the IAF. Since vertical separation of the parallel paths exists throughout this segment, the track slope of the segment will play an important role in how far inside the IAF vertical merging takes place. The advantage of deceleration along the descent track or along a segment whose slope is close to the descent track would be the minimization of the attitude change required by an airplane. However, if a deceleration track slope of 250 feet per nautical mile was used, complete altitude merging would be delayed until arrival at the threshold unless some additional track slope manipulation was performed inside the IAF. In addition, gradient requirements associated with deceleration along a descending track may exceed the capabilities of some of the current transports. Therefore, a level flight deceleration segment was used in the descent track. The distance between initial deceleration and the IAF should be set at a fixed quantity that is within the capabilities of current transports. A 10-nautical-mile level path length was initially chosen for the deceleration segment and was found to be just adequate for present day commercial transports, as shown in table 3-3. Therefore, a lengthening to 15 nautical miles was decided upon to ensure reliable deceleration performance.

The slope of the descent track from the entry fix to the deceleration segment was established at 250 feet per nautical mile based on proximity of the entry fix to the threshold, descent capabilities of current transports in clean configurations, and time controllability within the speed envelopes. The effect of shallow slopes is to move the entry fix further from the threshold and increase the total time controllability between the earliest and latest arrival at the IAF. The slope chosen places the entry fix at 37,000 feet and approximately 160 nautical miles out from the runway threshold. An additional 15 nautical miles has been added to this 160 nautical miles, however, to allow level deceleration from the highest cruise speeds to a standard descent speed.

3.1.5 Airplane Velocity Profiles

Up to this point a description of how airplane performance capabilities affect the actual physical structure of the descent track profile has been given. Now attention will be turned to the manner in which an airplane's velocity envelope affects the flexibility available

TABLE 3-1.—CLEAN CONFIGURATION DESCENT SLOPE CAPABILITY*

Model	Altitude	
	12,000 ft	6000 ft
737	328	330
727	338	340
747	322	324

*Feet per nautical mile at maximum landing weight and 250 KCAS

TABLE 3-2.—TRACK SLOPE RATE OF DESCENT

Altitude	Rate of descent*
10,000 ft	1450
5000 ft	1340
1500 ft	1275

*Required rate of descent in feet per minute for track slope of 300 feet/nautical mile and 250 KCAS

TABLE 3-3.—10 NAUTICAL MILE DECELERATION SEGMENT

Model	High speed limit (V_{MO})	Max change in velocity	Deceleration (kts/min)	Gradient required	Min gradient available *
727	390 KEAS	171 kts	110	0.0961	0.136
737	350	122 kts	73	0.0638	0.150
747	375	152 kts	95	0.0830	0.084

*With spoilers deployed at maximum landing weight and 12,000 feet.

for the descending flight. This is extremely important in terms of being able to schedule a conflict-free stream of arrivals at the runway threshold through knowledge of the earliest and latest possible times of arrival of each inbound airplane. Full use of an airplane velocity window is required to attain maximum flexibility. To determine the extent of this velocity window an understanding of the features that limit the magnitude is necessary. A general view of an airplane velocity profile is pictured in figure 3-4. Speed profiles of constant Mach number and constant calibrated airspeed are common descent procedures. When used along a constant track slope they are compatible. Constant equivalent airspeed profiles may be substituted for constant calibrated airspeed profiles with a slight increase in gradient-available requirements because of the dV/dh term of equation (5). Figure 3-5 illustrates the effect of spoiler deployment on the descent gradient as compared to the clean configuration.

The low-speed, low-altitude limitation on the velocity profile may be expressed as a minimum maneuver speed or the lowest speed at which necessary airplane maneuverability is available. This speed is usually expressed as a function of runway threshold speed plus some fixed constant calibrated airspeed (V_{ref} + constant KCAS). This limitation is insensitive to temperature variations but is sensitive to airplane gross weight through the V_{ref} value. The source of these data for each airplane is usually the airplane manufacturer.

The low-speed, high-altitude region is typically limited by the airplane buffet boundary, as shown in figure 3-4. This boundary is usually defined so that an airplane can execute a 1.3-g maneuver without buffeting. An airplane in level flight at a given weight flies along a constant W/δ line (W = airplane weight; δ = pressure at flight altitude/pressure at sea level). These constant W/δ lines, when plotted against C_L versus Mach number curves for the airplane (fig. 3-6), will define the safe speed range for a given weight and flight altitude. This range is marked by the speeds at which the W/δ curves intersect the low-speed (stall) limit and the high-speed (buffet) limit. The low-speed solution (intersection of W/δ with stall limit) is the value that applies here. This boundary limit is insensitive to temperature except as temperature affects Mach number.

Another low-speed limit on an airplane velocity profile might be a procedural flap extension speed. This is the speed at which flight instructions for the airplane specify that flaps must begin extension. This speed then places a lower limit on a clean configuration velocity profile.

The high-altitude, high-speed boundary is somewhat more complex in that it consists of high-speed buffet boundaries, structural placards, and thrust limited speeds.

The high-speed buffet limitation is simply the high-speed solution to the low-speed, high-altitude buffet limit shown in figure 3-7. This high-speed buffet boundary is usually more limiting than the maximum structural Mach number (M_{mo}), but it would be unusual if available thrust would not be the most limiting of the three.

Structural placards shown in figure 3-8 as M_{mo} and V_{mo} are expressed in terms of Mach number and, usually, equivalent airspeed. These are a function of airplane model type and not of gross weight as are all the other limits except flap extension speed. The structural

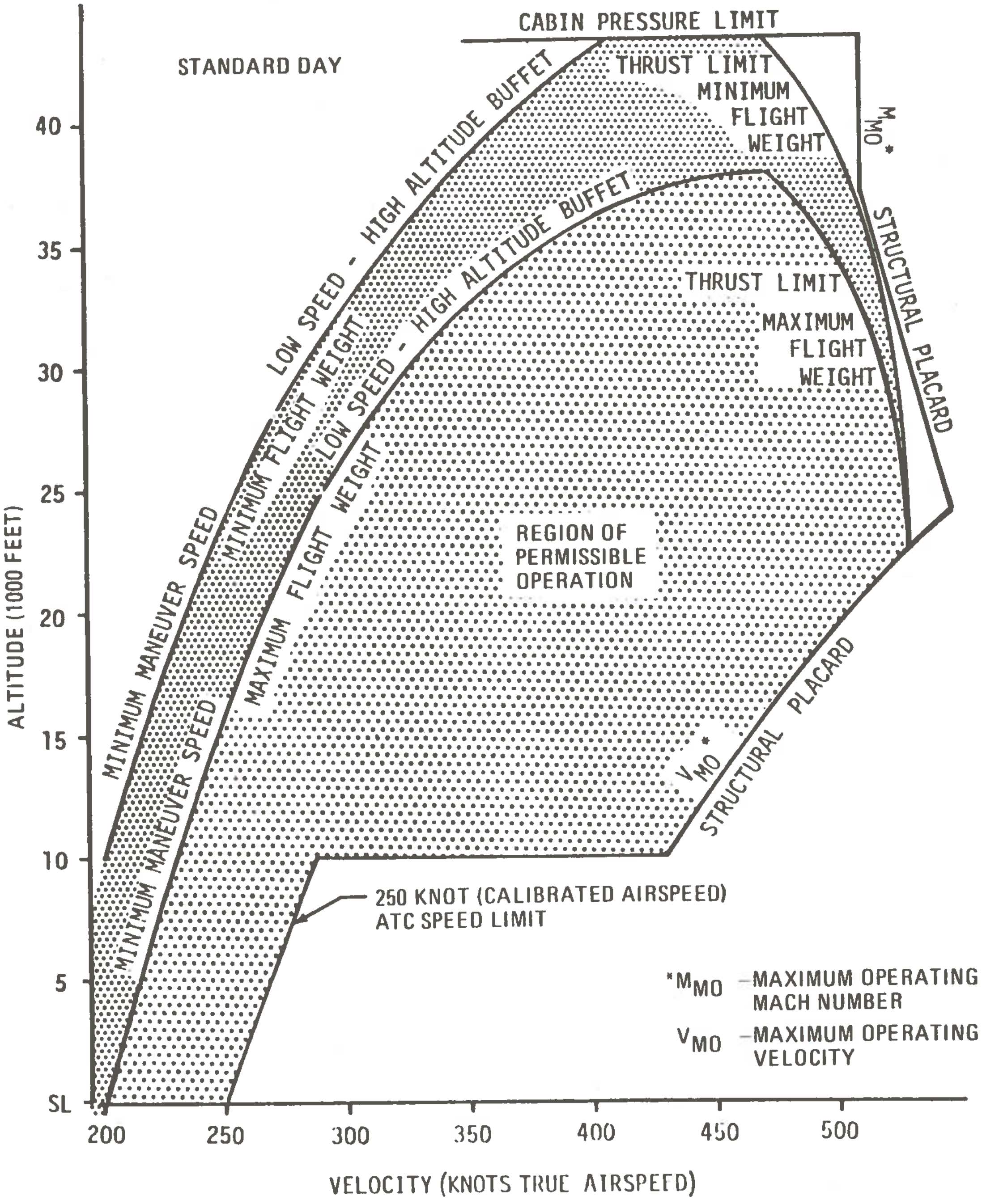


FIGURE 3-4.–VELOCITY PROFILE

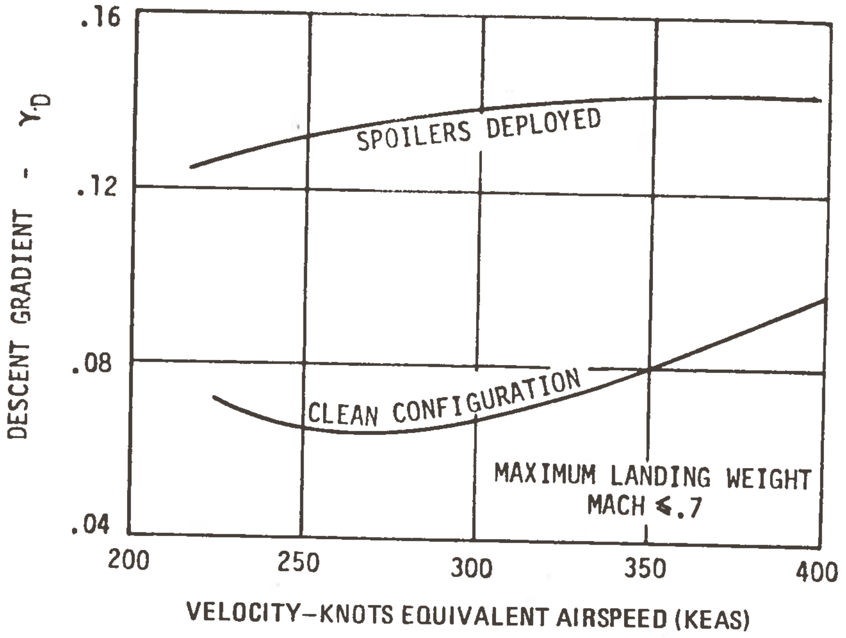


FIGURE 3-5.–DESCENT GRADIENT AVAILABLE IN CLEAN CONFIGURATION AND WITH SPOILERS DEPLOYED

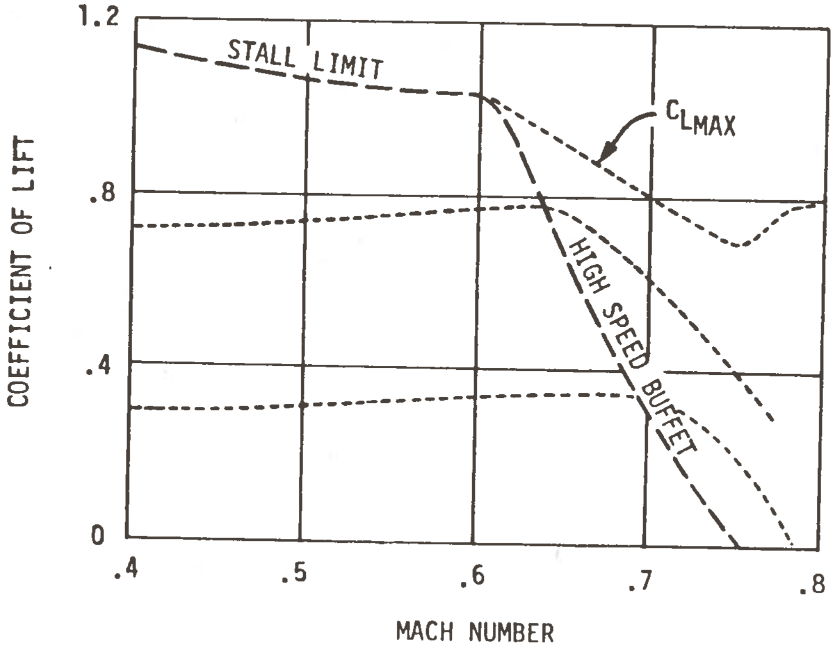


FIGURE 3-6.–SAFE FLIGHT REGIME

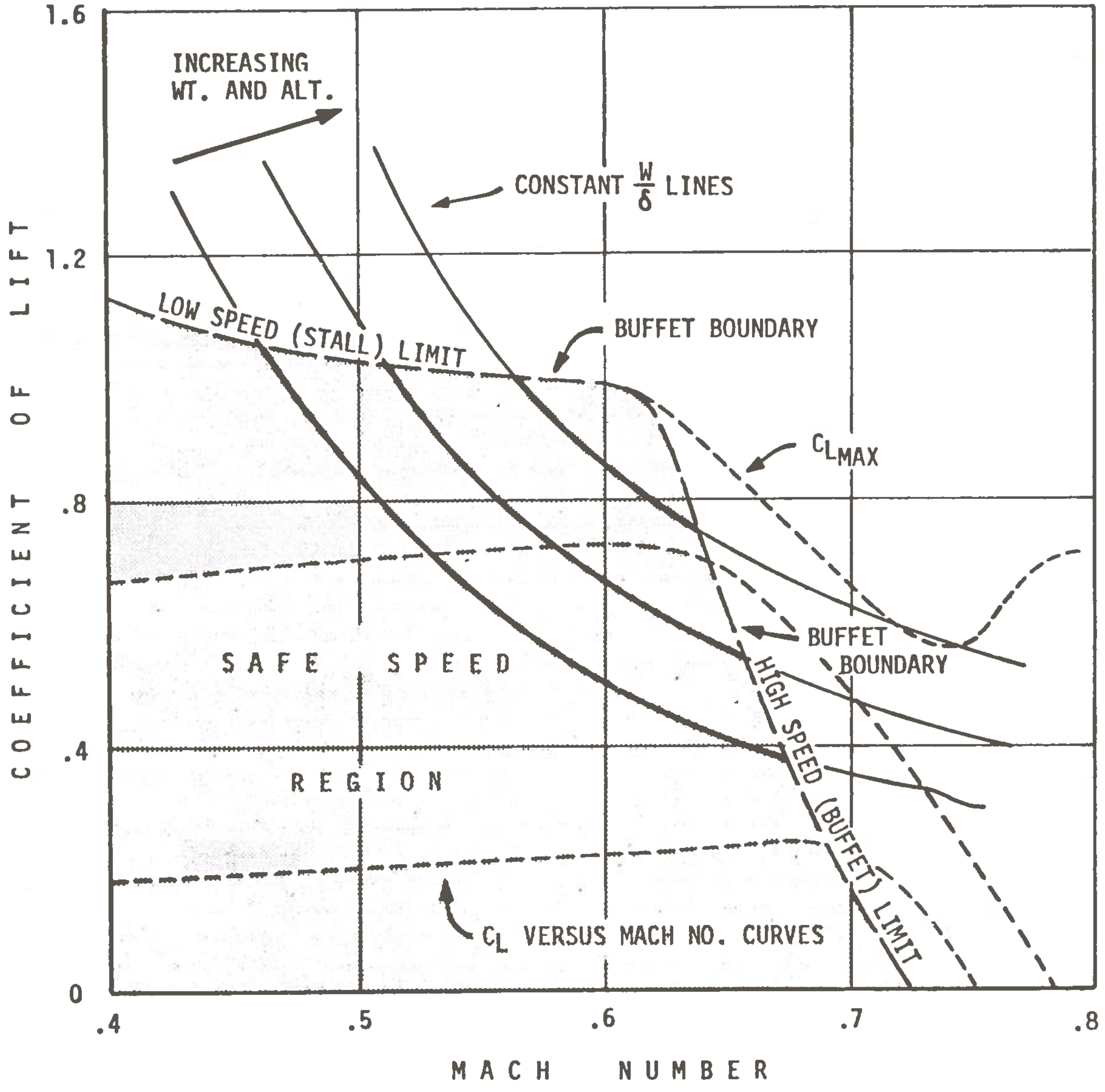


FIGURE 3-7.—SAFE SPEED RANGE LIMITS

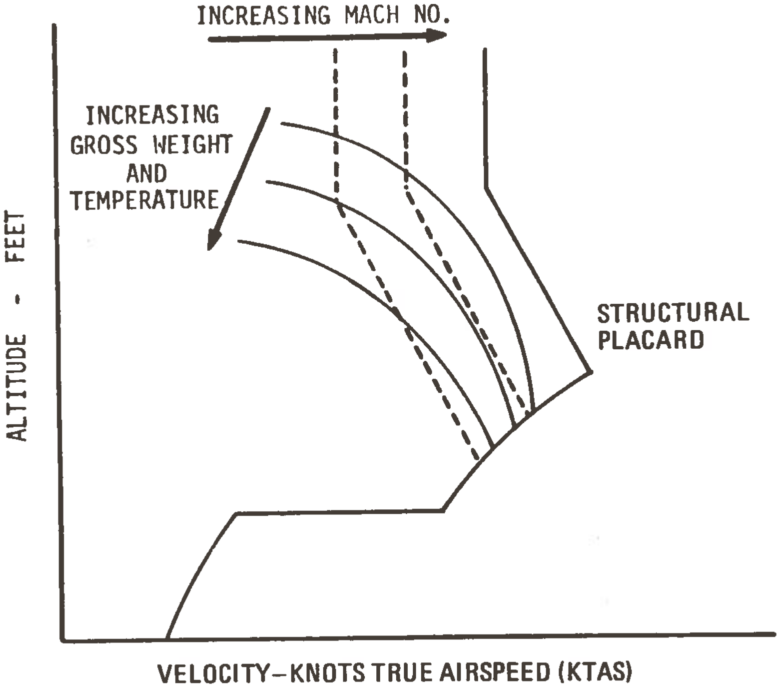


FIGURE 3-8.—GROSS WEIGHT AND TEMPERATURE EFFECTS ON HIGH ALTITUDE THRUST LIMIT

placard value V_{mo} defines the high-speed, low-altitude boundary above the 10,000-foot level, below which the 250 KCAS mandatory speed limit is in effect.

Maximum level flight speed capability at high altitude is shown in figure 3-9 as a function of gross weight and temperature. This is a maximum cruise thrust limited value. The drag of an airplane is constant at a particular Mach number as temperature changes but available thrust is a function of Mach number, altitude, and temperature. Consequently, this limit is a function of temperature as well as gross weight. This will be the most limiting for the majority of airplanes at high altitude.

One other limit on high-altitude capabilities is cabin pressurization. Each airplane cabin is stressed for a particular pressure differential between outside and inside conditions. This will specify the highest altitude the airplane can attain during cruise, since the pressure differential increases toward the airplane's maximum allowable value with increasing altitude.

These limitations as listed above specify the high- and low-boundary values for an airplane's speed capabilities but do not show the restricted speed zones inside these outer limits. For example, an especially clean airplane with respect to drag or an airplane that requires significant throttle settings to maintain air conditioning may not have sufficient drag to produce the required descent in the region of its minimum drag-to-lift ratio. If this situation does exist, it will appear as a restricted zone in the speed envelope, as shown in figure 3-9, and will be a function of gross weight.

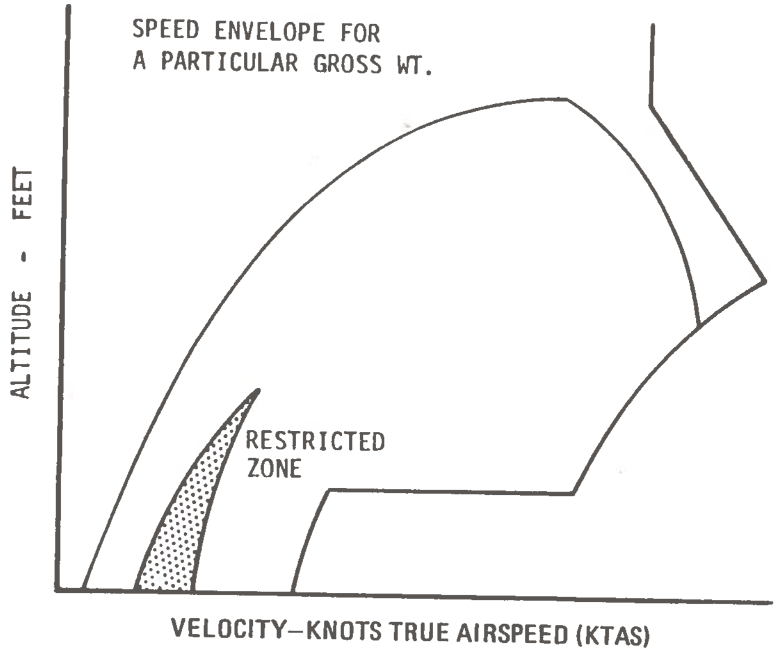


FIGURE 3-9.–SPEED ENVELOPE RESTRICTION ZONE

This generally encompasses the aerodynamic performance effects on the terminal descent. Aeroperformance restrictions and capabilities are generally the foremost criteria that determine both the descent track physical design as well as the airplane's performance capabilities while flying that descent track.

Airplane performance data specify the slope of the descent track and the length of the deceleration segments inside the entry fix point while constraining the descent track flying times for both the high- and low-speed solutions. This, in turn, will constrain the flight possibilities available to inbound airplanes at the terminal area and limit the ability to design nonconflicting descent schedules as traffic increases.

3.2 RUNWAY OPERATIONS

The runway utilization imposes a critical operational constraint on any terminal area control algorithm. The capacity of the entire air transportation system is critically limited in many operational situations at the runway. The efficiency with which arrivals and departures can be sequenced and scheduled to maximize runway use and minimize delay is a primary measure of the efficacy of postulated ATC systems in moving predicted traffic levels.

An analysis of runway operations must consider the required demand (traffic) level, safety, and delay criteria, which are translated into scheduling minimums, the control algorithm, and system performance in executing the control laws. These factors are represented in figure 3-10. The primary ATC system considerations (or criteria) are safety and efficiency. These criteria are measured by such performance factors as delay, operations rates, and conflict rates.

The runway operations section consists of a discussion of single and multiple instrument flight rules (IFR), runway operations constraints (secs. 3.2.1 and 3.2.2), and sequencing and scheduling considerations (sec. 3.2.3).

3.2.1 Single Runway Operational Constraints

The scheduling of the runway is based on (1) an airplane available to use the runway and (2) a sufficient (safe and efficient) separation from the previously scheduled airplane. Runway separation minimums are based on the preceding and current operation type (arrival/departure, arrival/arrival, etc.). Existing procedures and safety rules governing IFR operations on a single runway in the current (1973) ATC system (for airplanes over 12,500 pounds gross weight) include the following:

1) Only one airplane cleared to use the runway at a time

2) A 3-nautical-mile spacing minimum on approach for arrival/arrival pairs under IFR conditions (5 nautical miles for some light airplanes following heavy airplanes)

3) A departure clearance only when a preceding departure has taken off and has either crossed the runway end or turned to avoid conflict or is airborne and 6000 feet (category III aircraft) down the runway

4) Initial separation of successive departures on divergent courses (45° or more) as a function of divergence distance:

    a) 1-minute separation for divergence immediately after takeoff

    b) 2-minute separation for divergence within 5 minutes of takeoff

    c) 3-mile separation for divergence within 13 miles of takeoff using distance measuring equipment (DME)

5) A 2-mile separation minimum between an arrival following a departure

6) Departure cleared only after a previous arrival has cleared the runway

All of these factors constrain the rate at which airplanes can be scheduled at the runway. All are stated in terms of a time or distance separation or no joint runway occupancy.

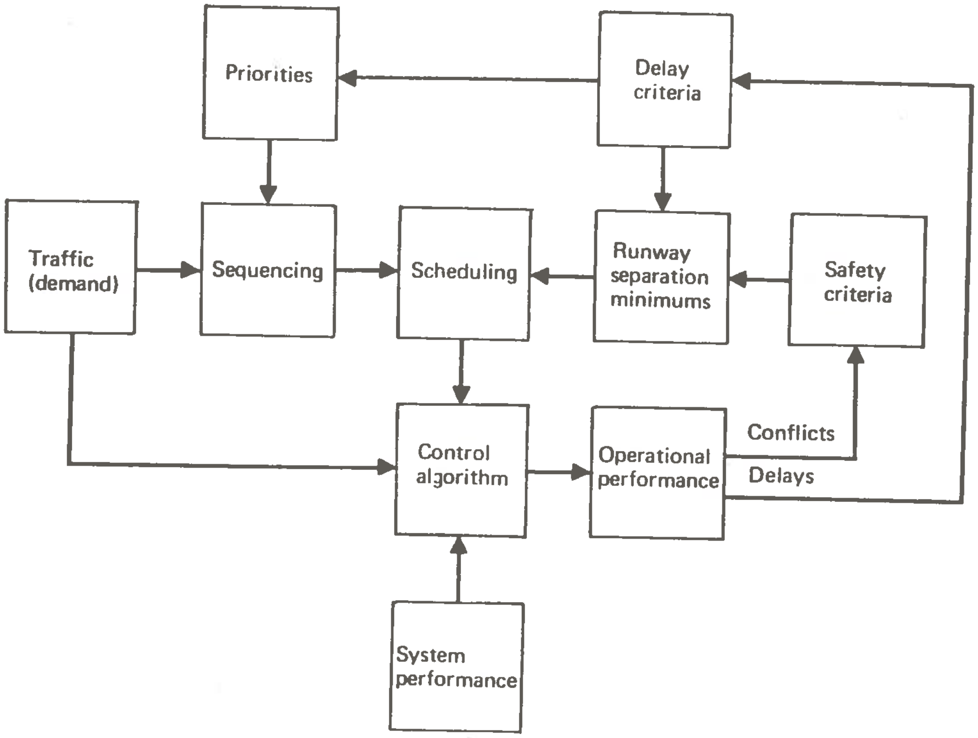


FIGURE 3-10.–RUNWAY OPERATIONS FACTORS

The strategic algorithm should provide flexibility of choice; interoperation constraints should be selected for:

- Time separation
- Distance separation
- No joint runway occupancy for the various operational sequences (arrival/arrival, departure/arrival, arrival/departure, and departure/departure)

In addition, arrival/arrival spacings should be adjustable to reflect various final approach velocities for approach pairs (fast/slow) combinations.

3.2.2 Multiple Runway Operational Constraints

Parallel runway operations at major airports may be divided into:

- Dual-lane operations
- Dependent parallel operations
- Independent parallel operations

These multiple runway operations allow progressively higher capacities.

The dual-lane system operates as a single runway with two surfaces. All in-air minimums apply as in the single runway case, but an arrival and a departure may be contemporaneous on the runway (separate lanes). Thus, a departure can be cleared for takeoff after an arrival has landed (rather than after arrival has cleared runway as in single runway case).

Dependent parallel operations are permitted on runways whose centerline spacing is at least 3500 feet. For such runways, takeoffs are allowed on one runway independent of arrivals on the other. Independent simultaneous IFR arrivals to the two runways are not allowed.

Independent parallel operations require at least a 5000-foot runway centerline separation (under instrument conditions). For independent parallels, the theoretical system capacity is twice that of a single runway.

The strategic algorithm should provide the capability to schedule airplanes on parallel runways for dual-lane, dependent parallel, and independent parallel operations.

3.2.3 Sequencing and Scheduling Considerations

The effective use of the runway requires a scheme by which the airplane can be systematically allocated runway time. Two factors are important: the order or sequence of the airplane assigned to the runway, and the block of time or schedule assigned.

The simplest sequencing and scheduling technique involves priority sequencing and scheduling. A rule or set of rules are stated (e.g., arrivals have priority over departures; arrivals priorities depend on first threshold capability). These rules assign a relative value to various candidate runway users (priorities) and select the user with the greatest value. Once the operational sequence is established, runway use is scheduled based on availability times of users and the separation minimums.

More sophisticated techniques include consideration of various mathematical techniques (including optimization procedures) for sequencing and scheduling. For example, a linear programming algorithm to minimize delay of all airplanes in a traffic set might be applied with the sequence a result of the scheduling process. Such programs, however, are less applicable to real-time algorithm implementation.

The sequencing and scheduling process to be selected for the strategic algorithm development should be:

- Computationally simple
- Applicable to real-time system implementation
- Modular in approach (to allow alternate techniques to be substituted)

3.3 PERTURBATIONS

The frequency of weather effects that would affect strategic control performance is investigated. These are errors in wind forecasts, frequency of occurrence (and duration) of clear air turbulence (CAT), and frequency of encountering severe weather. The lack of sufficient data on this subject prevents at present the drawing of significant conclusions on the interaction of perturbations with strategic control.

3.3.1 Clear Air Turbulence (CAT) Exposure

Statistics on turbulence exposure are generally based on records of airplane response to atmospheric gusts using accelerometers placed at the airplane center of gravity. The airplane accelerations are converted to gust velocities (referred to as derived gust velocities or U_{de}) that involve consideration of airplane weight, wing area, airspeed and lift slope, air density (altitude) assumed gust profile, and the airplane gust response characteristics. Errors arise in variations of these parameters that are not fully accounted for in the calculations, problems (especially at small acceleration values) of processing the raw data, and the difficulty of distinguishing atmospheric motions from pilot inputs or characteristic frequency vibrations of the airplane. The critical boundary between turbulence and smooth flight is reflected in the variable definitions of turbulence used in different studies. A standard, based on NASA criteria, is that turbulence exists when the accelerometer trace shows repeated excursions of 0.08 g (equivalent to derived gust velocities of 2 fps). Any portion of the record 15 seconds or longer not containing gust velocities of 2 fps is classified as smooth flight. The moderate turbulence criterion is accelerations of 0.25 g (U_{de} of approximately 6 fps) or greater.

Applying this turbulence definition to an accumulation of empirical data gives rise to table 3-4, which provides the statistical probability of exposure to light and moderate turbulence for altitude bands up to 70,000 feet. The ratios of moderate-to-light turbulence are estimated as 1:8 for altitudes above 20,000 feet, as 1:6 for the altitude band between 10,000 and 20,000 feet, and as 1:4 below 10,000 feet.

TABLE 3-4.—RECOMMENDED VALUES OF PROPORTION OF FLIGHT DISTANCE IN TURBULENCE (IN PERCENT) FOR ALTITUDE BANDS UP TO 70,000 FEET

Altitude (ft)	Turbulence	
	Light	Moderate
0 – 5,000	20%	5%
5 – 10,000	9%	2%
10 – 20,000	6%	1%
20 – 30,000	5%	0.6%
30 – 40,000	5%	0.6%
40 – 50,000	3%	0.4%
50 – 60,000	2%	0.2%
60 – 70,000	1%	0.1%

To derive statistically significant probabilities of flight distance in turbulence and gust exceedance distributions requires large sampling programs. Several special research programs on clear air turbulence have been sponsored by the U.S. Air Force (HICAT, MEDCAT and LO-LOCAT). In addition, observations have been taken during routine flights of commercial and military airplanes and summarized in reports by NASA, NATO, the Royal Aircraft Establishment, the National Research Council of Canada, and various private industry and research groups. A selection of these programs is noted in references 3-1 through 3-24.

Results of a number of turbulence measurement programs are presented in figure 3-11, which portrays variation in turbulence exposure as a function of flight miles and altitude. The curves are derived from the studies detailed in table 3-5, which also tabulates pertinent data concerning turbulence criteria, exposure percentage, altitude, location, and sampling magnitude.

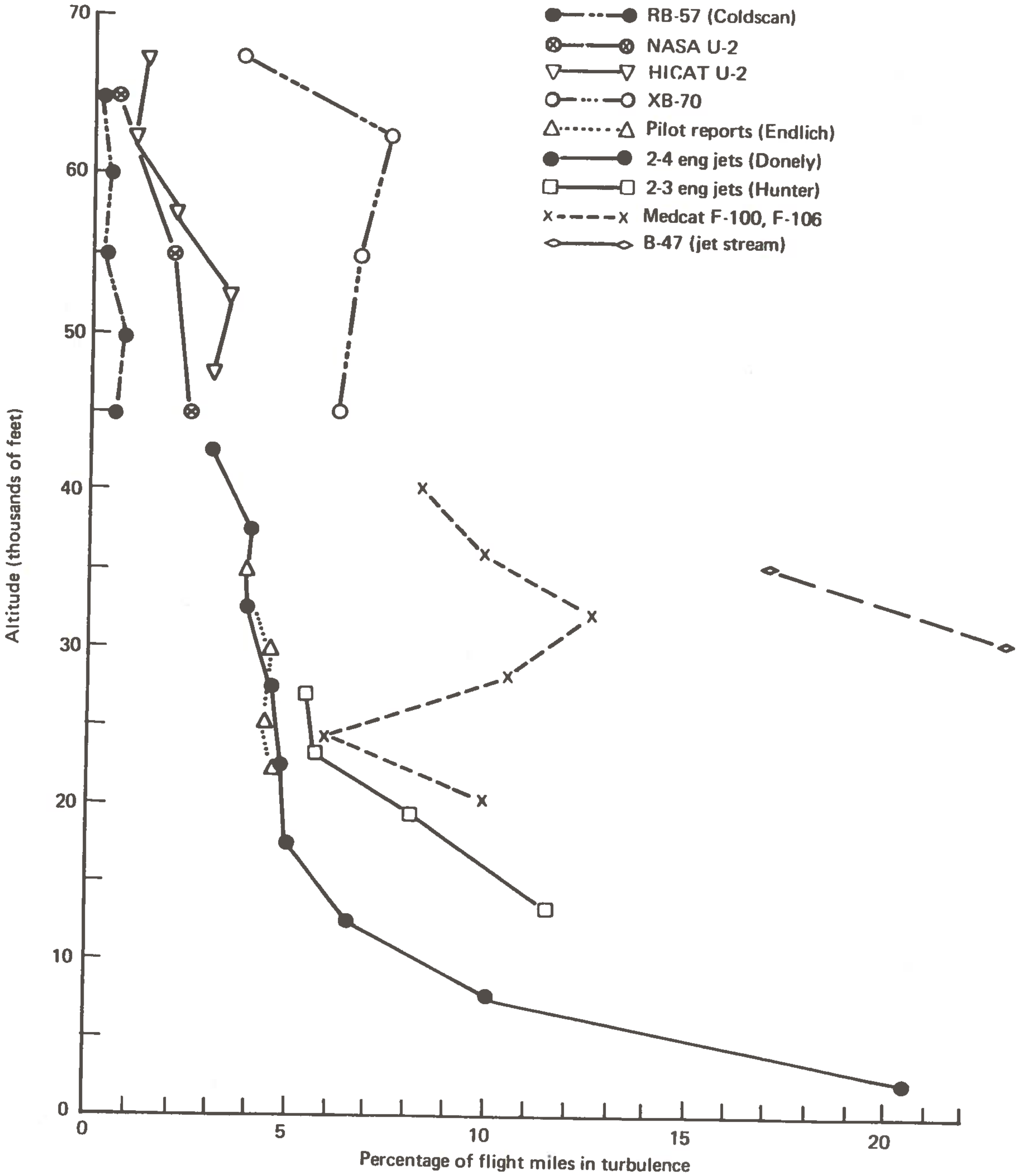


FIGURE 3-11.–PERCENTAGE OF FLIGHT MILES IN TURBULENCE FOR VARIOUS PROGRAMS

TABLE 3-5.—PERTINENT INFORMATION ON TURBULENCE DATA INCLUDING PROPORTION OF FLIGHT MILES IN TURBULENCE (P) FROM VARIOUS PROGRAMS

Program	Aircraft	Location	Flight Miles	Criteria	Altitude(ft)	P(%)
USAF, LO-LOCAT (1970)	C-131, T-33	U.S.	191,000	≥ Light	250, 750	63
NASA (Hunter - 1967)	2-3 Engine Turbojets	U.S., Foreign	1.5 million	$U_{de} > 2$ fps	13,000	11.5
					19,000	8.1
NASA (Hunter - 1968, 1970)	DC-8 Convair 880	EAST U.S., Oceans	3.6 million	$U_{de} > 2$ fps	0 - 5,000	18.8
					5 - 10,000	9.6
					10 - 20,000	6.8
					20 - 30,000	4.7
					30 - 40,000	4.0
					40 - 45,000	3.0
R.A.E. (Donely - 1971)	2-4 Engine Turbojets	World-Wide	15 million	$U_{de} > 2$ fps	0 - 5,000	20.5
					5 - 10,000	10.1
					10 - 20,000	5.8
					20 - 30,000	4.7
					30 - 40,000	4.0
					40 - 45,000	3.0
USAF AF19(628)-5173 (1968)	Commercial, Military	U.S.	10 million	≥ Light	20 - 30,000	4.7
					30 - 40,000	3.8
					40 - 45,000	2.2
USAF MEDCAT (1971)	F-100, F-106	U.S.	210,000	Accel. > 0.1 g	20 - 30,000	8.1
					30 - 40,000	10.7
Estoque (1958)	B-47	Eastern U.S.	55 Flights	Horiz.Gust Component ≥ 5 fps	30,000	23
					35,000	17
					40,000	3

TABLE 3-5.—CONCLUDED

Program	Aircraft	Location	Flight Miles	Criteria	Altitude(ft)	P(%)
NASA (Steiner - 1966)	U-2	World	820,000	$U_{de} > 2$ fps	40 - 50,000 50 - 60,000 60 - 70,000	2.5 2.0 0.6
USAF HICAT (1972)	U-2	World	500,000	Accel. > 0.1 g	45 - 50,000 50 - 60,000 60 - 70,000	2.9 2.7 1.2
NASA (Wilson - 1971)	XB-70	Western U.S.	94,000	Accel. $> .06$ g	40 - 50,000 50 - 60,000 60 - 70,000	6.3 6.8 5.5
COLDSCAN (Nat. Res. Council, Canada - 1971)	RB-57F	U.S., Panama, Atlantic	115,000	$U_{de} \geq 0.35$ g	45,000 50,000 55,000 60,000 65,000	0.6 0.8 [illegible] 0.4 0.1

With large accumulations of flight miles, a general trend becomes apparent showing reasonable agreement between altitude and turbulence exposure. This is exemplified by the turbine and U-2 curves. Summarizing the results, it can be seen that:

1) The percentage of flight with turbulence is fairly constant, and near 5% for the altitude range between 15,000 and 40,000 feet.

2) Below 15,000 feet turbulence increases with a marked increase below 5000 feet.

3) Above 40,000 feet turbulence decreases, dropping to 1% at 70,000 feet.

Some results deviate from this general trend that may be accounted for by several factors. The very high turbulence percentages of the B-47 Jetstream program resulted from selective sampling both in time and location. The 22 flights were flown under conditions highly conducive to turbulence; the jet core speed averaged 140 knots and turbulence near the core exceeded 30% of the total flight time.

With operation MEDCAT, the turbulence exposure values of approximately double the norm can be attributed to several causes: (1) There was a small sample size. (2) The fighter-type airplanes used are more sensitive to gusts than large transport-type airplanes (and not adequately reflected in the conversion to U_{de}). (3) There were effective turbulence search procedures. (4) No flights were conducted over water. (5) There was no discrimination between spurious gusts and real turbulence.

The U_{de} gust velocity illustrated for two- and three-engined jets has a higher trend than the four-engined data. Hunter (ref. 3-2) attributes this to the lower sample size and to the turbulence environment. The two/three-engined jets flew over land and commonly over mountains, whereas a significant percentage of flight routes for the larger jets was over water where turbulence is less frequent.

Many of the flights of the XB-70 were along the lee of the Sierra Nevada and Cascade mountain ranges in the western U.S., parallel to the ridge, which would tend to increase both the probability of turbulence and the length of the runs. Some of the XB-70 runs were up to 450 miles, and it is suggested that these lengthy turbulence encounters contained either significant patches of smooth data or long wave motions that would not ordinarily be detected by the slower flying U-2. Finally, the XB-70 detection cutoff was 0.06 g which, extrapolation demonstrates, will record approximately 60% more turbulence than with the 0.1-g cutoff used in the high-altitude U-2 flights.

3.3.2 Terrain Effects on CAT

The effect of terrain has already been mentioned in the previous section and the increase in turbulence over rough terrain and mountains is well documented. However, it is difficult to establish firm statistics.

Table 3-6 shows the proportion of flight miles in turbulence for the XB-70 and U-2 flights over the western U.S. for high mountains and for combined flatland and low mountains.

TABLE 3-6.–RATIO OF TURBULENCE EXPOSURE TO TERRAIN

Airplane	High mountains		Low land/low mountains		Turbulence ratio
	Turbulence	Distance	Turbulence	Distance	
XB-70	8%	29,000 mi	3.3%	19,000 mi	2·43
U-2	4.8%	28,000 mi	2.0%	30,000 mi	2·40

The mean flight altitudes for both these programs was within 1000 feet of flight level 560. The less stringent requirements for designating turbulence, as discussed earlier, give rise to higher turbulence exposure percentages for the XB-70. The flights for the U-2 were fairly evenly divided between high mountains and lowland, whereas the XB-70 flights favored the high mountains. Despite these differences, the ratio of turbulence between high mountains and lowland for both programs is remarkably similar at 2.4:1.

Data in a report (ref. 3-22) documenting 170,000 flight miles over North Africa at a 200-foot altitude showed that 17 times more U_{de} gusts greater than 10 fps occurred over land than sea, and 30 times more for gusts greater than 20 fps. A small sample of flights over hilly desert at midday showed gust frequencies greater than 10 fps were 150 times higher than over water.

A Russian report (ref. 3-13) of high-altitude supersonic flights over the USSR recorded mean maximum gust acceleration for turbulence encounters that were three times the average for flights over the plains. The COLDSCAN RB-57 flights (ref. 3-12), plotted in figure 3-11, had 5.0 moderate or greater turbulence encounters per 10,000 miles over mountains as compared to only 1.5 occurrences over water and flat terrain, a ratio of 3.3 to 1.

3.3.3 Gust Distributions

The most comprehensive report to date on gust exceedance measurements was published in 1971 and involves data from commercial and military airplanes of seven NATO countries (ref. 3-17). Data were gathered over 60 million miles relating gust exceedances and magnitude per flight mile by altitude and season. Unlike turbulence exposure, gust distributions are not so dependent on either the critical boundary between turbulence and smooth air or subjective treatment in their derivation. However, gust exceedance measurements do not exclude pilot inputs, spurious noise, or effects due to differing airplane characteristics. The vast amount of accelerometer data collected in the NATO program partially balances these uncertainties and maneuver accelerations were separated from the turbulence whenever possible. Nevertheless, it may be appropriate to consider the results qualitatively rather than quantitatively.

Figure 3-12 summarizes the results of the NATO program, showing gust exceedances per nautical mile of flight as a factor of gust velocity for different altitude bands. Gust velocity is derived by dividing the acceleration deviation from the 1-g level (Δn) by the gust

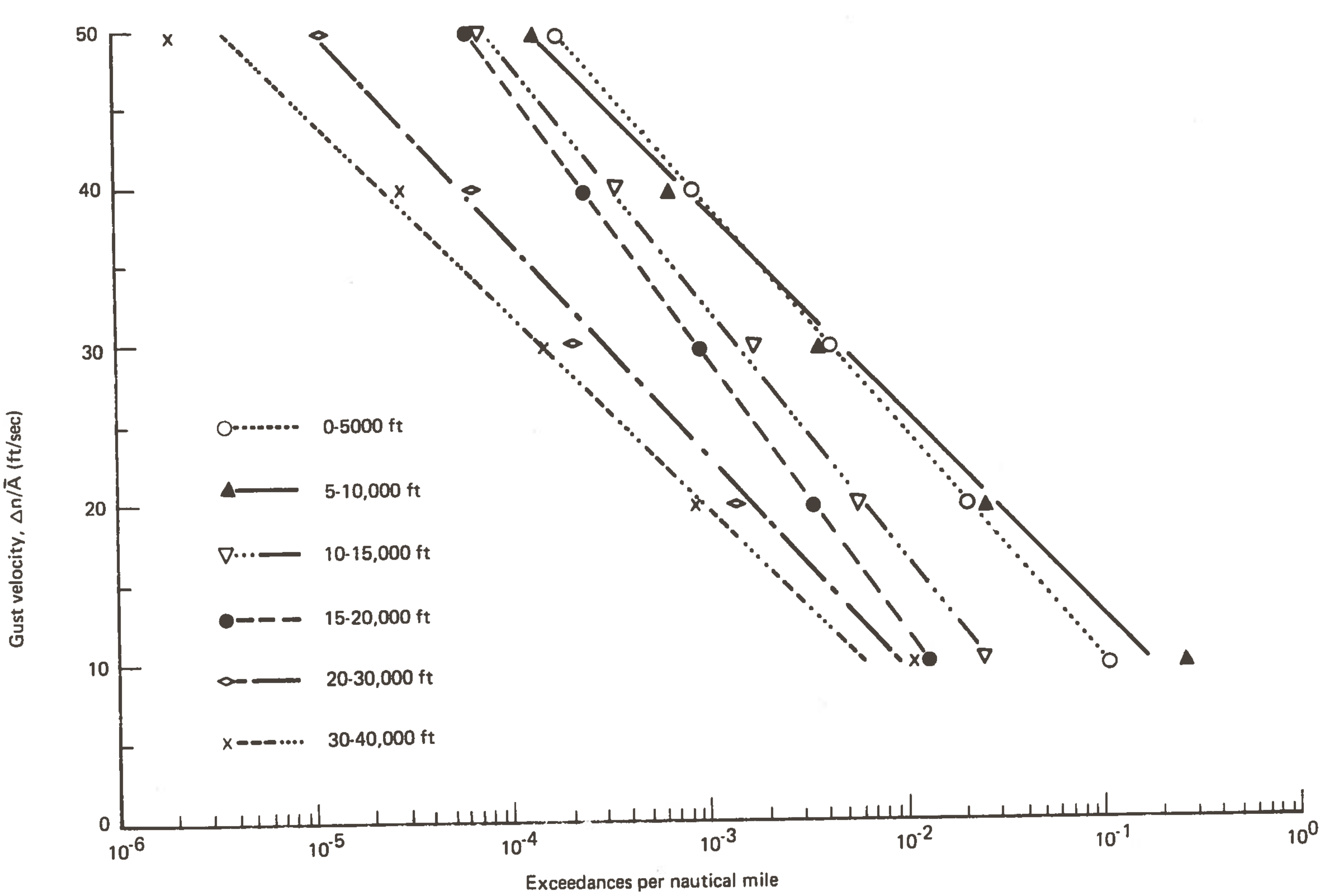


FIGURE 3-12.–EXCEEDANCES, VELOCITY AND ALTITUDE RELATIONSHIPS

response factor ($\bar{A}$). It was found that changes due to seasonal variations are minimal. Examining these gust exceedance curves shows:

- Exceedances decrease exponentially with increasing magnitude.
- The number of gusts exceeding given levels decreases fairly uniformly with increasing altitude.
- The decrease with altitude increase is most pronounced above 20,000 feet for large gust values.
- There is a relatively high frequency of gusts $\geqslant 10$ fps at the higher altitudes.

From this brief overview of data, it is apparent that turbulence occurrence is less over water and that frequency of exposure increases as a factor of terrain roughness. However, these data are not in a form to support a confident argument as to the percentage of time a strategic flight would be required to deviate from the assigned route-time profile so as to affect system scheduling.

3.3.4 Wind and Weather Prediction

Weather forecasting involves a detailed knowledge of present and immediately past weather and a means of predicting how this will change. The condition of the atmosphere at a particular instant in time is determined from analysis of concurrent observation at a network of stations. These concurrent or synoptic observations are quantitative evaluations of physical properties such as pressure, temperature, humidity, wind, precipitation, and cloud cover. The main factors controlling the accuracy of meteorological forecasts may be briefly summarized as:

- The inherent variability of the parameter of interest
- The accuracy of specification of the initial state of the atmosphere
- The prognostic procedures used

The inherent variability varies with geography, altitude, and season. Repeatability and predictability are more constant in the tropics than in middle latitudes. Accuracy degrades with altitude as properties of the real atmosphere vary in time. There are errors in the measurement of altitude. Table 3-7 (extracted from ref. 3-25) shows error in pressure altitude measurement during the 1970 time period for U.S. meteorological equipment. Winter forecasts are less reliable than summer forecasts. Detailed climatological summaries of wind and temperature for likely SST routes (ref. 3-25) showed that monthly mean patterns for individual summer months were consistent, whereas the patterns for winter months varied from year to year.

Specification of the initial state depends upon accuracy of observations, station spacing, and frequency of observations. A network of ground stations measures standard parameters and transmits these and remarks concerning significant local weather such as fog,

TABLE 3-7.–STANDARD DEVIATION OF PRESSURE ALTITUDE

Altitude (ft)	One sigma (ft)
0	3
10,000	27
20,000	45
30,000	80
40,000	105
50,000	147

rain, thunder, etc., to a central office for analysis and preparation of spatial variation maps, which are then disseminated, as needed, on a worldwide basis. There are some large gaps in station spacing in the oceans and in underdeveloped areas of the world. In such areas information is supplemented by reports from airplanes and ships. Weather satellites provide great assistance for cloud cover measurement and detection of large-scale weather systems such as cyclones, hurricanes, and large thunderstorms. Satellite pictures sometimes permit accurate determination of jetstreams (which occur at the tropopause and in the boundary region between conditions of warm and cold air) and reveal the existence of mountain and lee waves. Synoptic charts are prepared to forecast values for 3, 6, 12, 24 or more hours ahead.

Measurement sample rate varies from continuous to daily. Sounding balloons will be released only once or twice a day; actual balloon release time may occur up to an hour before or after nominal observation time, and consequently observations are only approximately synoptic. There is also a delay between data observation and presentation to the pilot due to the finite time required to collect data, analyze inputs, prepare charts, and communicate this information.

Claimed predictability of weather (ref. 3-26) is that on a 5000-kilometer scale it can be forecast on a 5-day basis, whereas on a 5-kilometer scale forecasts can only be on a 2-hour basis. Large-scale agreement between forecast and subsequent actual pressure patterns is generally close. Position of major features, such as fronts and centers of high- and low-pressure areas, may be wrong by a hundred miles, but the effects of such errors are usually in the time at which specified weather reaches a particular place. In some situations minor errors in forecasting the pressure field can result in radical errors in forecasting the weather. For example, an error of 20° to 30° of wind direction can make the difference between a cold, windy, clear winter day and a blizzard. Similarly, the forecasting of the lifting of fog is rarely reliable to better than an hour and can sometimes be wrong by several days.

Figures 3-13 and 3-14 summarize findings for a 200,000-square-mile area in the middle latitudes of the northern hemisphere (ref. 3-27) and show wind forecast errors for summer and winter. They are based on the assumption that a wind sounding to 100,000 feet is available close to the area of validity shortly before forecasting time.

The three common prognostic procedures are the climatology, persistence, and conventional forecast methods although computer-derived dynamic analyses or numerical weather predictions are also in use. The latter is based upon universal physical principles as expressed by the general equations of hydrodynamics.

Climatology concerns the analysis of accumulated observations to define means, medians, modes, and dispersions of frequency distributions of the parameters of interest. While this technique can provide an estimate of the probability of occurrence of a specific departure from the mean value of a parameter, it is unable to predict trends or the specific time of occurrence.

The persistence method postulates that the most recent observed value is the best estimate of a future value of the parameter of interest. The validity of the hypothesis derives from the fact that most geophysical time series (including those of wind and temperature) exhibit considerable autocorrelation over time intervals of practical interest.

Conventional forecasting constructs prognostic charts, mentally or formally, on the basis of experience, empirical rules, and some kinematic and dynamic computations, with the weather distribution inferred through use of idealized models and thermodynamic considerations. The forecast skill inherent in these methods varies significantly between individual forecasters.

Figure 3-15 shows comparative capabilities of climatological, persistence, and conventional forecasts for upper winds as domains of a plane defined by prognostic period and altitude (ref. 3-28). The specific partition of the various domains will vary with season and location, but probably not excessively. The least certain aspect of the figure concerns the true intersections of the lines separating the various domains.

3.4 COMMUNICATION REQUIREMENTS

3.4.1 Postulated Environment

To determine the specialized communication requirements for strategic control requires an assessment of the anticipated communication environment. An earlier study, reported by RTCA Special Committee 110 (ref. 3-29), conducted an empirical investigation of communication messages and divided them into eight categories, which are listed in table 3-8 together with their domestic and international percentiles.

The greatest area of disparity between domestic and international communication requirements concerns traffic advisories. These represent almost a quarter of the total of international messages but less than 1% of domestic messages.

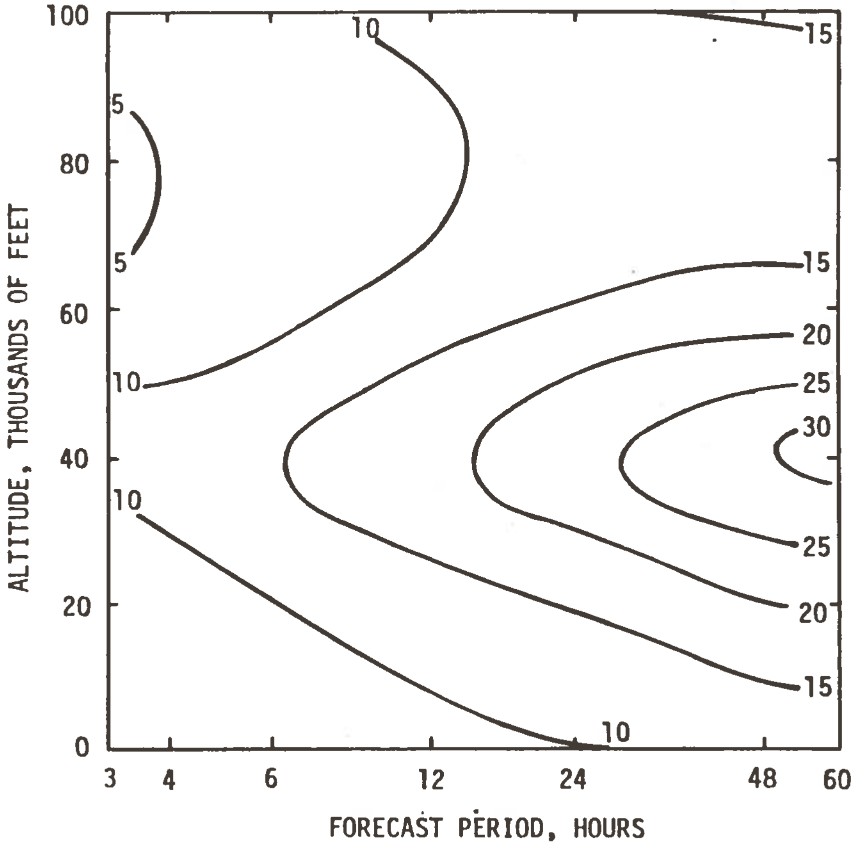


FIGURE 3-13.—ROOT MEAN SQUARE WIND FORECAST ERROR (KNOTS) MIDDLE LATITUDES, SUMMER

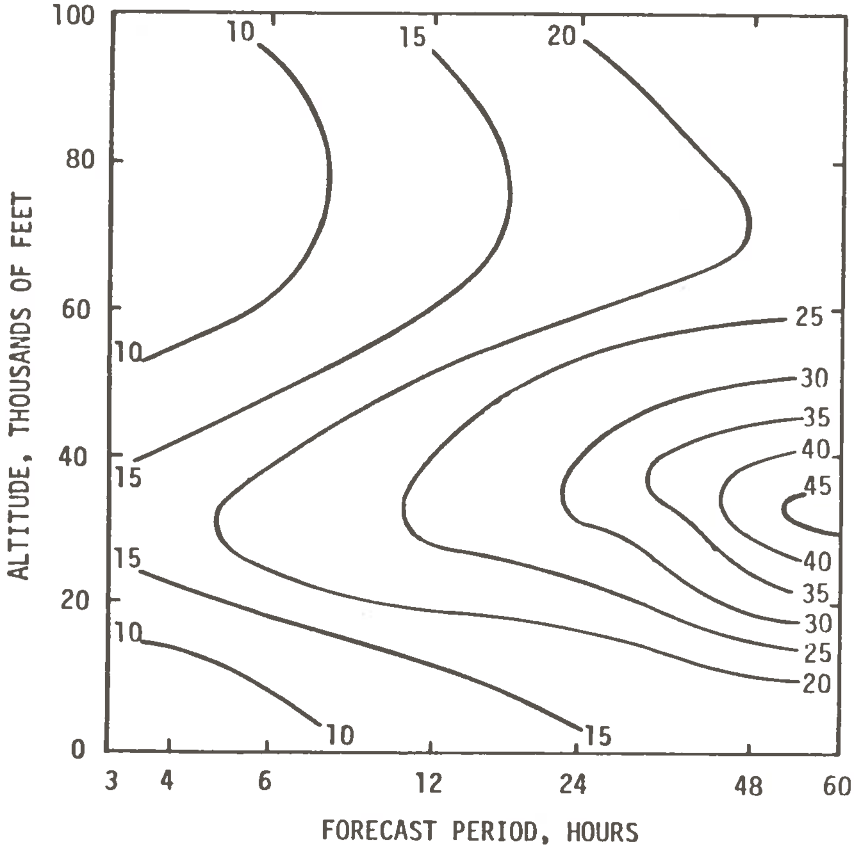
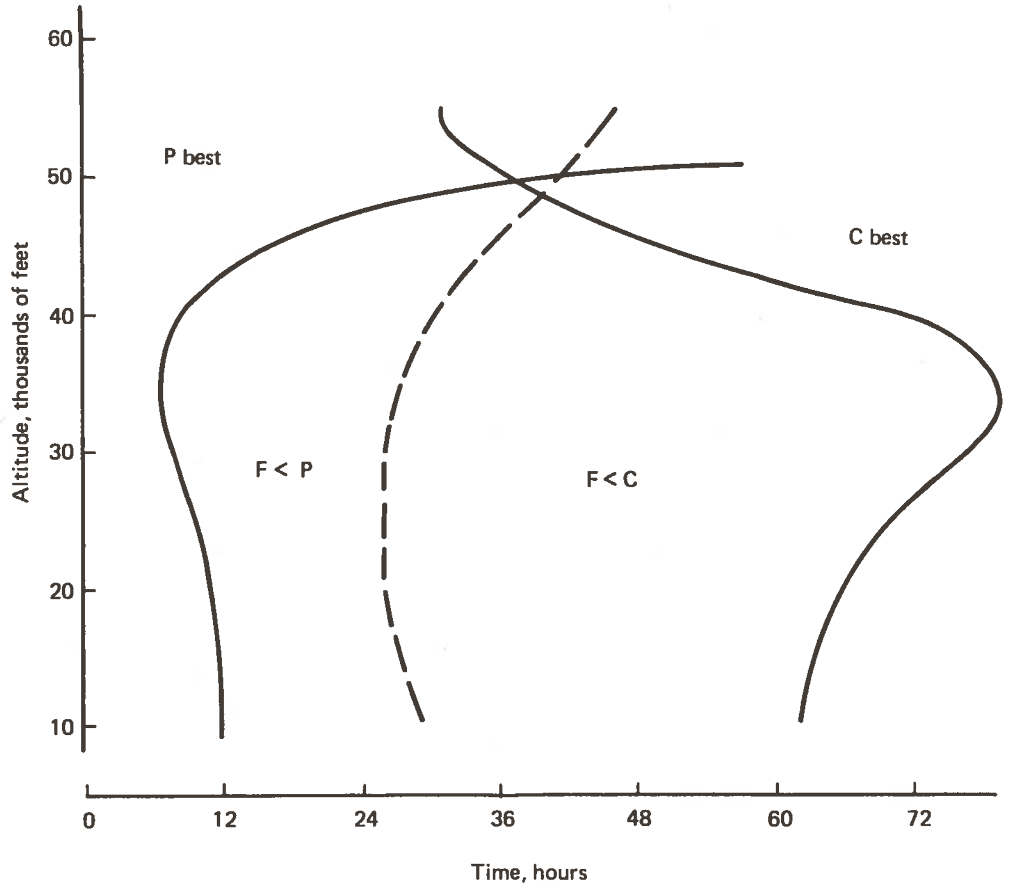


FIGURE 3-14.—ROOT MEAN SQUARE WIND FORECAST ERRORS (KNOTS) MIDDLE LATITUDES, WINTER



Note: Space-time domains of relative error variances in wind forecasts by persistence (P), conventional forecast procedures (F) and climatology (C).

FIGURE 3-15.—FORECASTING CAPABILITIES

TABLE 3-8.—DISTRIBUTION OF MESSAGE CATEGORIES

Message category	Domestic (percentage)	International (percentage)
Position reports	75.4	55.0
Terminal forecasts	0.05	3.0
ARTC traffic	0.55	23.0
Maintenance messages	1.64	0.64
Weather messages	15.7	2.6
Radio and ramp checks	2.22	5.5
Messages from passengers	0.23	0.84
Miscellaneous	4.21	9.42

This difference is due primarily to the use of procedural control for transoceanic flights versus radar control over the CONUS. With the improvements in surveillance capability and the advent of a worldwide navigation system as projected for the Advanced Generation ATC, these differences will be dissipated and, for the purpose of this study, the domestic figures can be taken as representative and realistic.

By far the greatest percentage of all communication congestion is due to position reports. With the current implementation schedule for mandatory mode C transponders, en route NAS stage A, and terminal ARTS equipment, the need for position reports will be eliminated. Additionally, the proposed DABS (discrete address beacon system) data link, or an alternative system providing a data link capability, will be in operation by the time strategic control is introduced and it can be assumed that ATC will have available continuously and automatically updated information on airplane identity, position, altitude, velocity (groundspeed), and heading. It is assumed that data link will be an inherent facet of strategic control.

Another assumption made is that the automatic terminal information service (ATIS) will continue in operation and that it will be utilized by all arrivals and departures. The ATIS will provide the terminal forecast supplying information on ceiling, visibility, wind, altimeter setting, instrument approach, runways in use, and pertinent NOTAMs. The ATC controller will still retain the prerogative to supplement or override the ATIS data if conditions warrant such action.

It may also be argued that traffic messages will be redundant with the introduction of stategic control. Under normal operation all traffic will be positively controlled. An airplane deviating from its programmed flightpath will constitute an abnormal situation. Under this circumstance other traffic will be given avoidance commands (which will be covered later under nonstandard operation) and will not operate under the current "see and avoid" procedures.

The remaining categories of messages listed are not pertinent to the strategic control situation; however, most of them will be data linked. Voice communication will be reserved for miscellaneous nonroutine messages, which will constitute less than 10% of the total communication load. ARINC characteristic 586, currently in draft issue number five, deals with air-ground-air data link systems and there are a number of industry, airline, and government study groups (refs. 3-30 through 3-34) analyzing data link requirements for communication. The emphasis of these study groups is on signal format, flight deck information presentation, and routine communications embracing ATC operational control, flight plan clearances, weather reports, intermittent positive control (IPC), company messages, ramp checks, and maintenance data transmissions. Although much of this work is still in the conceptual stage the broad principles are agreed upon and will be assumed to be operational. Consideration will be given to the additional requirements imposed by the introduction of strategic control.

3.4.2 Ergonomic Considerations

No attempt has been made in this evaluation to suggest a method of message selection, information presentation, or message priority. (For example, collision avoidance and IPC messages must require immediate attention.) For the ground controller, discrete selection devices for the more common messages (altitude, time, etc.) would appear beneficial; however, a separate input selector for each required message could be overwhelming and confusing. In the flight deck some form of orthographic projection may be used; accepted abbreviations will be standardized and less common words spelled in full. Display presentations under consideration vary from dedicated alphanumeric panels to time-shared CRT devices. One system involves a synthetic voice verbalizing the message to the pilot in conjunction with an abbreviated soft copy display. This is demonstrated in figure 3-16, which shows part of the ATC messages suggested by the DOT Transportation Systems Center for data linking with various possible readout formats. Whether or not command messages should feed directly into the airplane guidance and control system is another decision to the resolved; the trend, at the moment, is for this to remain a pilot option.

3.4.3 Strategic Requirements

The route-time profile concept of strategic control will require certain specialized messages and will make a finite capacity demand upon the data link channel. A logic for determining strategic control communications requirements is shown in figure 3-17. The total communication requirement is the product of the messages per flight times the number of flights.

Analysis of strategic control communications requirements can be divided into nominal and nonstandard operation. Each will involve unique message contents, which are summarized in table 3-9 together with the digital data bit count. The bit counts, which provide an indication of capacity demand, may be different in the implemented system since the actual requirement will be determined by the particular code in use. For this analysis a combination of ASC (standard seven-unit code) and absolute binary has been used. It is postulated that standard phrases, words, and alphas will be transmitted using ASC and that numerical data and other parameters will be transmitted in binary.

		Verbalization (Voice or synthetic speech)	7-window	32-window	Charac-tron	Three 7-window
Metering and spacing	Heading	Maintain heading XXX degrees	HDG XXX	*HDGXXX* ALTXXX SPDXXX	Hold HDG XXX	HDG XXX ALT XXX SPD XXX
		Turn right, heading XXX degrees	H→XXX	*H→XXX* ALTXXX SPD XXX	Turn → → XXX	H→XXX ALT XXX SPD XXX
		Turn left, heading XXX degrees	H←XXX	*H←XXX* ALTXXX SPDXXX	Turn ← ← XXX	H←XXX ALT XXX SPD XXX
	Altitude	Maintain altitude XX thousand feet	ALT XXX	HDGXXX *ALTXXX* SPDXXX	Hold ALT XXX	HDG XXX ALT XXX SPD XXX
		Climb to altitude XX thousand feet	A↑XXX	HDGXXX *A↑XXX* SPDXXX	↑ ↑ ALT XXX	HDG XXX A ↑XXX SPD XXX
		Descend to altitude XX thousand feet	A↓XXX	HDGXXX *A↓XXX* SPDXXX	↓ ↓ ALT XXX	HDG XXX A ↓XXX SPD XXX
	Speed	Maintain speed XXX knots	SPD XXX	HDGXXX ALTXXX *SPDXXX	Hold speed XXX	HDG XXX ALT XXX SPD XXX
		Increase speed to XXX knots	SPD XXX	HDGXXX ALTXXX *SPDXXX*	↑ ↑ Speed XXX	HDG XXX ALT XXX SPD XXX
		Slow to XXX knots	SPD XXX	HDGXXX ALTXXX *SPDXXX*	↓ ↓ Speed XXX	HDG XXX ALT XXX SPD XXX

Note: Source DOT-TSC presentation, 9/8/72

FIGURE 3-16.—GROUND-AIR SHORT ATC MESSAGES

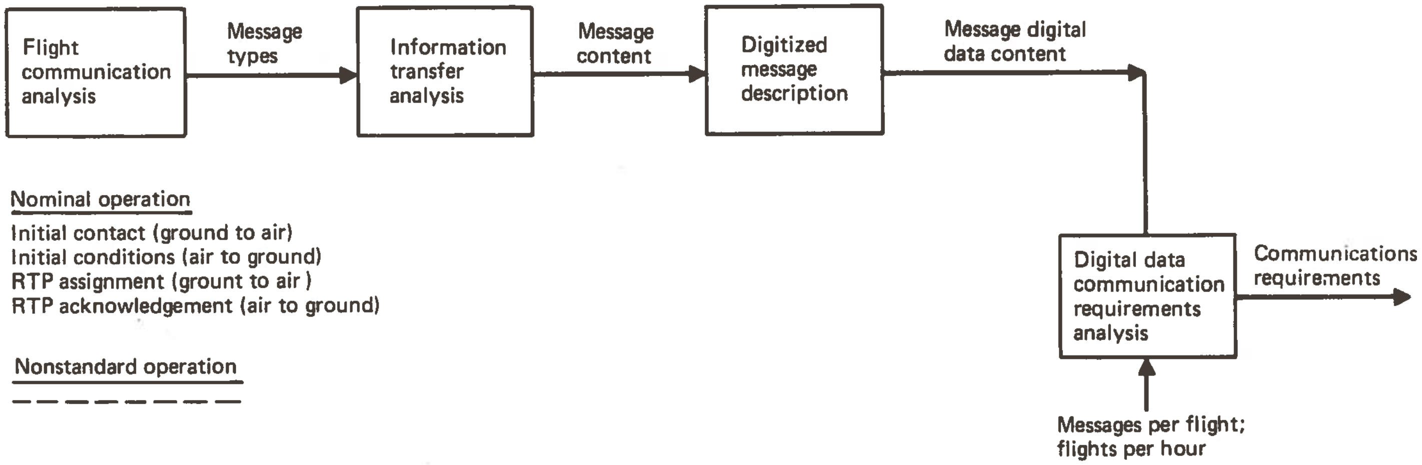


FIGURE 3-17.—STRATEGIC CONTROL COMMUNICATION REQUIREMENTS

TABLE 3-9.–ARRIVAL-CONTROL DIGITAL MESSAGES

Message type	Message format	Bit count
1. Initial contact (ground to air)	Airplane address	20
	Control address	10
	Approach aid	7
	Runway	15
	Data request	7
	End of message	7
	Total	66
2. Initial conditions (air to ground)	Control address	10
	Airplane address	20
	Gross weight	27
	Approach velocity	15
	End of message	7
	Total	79
3. Route-time profile assignment (ground to air)	Airplane address	20
	Control address	10
	Waypoint number	17 x 12
	Latitude/longitude	56 x 12
	Altitude	23 x 12
	Time	25 x 12
	End of message	7
	Total for 12 waypoints	1489
4. Route-time profile acknowledgment (air to ground)	Control address	10
	Airplane address	20
	Acknowledgment	7
	End of message	7
	Total	44

3.4.3.1 Nominal Operation

Initial Contact–It is assumed that ground control has knowledge of the airplane number, type, altitude, current position, and estimated time of arrival at the entry fix. The purpose of the initial contact is to notify the approaching airplane of the designated runway and the approach aid and to request information necessary for the ground computer.

A typical message could be verbalized as "United three two one is cleared by Los Angles Control for MLS approach to runway two four right; what are initial conditions?"

The message breakdown with bit count is:

	Bits
Airplane address	20
Control address	10
Approach aid	7
Runway	15
Data request	7
End of message	7
Total	66

Initial Conditions—This will be an air-to-ground message, with an implicit acknowledgment of the initial contact, supplying information with respect to gross weight (measured to the nearest hundred pounds) and approach velocity, V_{app} (to the nearest knot). Entry velocity is unnecessary as the ground control has knowledge of this parameter due to the four-dimensional area navigation environment. It could also be argued that approach velocity is unnecessary as the computer can determine this knowing the airplane type and gross weight. Gross weight is necessary, however, as this will affect the allocated route-time profile.

A typical message response could be verbalized as "Los Angeles Center, United three two one has gross weight of two hundred and ninety eight thousand pounds, approach velocity will be one hundred and twenty six knots."

The message breakdown is

	Bits
Control address	10
Airplane address	20
Gross weight	27
Approach velocity	15
End of message	7
Total	79

Route-Time Profile Assignment—With the filed knowledge of entry fix position and the airplane time, altitude, and groundspeed at the entry fix, the controller can now enter the unknown parameters of airplane gross weight and approach velocity for generation of the route-time profile from entry fix to touchdown.

The next transition will supply these data to the airplane. The message content will be to allocate sequential waypoint numbers, to identify these waypoints in terms of latitude and longitude (to the nearest one thousandth of a minute, i.e., approximately 6-foot resolution) and to specify the altitude (to the nearest foot) and time (to the nearest second) at each waypoint. Linear acceleration is assumed between waypoints. Groundspeeds used in determining the route-time profile are not transmitted as this parameter is forced by the airplane to make good the time at each waypoint.

The message breakdown is:

	Bits
Airplane address	20
Control address	10
Waypoint number	17
Latitude/longitude	56
Altitude	23
Time	25
End of message	7

Items 3 through 6 will be repeated as many times as there are waypoints.

The average number of waypoints is estimated at 12. Thus, the average message will contain 1489 bits.

Route-Time Profile Acknowledgment—There will be a requirement for the airplane to acknowledge receipt of the route-time profile (RTP) assignment. The acknowledgment could take different forms depending on the transmission signal format. It may require a repeat of the total assignment to the ground control for cross check and verification. In this case the bit count will be the same as for the route-time profile assignment. However, if the assignment message format includes an omission and correction code, the RTP acknowledgment could be a simple "message received and will comply" (WILCO) transmission.

The message breakdown could be:

	Bits
Control address	10
Airplane address	20
Acknowledgment	7
End of message	7
Total	44

Nonstandard Operations—There could be many reasons for operations that perturb the nominal strategic concept and give rise to nonstandard operations. Airplane equipment malfunction could cause performance deviations or prevent RTP assignment adherence. An unexpected emergency, such as an airplane blocking a runway, may require deviations, holding, runway change, or diversion to an alternate airfield.

The urgency or seriousness of such nonstandard operations depends on many factors—is the airplane inside or outside the terminal area, the volume of other traffic, slot availability, the nature of the deviation, etc. Although provision is made within the overall strategic concept for such operations the additional impact upon communication requirements is negligible and already within the postulated system capabilities.

Nonstandard operations that could warrant immediate evasive action or other short-term response will impose a communication requirement analogous to today's vectoring techniques. These high priority type commands will be an inherent facet of intermittent positive control and will be satisfied by the message format given in figure 3-13. (In an emergency, backup voice communication will still be available.)

Nonstandard operations of less urgency may require dynamic rescheduling of all or part of the traffic already assigned route-time profiles. This imposes an additional demand upon the ground computer but, as far as the airborne computer and communication network is concerned, flight plan amendments and RTP reassignments are the same as original clearances. They will require the same action, impose the same workload, demand the same capacity and, in all respects, be treated the same as nominal operation.

3.5 GROUND VERSUS AIRBORNE DATA PROCESSING

The following discussion of ground-based versus airborne data processing is to identify potential areas of trade and to identify strategic system implications. The communications impact is also discussed.

The system computers (both airborne and ground-based) may be viewed as transfer functions that are driven by input or sensor information and have predictable resulting outputs. In this context, if either the airplane or the ground system are both the sensor source and the sole output user, then communication loading is unnecessary if the computing function is accomplished at the using location. This division also results in parallel redundancy from a total system point of view. A more difficult situation exists in allocating computational functions where the primary data sensor is not located where the results or output are to be used. For example, the location of all airplanes in the system is known from the surveillance function to the ground system and is not known to each airplane (i.e., in general, an airplane only knows its own position). This form of information acts as an input to a collision detection and resolution function in which the result is eventually used to provide guidance information for some or all of the airplanes. The output in this example is used by the airplane from raw data sensed on the ground. Theoretically, the computation itself could be accomplished in the airplane if the raw data were transmitted to it but at heavy communications burden. In addition, since many more airplanes exist than ground installations, this results in a much greater total system installed computing capacity. If a system of 7000 strategic airplanes and 25 strategic terminal areas is postulated for late in this century, there exists a 280:1 lever in favor of installing a computing function on the ground if all other considerations (e.g., failure mode backup, communications loading, response time, etc.) are ignored.

In a very general sense then, all computations should be accomplished where it is possible to minimize massive raw data transfer (i.e., where the sensed information is present) and still obtain total system objectives such as cost reliability, performance, and redundancy.

Another consideration is information storage of data, which is determinable well before the flight takes place. Airplane performance information could be carried in the airplane's computer or alternatively stored in the ATC system computers. It appears that this type of information should be stored at the location that will be the ultimate user. In some cases it may be reasonable to store information in both the air and ground systems.

In considering the strategic control concept, the functions that involve the interactions of more than one airplane were assigned to the ATC system computers. This included functions such as sequencing, scheduling, route-time profile generation, and the resulting metering and spacing. Functions that involved the execution of desired system objectives by a single airplane were allocated to that airplane. This division reduces communication to a small requirement and yields a positive separation of the direct navigation and surveillance functions with a resulting excellent degree of nonsimilar redundancy in case of failure.

The principal area of overlap noted is the question of path storage. The airplanes could store all paths for their area of operation (e.g., analogous to SIDs and STARs) and use the particular one directed by the ATC system. This means that the communications system would contain only identification and timing information rather than a total series of waypoints but at the expense of storage both on the ground and in the air. In addition, the airspace utilization flexibility to accommodate weather avoidance and other system perturbations would still have to be provided for in another way. Consideration of this problem indicated it was superior to transmit waypoints to the airplane prior to entering the terminal area along with the desired time objectives. This results in an airplane computing capability that needs only to store the active route but at the expense of communications bandwidth. However, this type of storage division also provides flexibility for change as a new flight plan can be transmitted to the airplane with exactly the same system in case of system perturbation.

4.0 STRATEGIC CONTROL ALGORITHM

This section explains the basic strategic control algorithm and its evolution. Volume III presents the logical detail and volume IV contains the computer program implementation detail. The reader is referred to these volumes for specific detail of the mechanized algorithm.

The single runway case is discussed in section 4.1. The discussions of runway reversal (sec. 4.2), and parallel runway considerations (secs. 4.3 and 4.4) rely heavily on analogy to the single runway case with modifications required.

4.1 SINGLE RUNWAY ANALYSIS

The single runway analysis addresses the problem of determining the detail necessary to mechanize the strategic control concept for arrival airplanes. This task results in a basic arrival control algorithm, which is judged to represent a balance between the expected avionics technology, potential airspace benefits, airplane performance capability, system flexibility, safety, and efficiency. The algorithm resulting from this effort provides the first step in the evolutionary process of continuing refinements that will ultimately provide a sophisticated algorithm for operational use.

4.1.1 Basic Assumptions

The primary assumptions underlying the algorithm development are as follows:

1) The airplanes that are the primary users of the strategic system have the inherent avionics and control capability to store and execute a four-dimensional route-time profile (within the aeroperformance window) to tolerances that are small compared to the desired spacing between airplanes.

2) The primary means of achieving the necessary time controllability to derandomize arrivals is by speed control as opposed to geometrical path stretching.

3) The communications capability between the airplane and the ground is of the form of a digital data link providing computer-to-computer interface.

4) The surveillance function is independent of the strategic control system, but a necessary adjunct.

5) The strategic routes are protected from intruders by a function independent of the algorithm, such as a modified IPC capability.

6) The weather forecasting system is an independent system but a necessary adjunct.

4.1.2 Geometrical Considerations

The choice of a system geometry results from a complex trade between route flexibility, sufficient path length to achieve the required time controllability, airplane performance capability, minimization of crossing and merge points, and airspace utilization.

The first considerations that have to be satisfied in order to have a viable system are the airplane performance capability and satisfactory time controllability. The airplane is limited by its speed/altitude window and its ability to descend at any given speed (see discussion of gradient in sec. 3.1). The time controllability is a function of the extreme velocities that the airplane may fly, integrated over the path distance. Additional time controllability is, of course, available by holding patterns, but this is a form of geometrical path stretching and was not considered to be the primary means of achieving the desired function.

Early consideration of the metering and spacing work as well as work of the FAA/industry RNAV task force provided insight into various aspects of the geometry problem. In viewing the metering and spacing (M&S) configuration, the following considerations are noted: (1) the total time controllability proposed by the double direct course error (DICE) mechanization is on the order of ±3 minutes from the nominal path for a total of 6 minutes; (2) while speed is regimented, path stretching in the near-terminal area was the means used for derandomizing the arrival stream and achieving separation at merge points; (3) the system is basically tactical in structure; and (4) the system did schedule to gate times rather than the relative separation of present day tactical systems. Both the RNAV task force and M&S have evolved present day terminal area considerations into a basic terminal area geometry based on a four-quadrant system of initial approach fixes. The RNAV work went one step further by allowing three feeder fixes at approximately 45 miles to feed each approach fix. Our conclusion from these works is that while the generalized four-quadrant terminal area has considerable merit and basic simplicity, the penalties imposed by the DICE path-stretching technique on the congested near-terminal airspace is undesirable from both an airspace utilization and efficiency point of view. It is reasoned that if a single path is used for each quadrant a considerable saving is made in airspace used and, more importantly, the airspace used is not a function of the control system traffic loading. This, however, means that a relatively low gain speed control technique over fixed paths is necessary to derandomize the traffic. As the initial approach fixes are perhaps 30 to 40 miles out and all merging must be accomplished by final approach, this technique does not seem to be a viable candidate.

Investigation of the avionics technology and the airspeed performance windows for the commercial jet fleet in the near-terminal area suggests that common speed profiles were feasible. If common speed and path profiles were to be used from an initial approach fix to the outer marker and these were referenced to absolute time, the ability to predict the merge points and separations would be possible. The principal difficulty, of course, is that no time controllability existed in such a system. Thus the airplanes need to arrive at the initial approach fix in exactly the right order and at the right time so that the common profiles produce the necessary spacing and time objective. Furthermore, the rigid arrival accuracy required at the initial approach fix is equivalent to derandomizing the airplanes before they arrive at this fix. The limitation is imposed primarily by the concept of the 30-

to 40-mile terminal area. Investigation of the aeroperformance curves indicates that it is possible to achieve approximately 6 minutes of time controllability during the letdown from en route altitude to the initial approach fix (IAF) altitude. Thus it is possible to project a desired runway threshold time schedule back to the IAFs by using the common speed/path system in the near-terminal area and then project an en route letdown velocity schedule that satisfied the desired IAF times.

In order to achieve this goal, a concept was evolved of a terminal area ATC system that receives the arrivals at en route altitude and perhaps 150 nautical miles from the runway. The airplanes cross an entry fix at en route altitude via a given route-time profile that accurately delivers them to the IAFs and then over common speed/path profiles to the outer marker. From the outer marker to the threshold each airplane's speed is unique depending on type and gross weight, but predictable. This technique conserves airspace in the near-terminal area and has the potential for a predictable geometry from en route altitude to the runway. As the system was to operate on speed control rather than path stretching, the requirements imposed on waypoint positions in the near-terminal area are primarily those related to the desired path for organization, merging, noise control, and flyability.

As a result of the above considerations, a four IAF quadrant type geometry is selected for the near-terminal area. Figures 4-1 and 4-2 are plan view representations of this geometry. The IAFs each feed a turn fix. These turn fixes provide routing flexibility. The turn fixes each feed a merge fix. The merge fixes are established on the basis of one for two quadrants or IAFs. The output streams of the two merge fixes are fed to the final approach fixes. The final approach fix is positioned on the final approach course and acts as a final merge point to collate the right and left arrival streams. The final approach fixes in turn feed the outer marker and ultimately the runway threshold.

Consideration of the entry fix to IAF region (outer terminal area) reflected that four entry fixes were insufficient. As these entry fixes are approximately 150 nautical miles from the runway, considerable distance penalties are imposed on arrivals from some directions, if only four entry fixes are used, due to the "dogleg" nature of the geometry structure. A system of three entry fixes per IAF provides entry capability every 30° around the outer terminal area boundary, and this technique was ultimately selected as a reasonable compromise.

As the airplanes are to be controlled in speed during the transition of the outer terminal area the next problem is to determine a means of ensuring separation and passing capability during this phase of flight. Investigation of airplane descent profiles indicates that a straight line descent is possible with respect to the earth providing the slope is picked such that the airplane descent gradient capability is not exceeded. Because airplanes descend with respect to the airmass, this slope must be consistent with existing wind conditions. This suggests that either the start of letdown must be far enough out to encompass adverse tailwinds or that the entry fixes should be dynamically allocated based on existing conditions. For this basic algorithm, the former choice is made with the latter refinement left for future investigation. The choice of straight line descents allows a geometrically simpler way of accommodating a parallel path structure and also makes the airspace utilization a predictable quantity. Five parallel paths are selected to provide conflict-free path assignment from each entry fix to the IAF. If an airplane requires a route-time profile

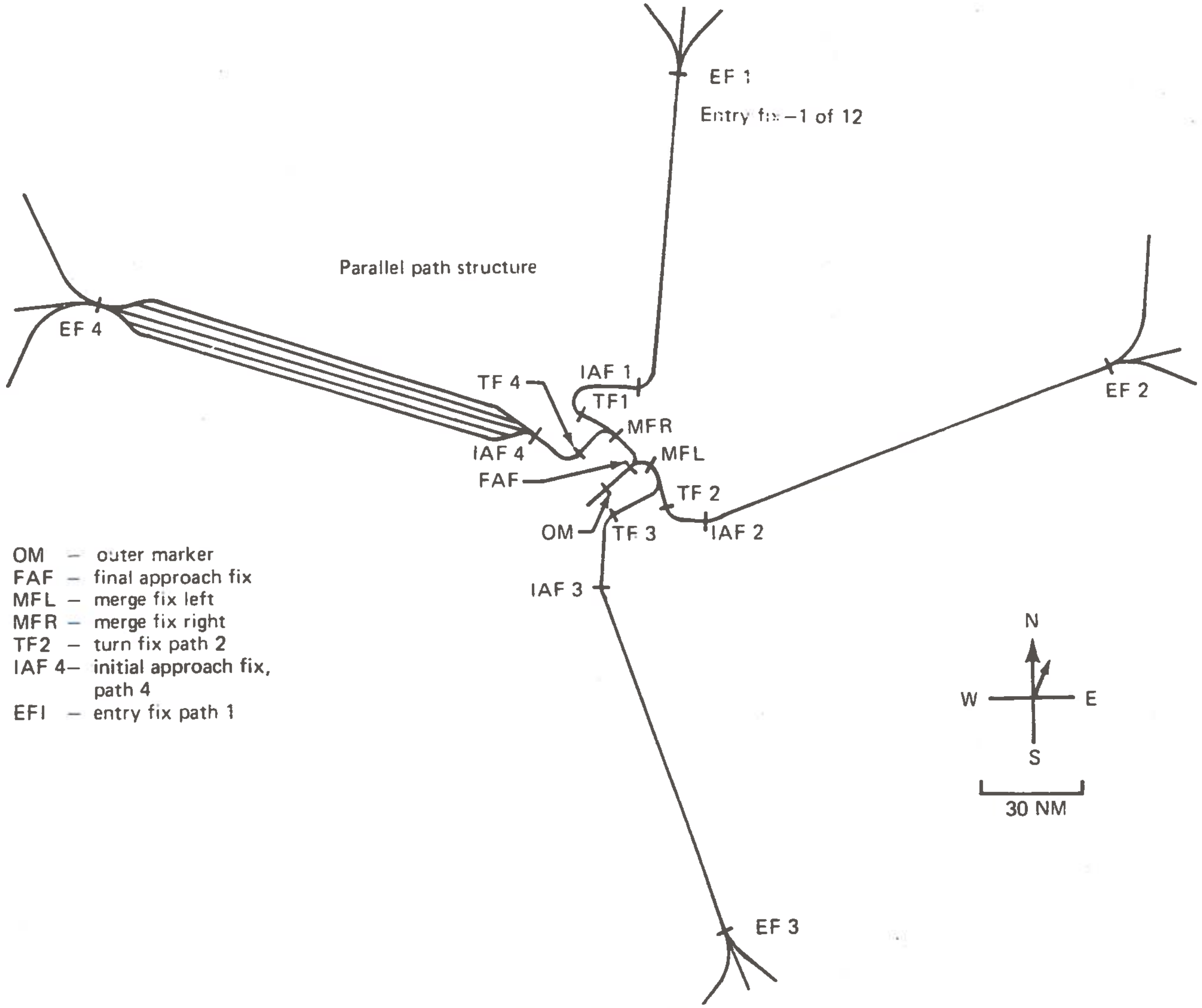


FIGURE 4-1.—STRATEGIC ARRIVAL CONTROL GEOMETRY STRUCTURE

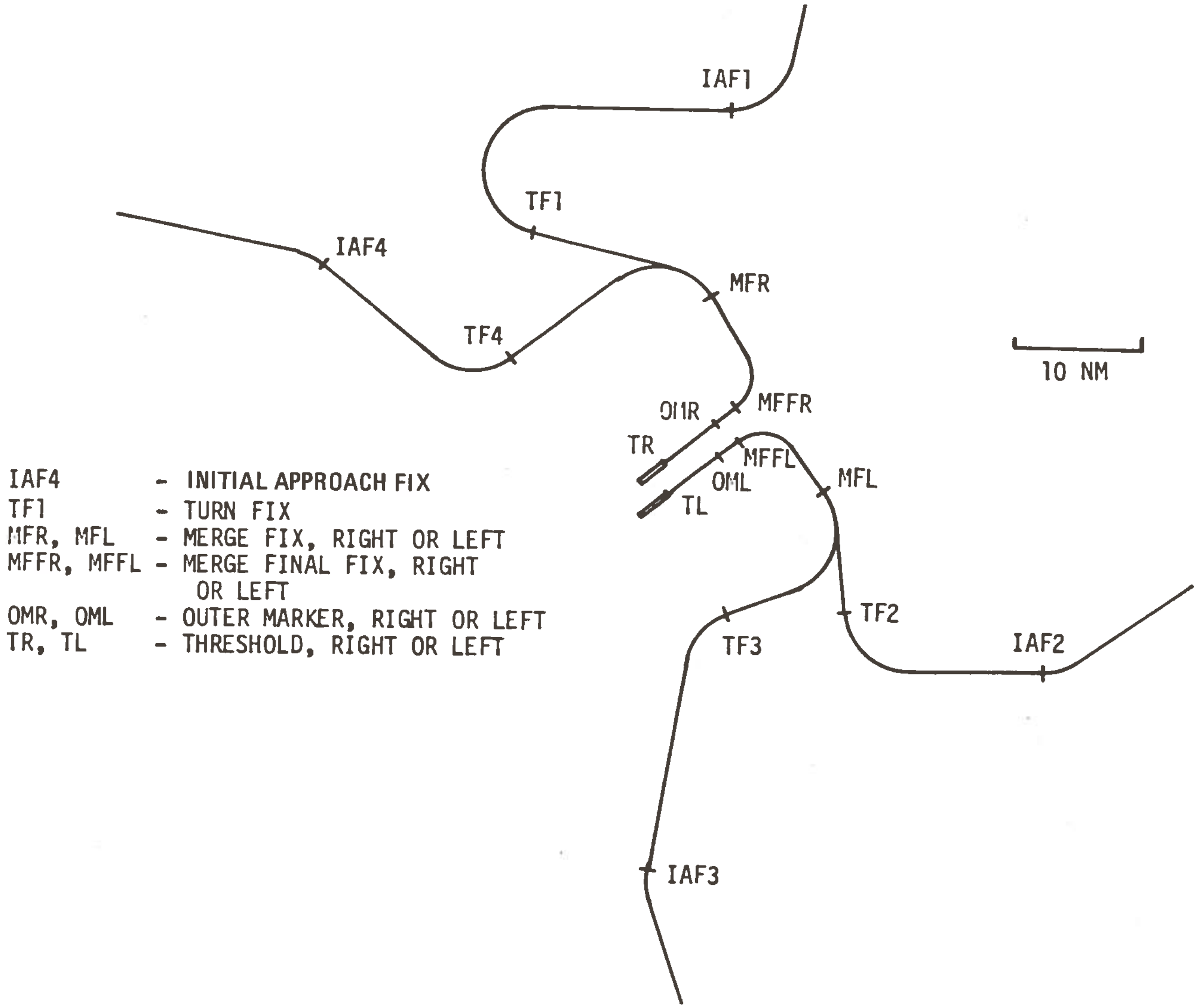


FIGURE 4-2.—INITIAL APPROACH FIX TO THRESHOLD DETAIL GEOMETRY

that would cause longitudinal overtake or passing, it is assigned to a parallel on which there exists no conflict with the airplane ahead.

The choice of three entry fixes, with five parallel paths each, all feeding one IAF results in many crossing points between the various paths near the IAF. This presents an untenable situation with respect to conflict prediction and resolution between airplanes transitioning from different entry fixes to a common IAF. To resolve this difficulty a system whereby each entry fix would feed a separate altitude at the IAF was selected. This results in complete separation (i.e., no crossings) between the parallel path geometries of each entry fix feeding an IAF. As the airplanes are to be properly spaced in the horizontal plane upon reaching the IAF, the final altitude merge can safely proceed on the first leg inside the IAF where all airplanes are on a common speed profile and hence will maintain their horizontal separation.

This system requires that all airplanes have a common speed at the IAF. As the airplane could have an assigned speed that is significantly different from this value, a level flight deceleration zone is created just prior to the IAF. This deceleration path length is assigned a value of 10 nautical miles and is based on the time required to decelerate from V_{mo} (i.e., the fastest speed allowed) to 250 KCAS. Figure 4-3 shows the resulting altitude versus along-track distance resulting from the above considerations. Investigation of the airplane performance windows indicates a descent gradient of 250 feet per nautical mile is required to accommodate descents in a clean configuration. The gradient could be increased if drag-inducing devices were permitted for operation in this region of flight.

All turns are treated as constant radius turns with the associated waypoint being the exit point of the turn. A number of other mechanizations exist with respect to choice of waypoint location with respect to the turn. The particular choice was made only for modeling purposes and should a technique such as a waypoint at the intersection of the entry and exit vectors or at the start of the turn be used, a coordinate transformation will accommodate the change.

All necessary distances, altitudes, and angles required for the algorithm are computed only once and stored by the geometry subroutine from the input waypoint locations, turn radii, and offset distances for the parallel paths.

4.1.3 Sequencing Considerations

In determining the order in which airplanes are to be accommodated at the threshold, a modified first-come-first-served strategy is employed. Based on the estimated entry fix arrival time, a route-time profile is created via the longest parallel and the associated estimated earliest landing time (EELT) is computed. The values of EELT for the arrivals are then ordered to reflect earliest threshold capability first. The threshold order is determined by sequencing down this list.

An associated calculation is accomplished to determine the estimated latest landing time (ELLT) for each arrival. This value is generated based on the shortest parallel path. The times between the EELT and the ELLT represent the "scheduling window." This scheduling window reflects the times that may be scheduled without need for a holding action outside the entry fix.

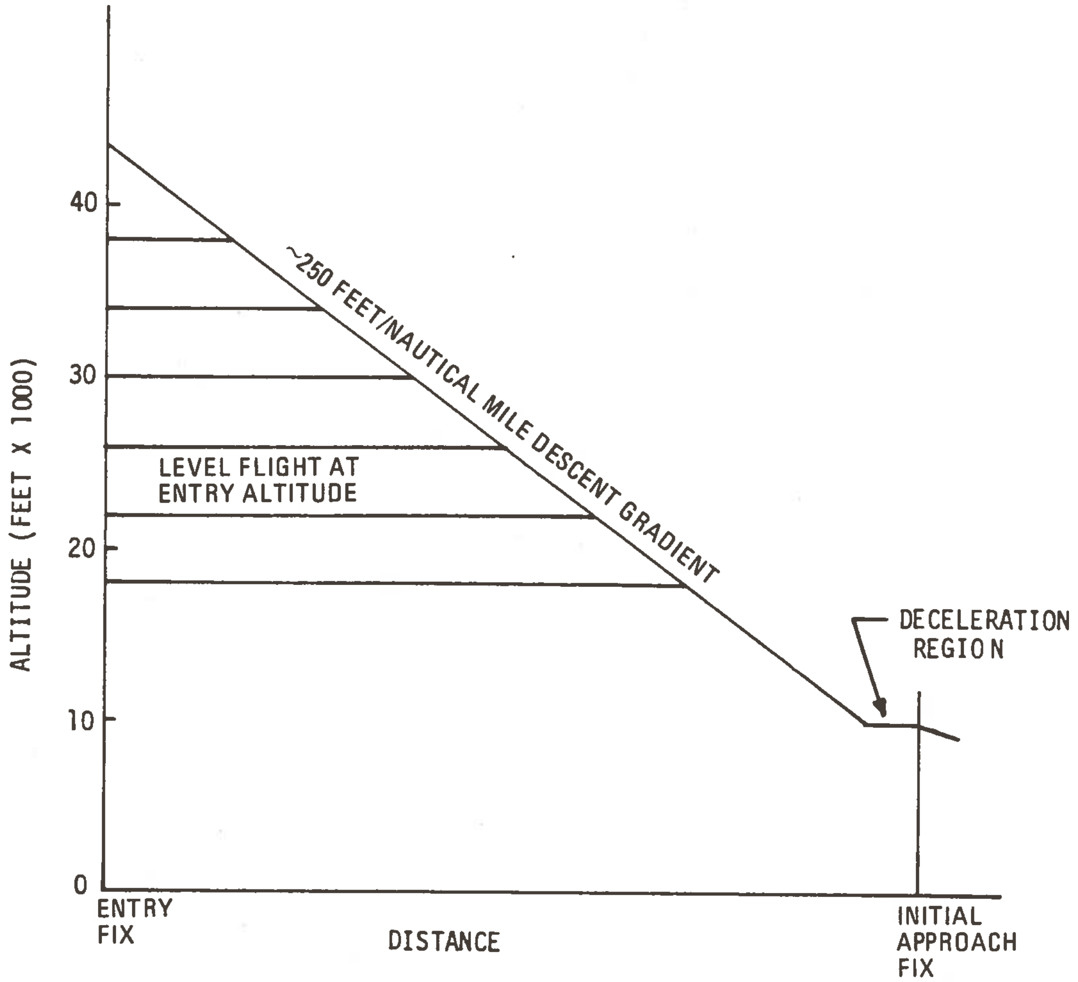


FIGURE 4-3.—TRANSITION ALTITUDE MERGE GEOMETRY

The reason for determining the EELT on the longest path and the ELLT on the shortest path is to ensure that the resulting scheduling window is independent of the particular path that ultimately will be assigned by an RTP generator.

Figure 4-4 shows the macrologic for the sequencing function. One additional function of the sequencing logic is to determine if the airplane's cabin repressurization rate is a limiting value on descent time. In the event that this limit was significant, the EELT is modified to reflect this limitation. This technique ensures a scheduling window consistent with the airplane's descent capability for repressurization.

4.1.4 Scheduling Considerations

The scheduling window resulting from the sequencing function is the time in which an airplane may be assigned a threshold time. The purpose of the scheduling function is to determine the particular time to be assigned within that window or to determine some other available time and create a preentry fix hold that adjusts the scheduling window to include this new time. Three separate scheduling logics were developed to accommodate (1) absolute arrival scheduling priority, (2) arrivals scheduled with assured opportunity departure slots, and (3) equal arrival and departure priority using prescheduled target departure times. Figures 4-5, 4-6, and 4-7, respectively, illustrate the functional logic for each of these techniques.

The scheduling function builds a table of scheduled landing times for the arrival stream and a table of scheduled release times for departures. In accomplishing this each succeeding airplane must be given adequate separation from the airplane ahead. This separation may be constrained either by runway occupancy time of the airplane ahead or it may be based on in-air separation times or distances.

The mechanization of this function selects the most limiting of these considerations when assigning the scheduled times. In addition, the provision is made for determining when a departure can be safely released or conversely adjusting the arrival times to accommodate scheduled departures. The runway occupancy times for the various airplane types and the ATC rules are inputs to a separation constraint time determination function. Four separate functional logic elements have been defined to provide the required separation time for the considered situation (i.e., arrival/arrival, arrival/departure, departure/arrival, and departure/departure) and the appropriate ATC rules. These separation constraint elements examine the in-air time and/or distance constraint as well as the runway occupancy constraint and return the time imposed by the most restrictive constraint to the scheduler function. The separation constraint time functional elements are available to each version of the main scheduling function and therefore are required no matter which scheduler is actually being used. Figures 4-8, 4-9, 4-10, and 4-11 illustrate the required functional logic.

The scheduling function must also consider that the critical scheduling parameter is not always the runway, as the final approach speeds may be different for each airplane. The case of a fast airplane preceding a slow one means that the separation is opening (i.e., separation is minimum at the outer marker) during final approach. In this case the threshold schedule is relaxed to provide satisfactory separation at the outer marker. If the arrival stream has satisfactory separation at these points, and assuming the airplanes fly the common

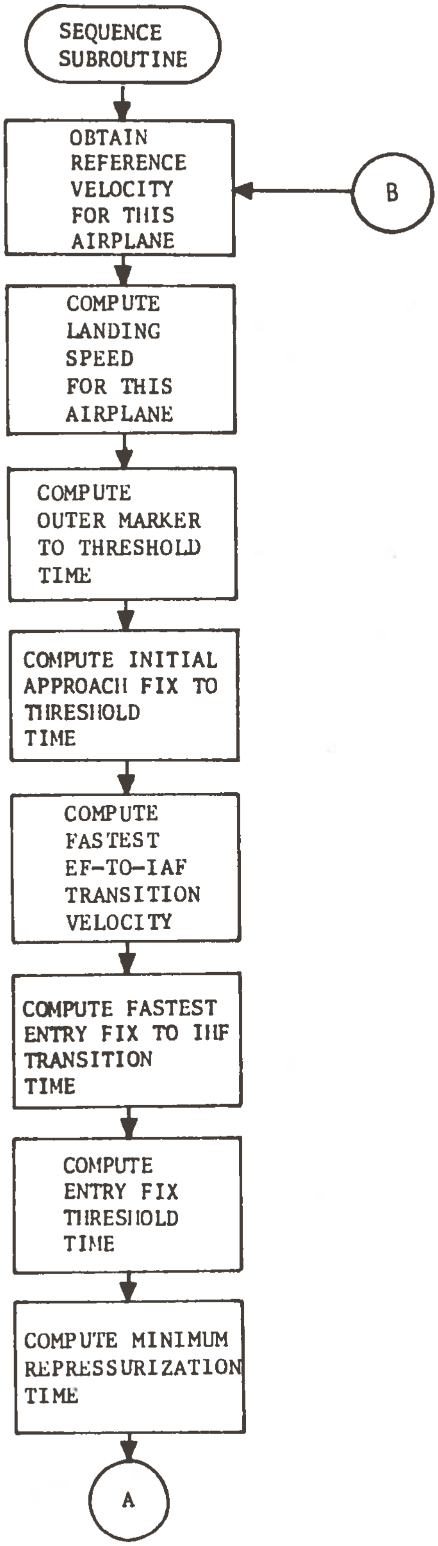


FIGURE 4-4.—SEQUENCING LOGIC

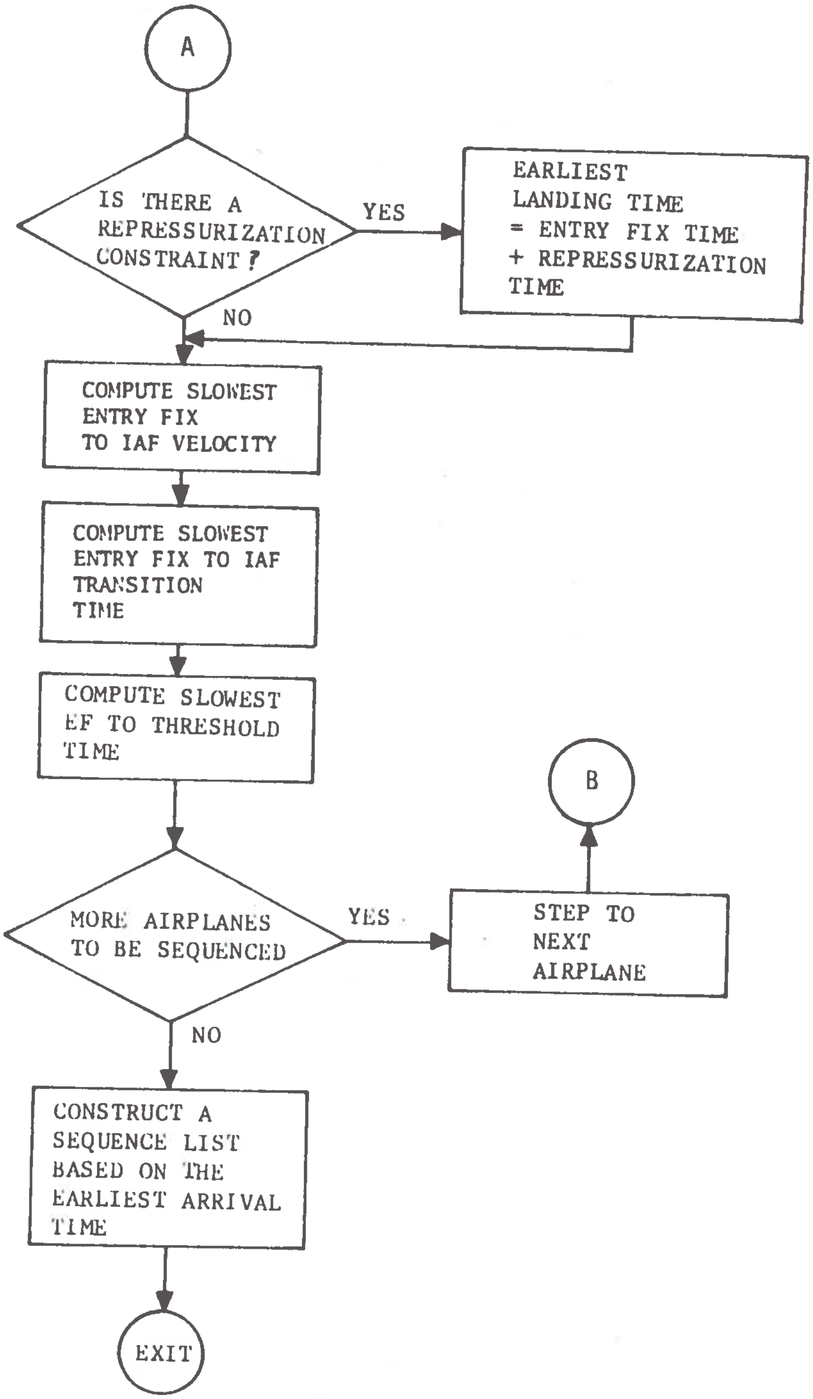
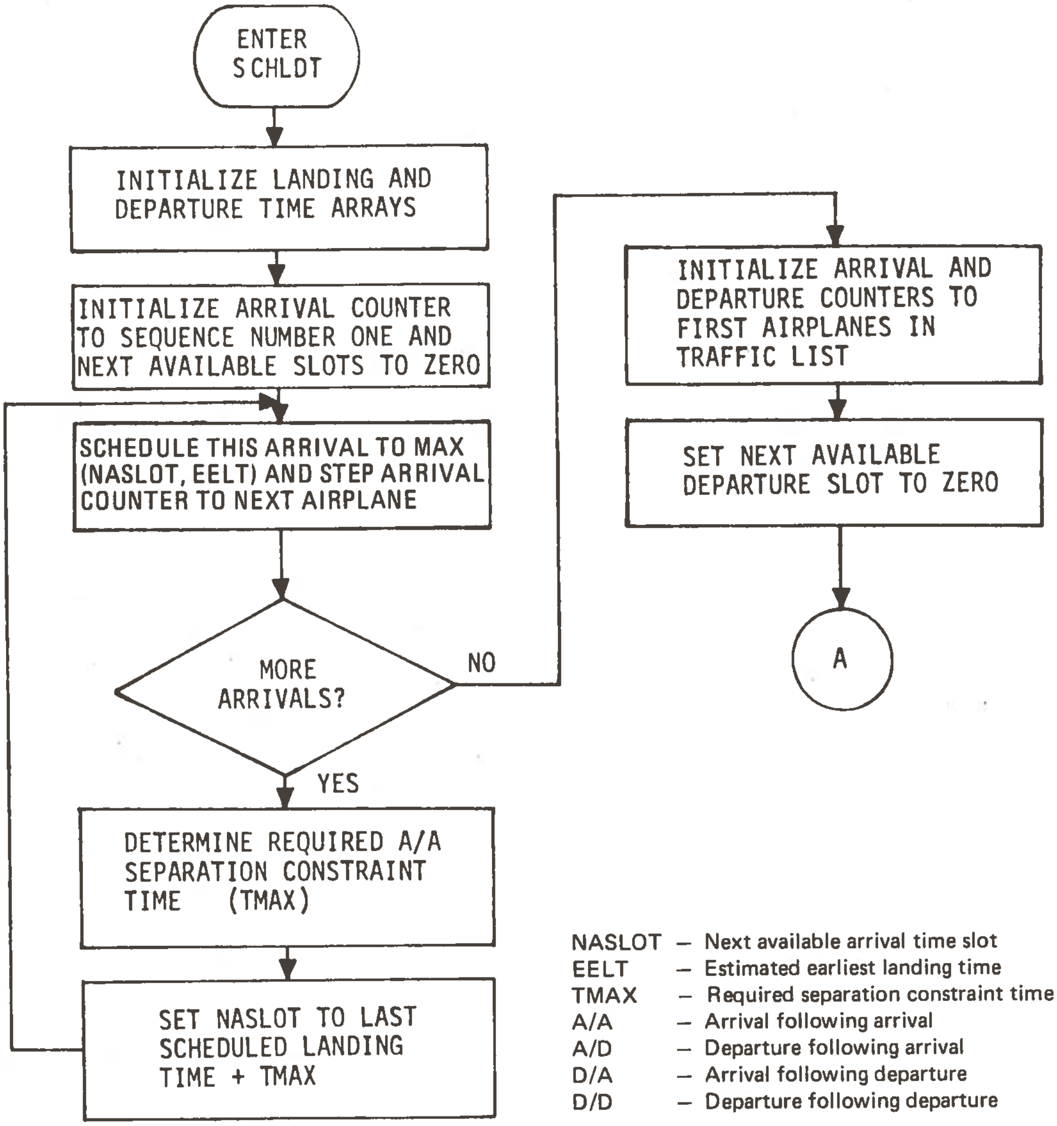


FIGURE 4-4.—CONCLUDED



NASLOT – Next available arrival time slot
EELT – Estimated earliest landing time
TMAX – Required separation constraint time
A/A – Arrival following arrival
A/D – Departure following arrival
D/A – Arrival following departure
D/D – Departure following departure

FIGURE 4-5.–SCHEDULER (VERSION 1) FUNCTIONAL LOGIC

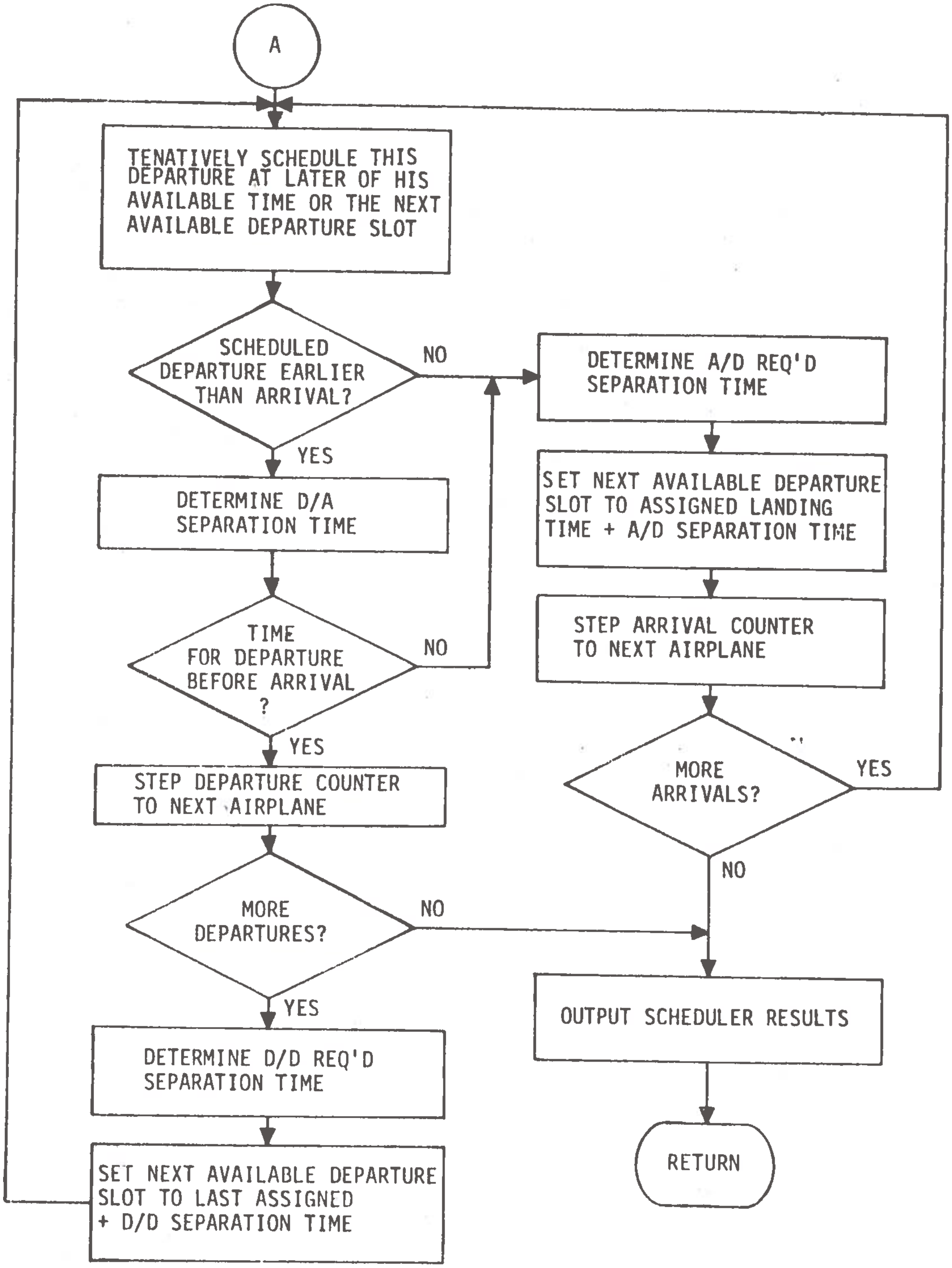
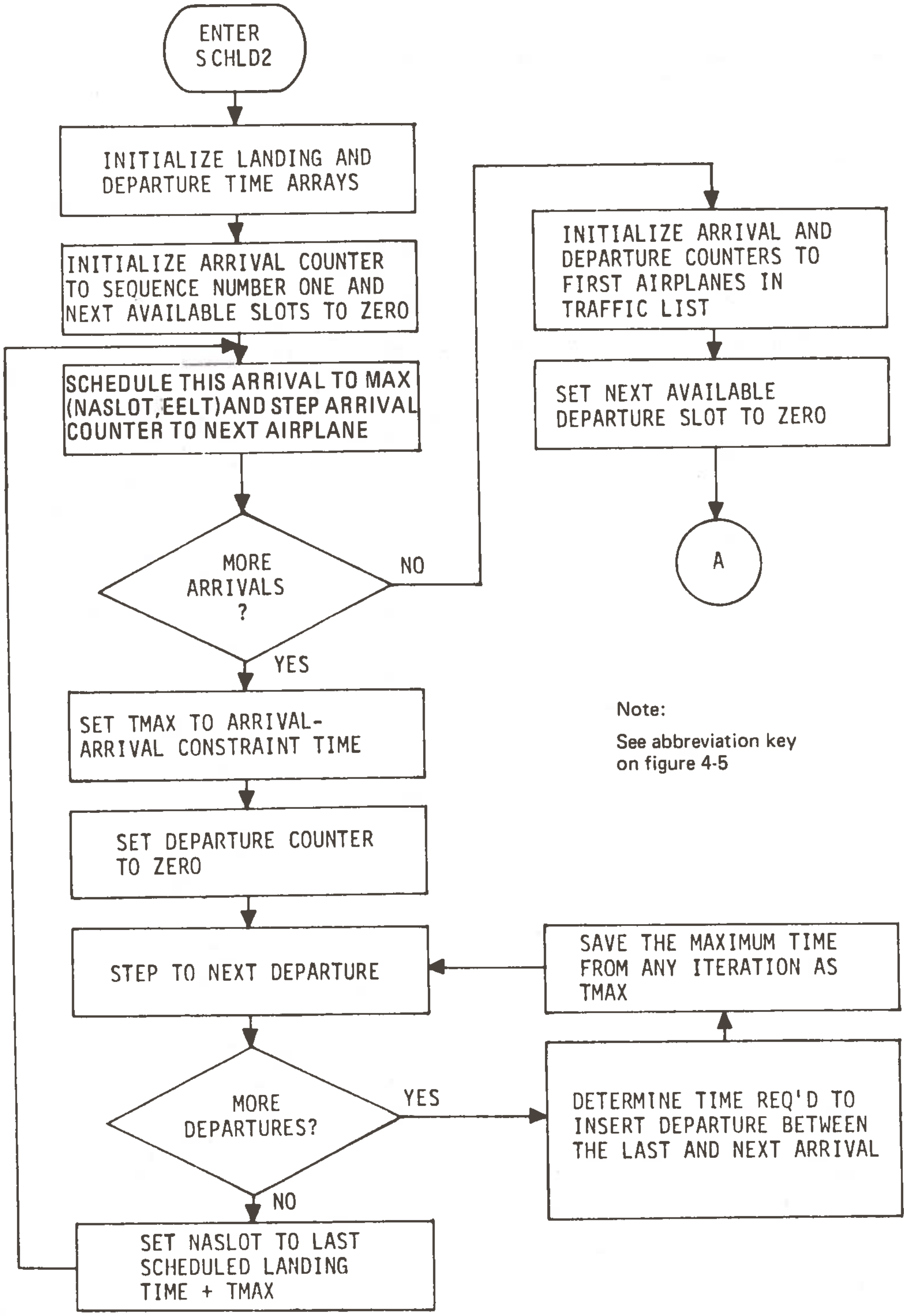


FIGURE 4-5.—CONCLUDED



Note:

See abbreviation key on figure 4-5

FIGURE 4-6.—SCHEDULER (VERSION 2) FUNCTIONAL LOGIC

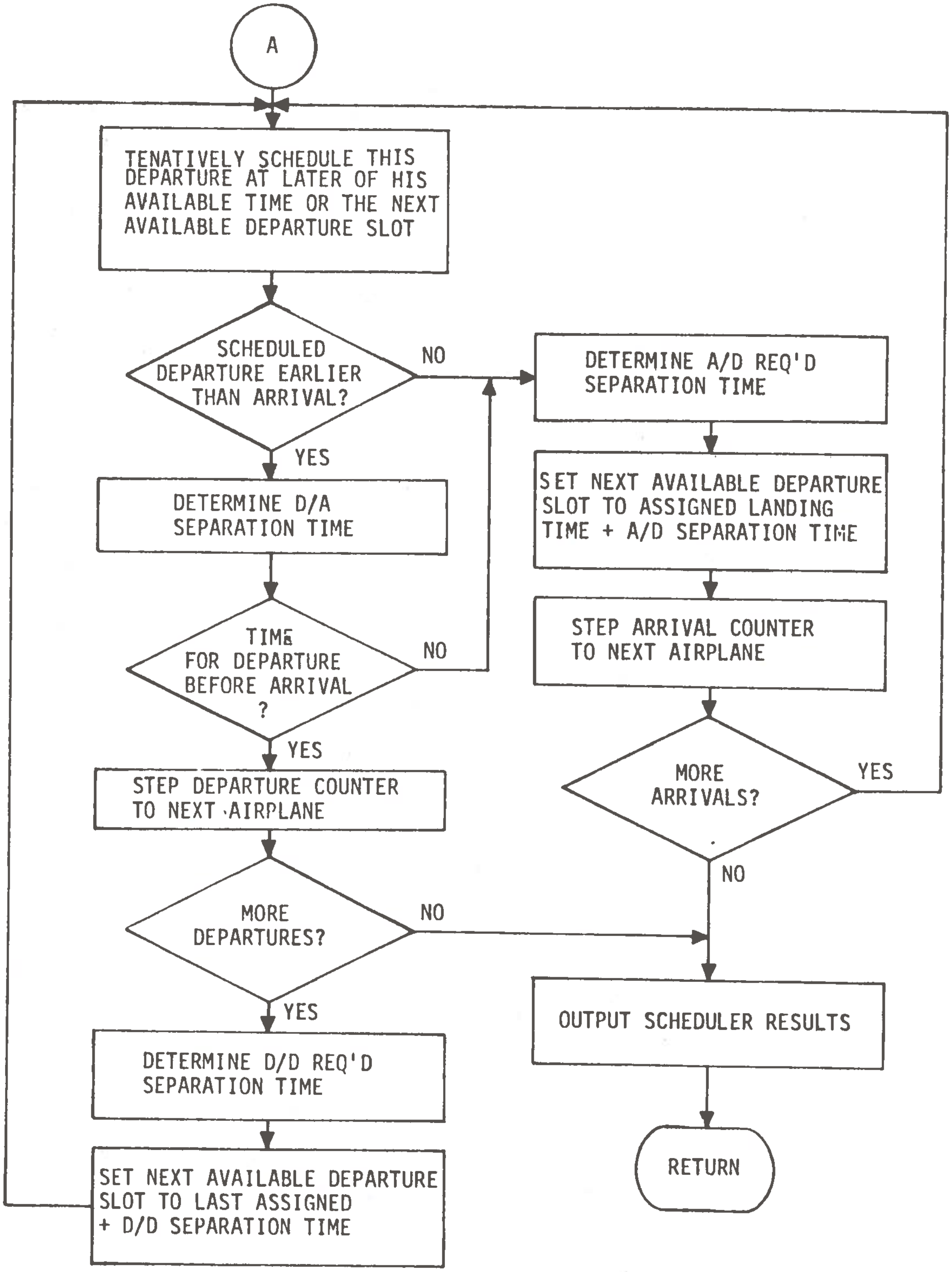
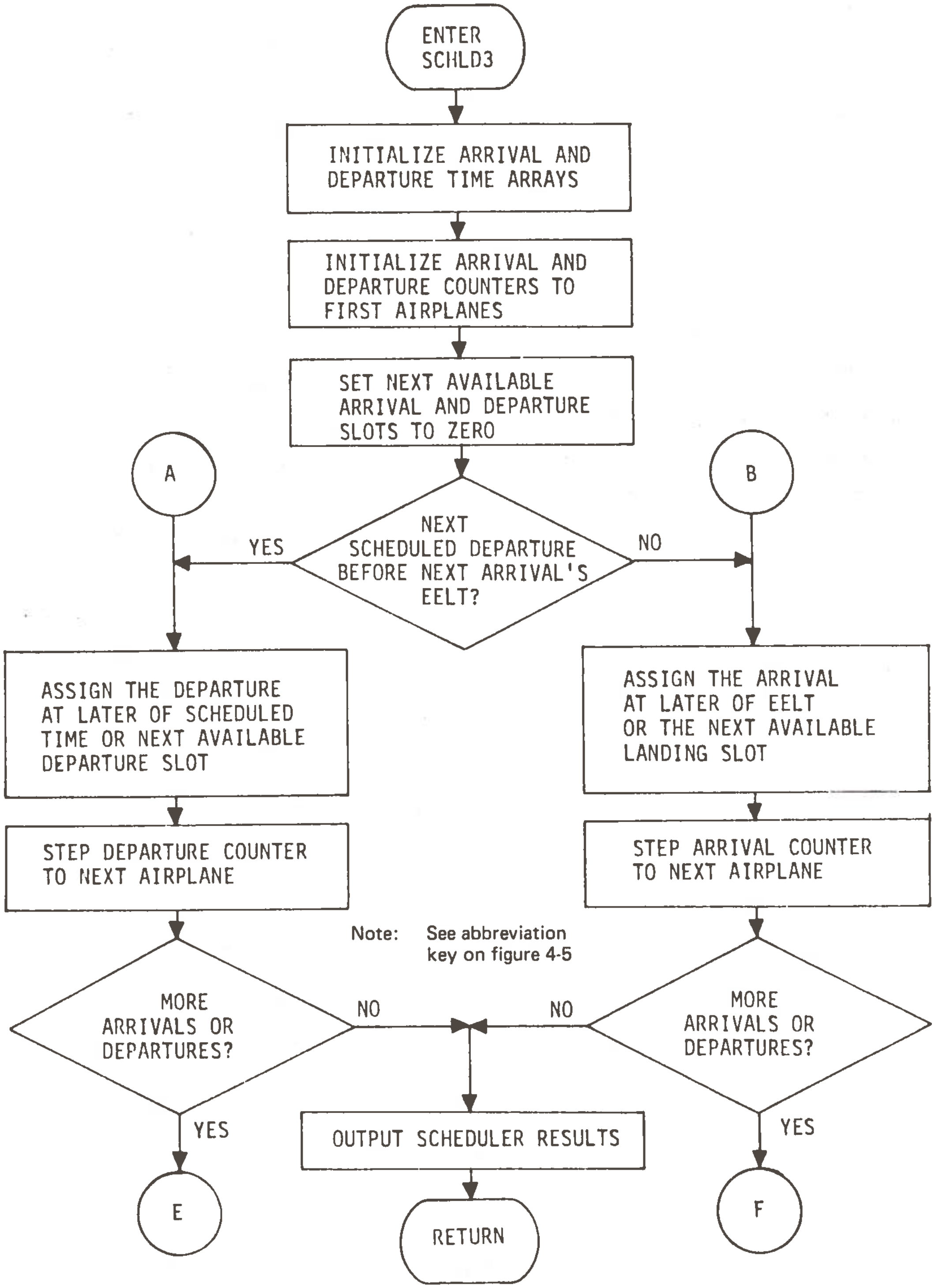


FIGURE 4-6.—CONCLUDED



Note: See abbreviation key on figure 4-5

FIGURE 4-7.—SCHEDULER (VERSION 3) FUNCTIONAL LOGIC

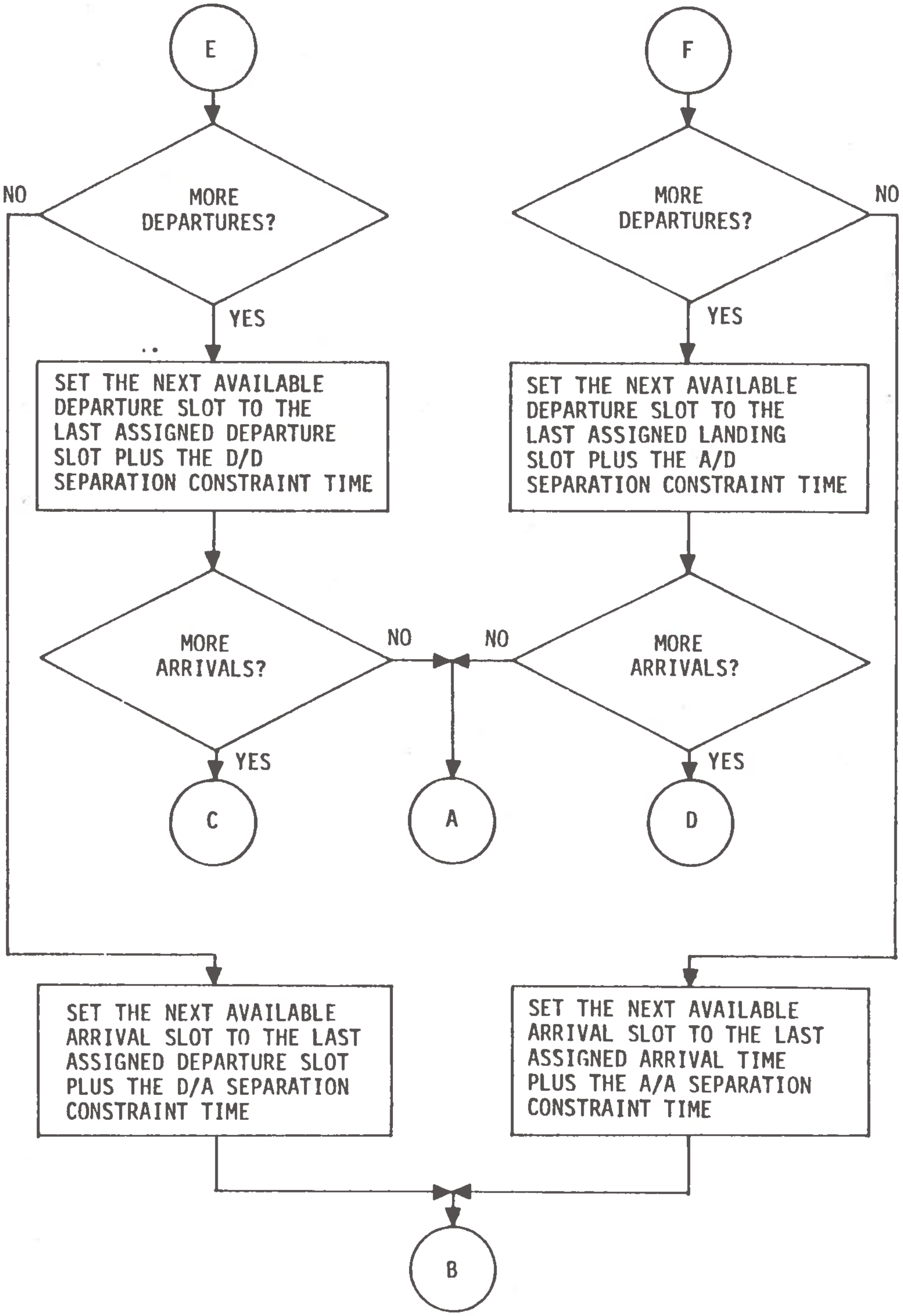


FIGURE 4-7.—CONTINUED

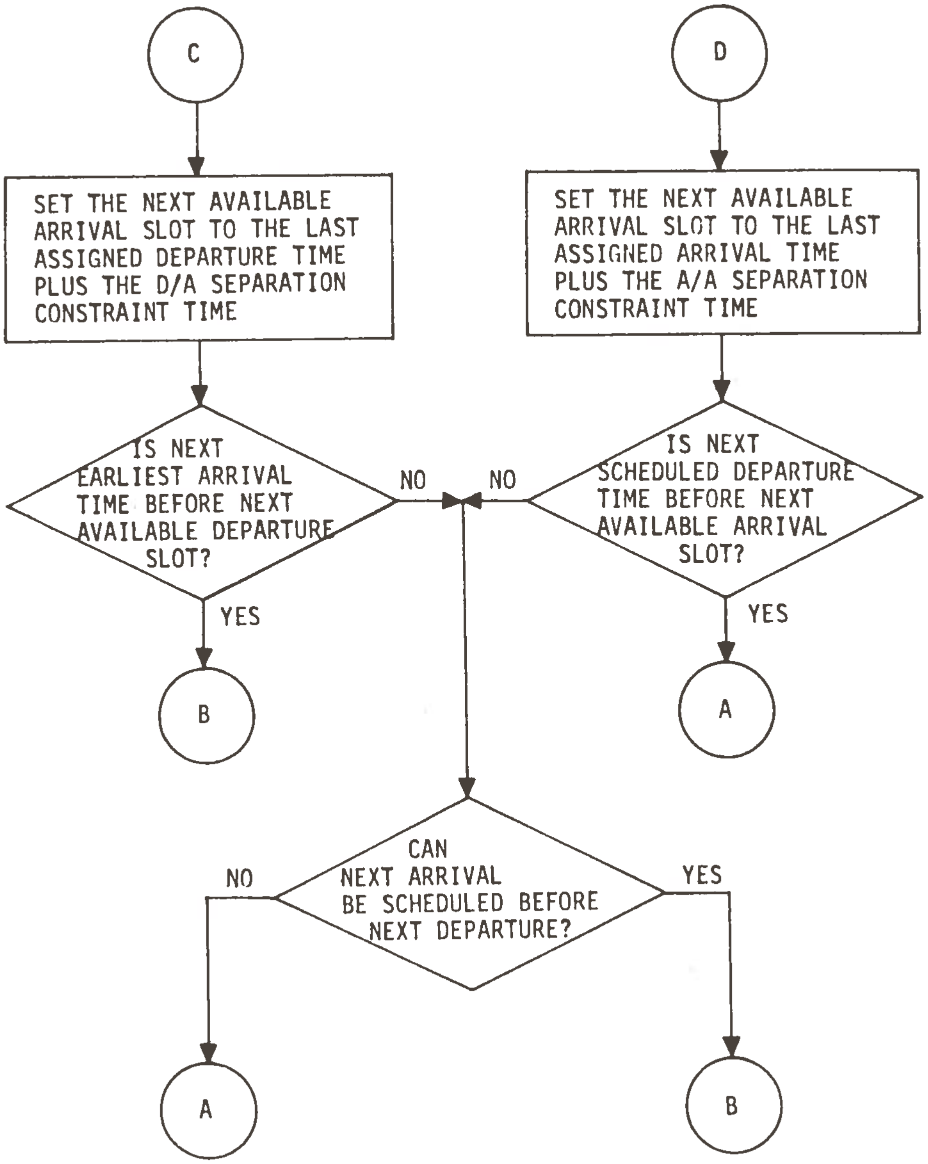


FIGURE 4-7.—CONCLUDED

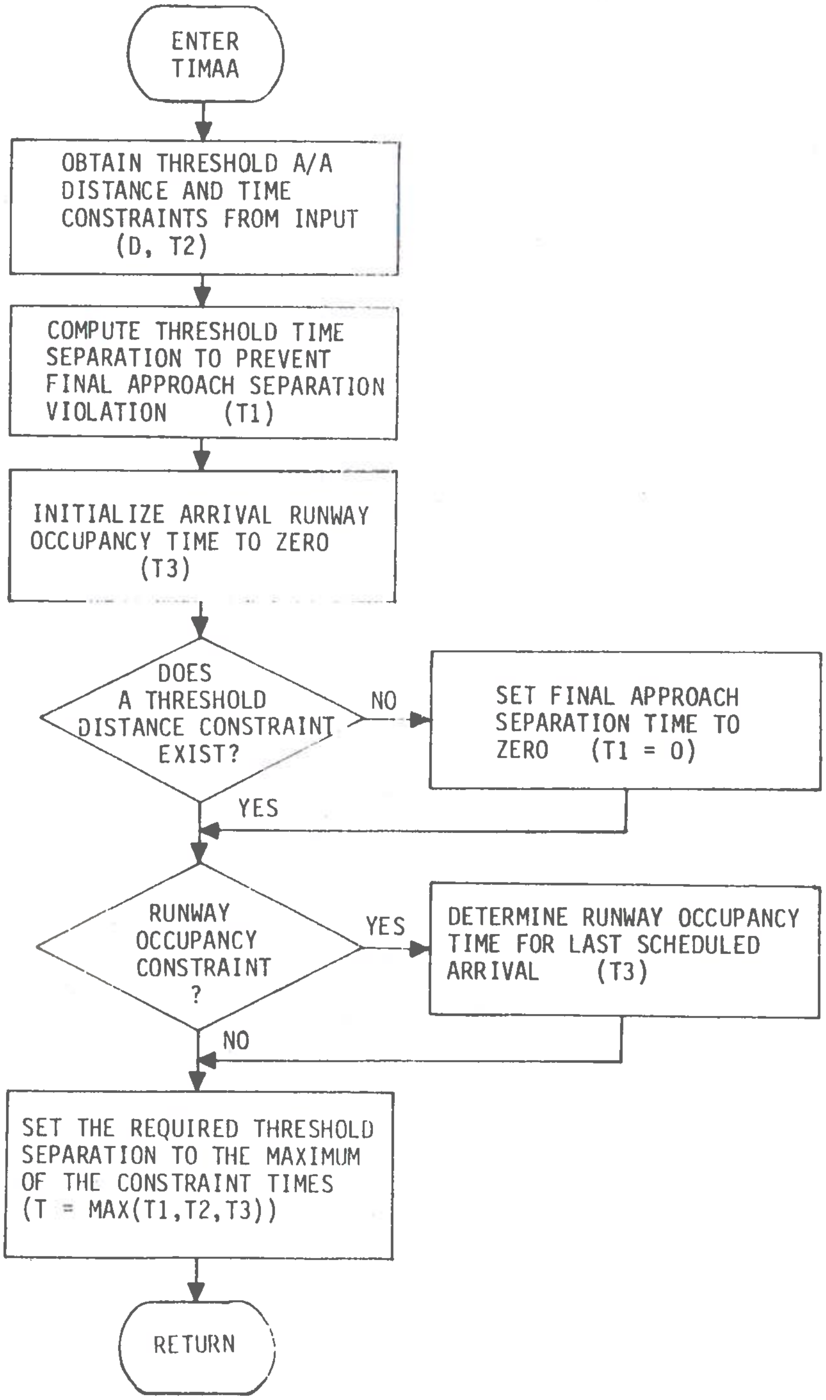


FIGURE 4-8.—ARRIVAL-ARRIVAL SEPARATION TIME CONSTRAINT DETERMINATION

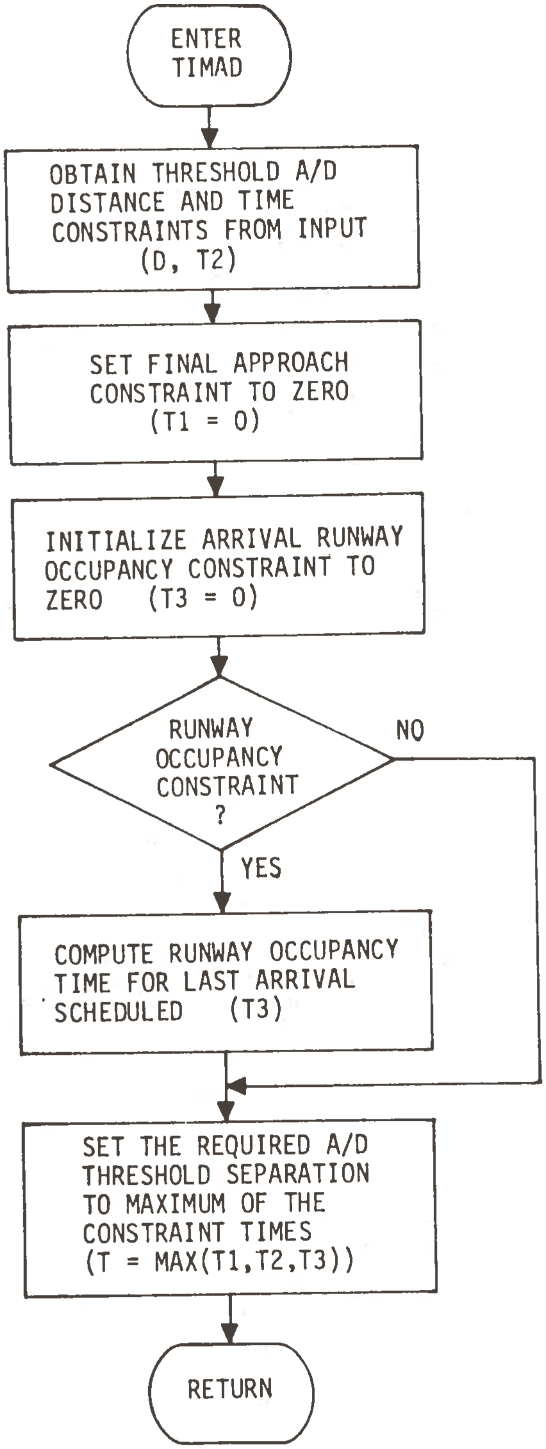


FIGURE 4-9.—ARRIVAL-DEPARTURE SEPARATION TIME CONSTRAINT DETERMINATION

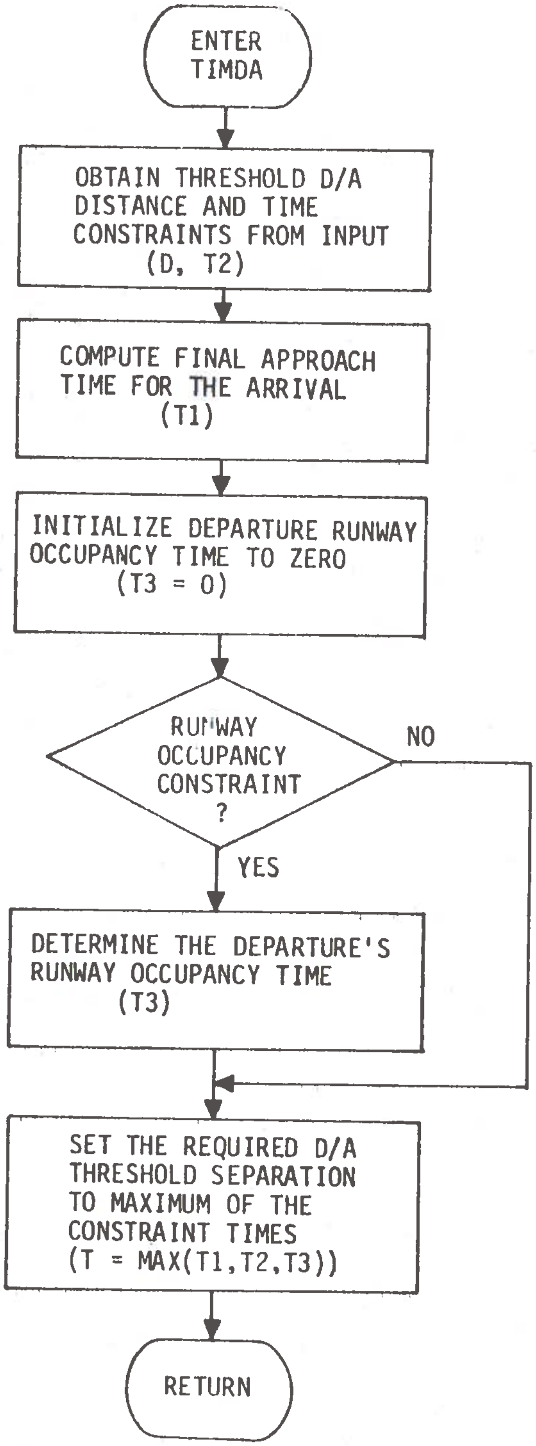


FIGURE 4-10.—DEPARTURE-ARRIVAL SEPARATION TIME CONSTRAINT DETERMINATION

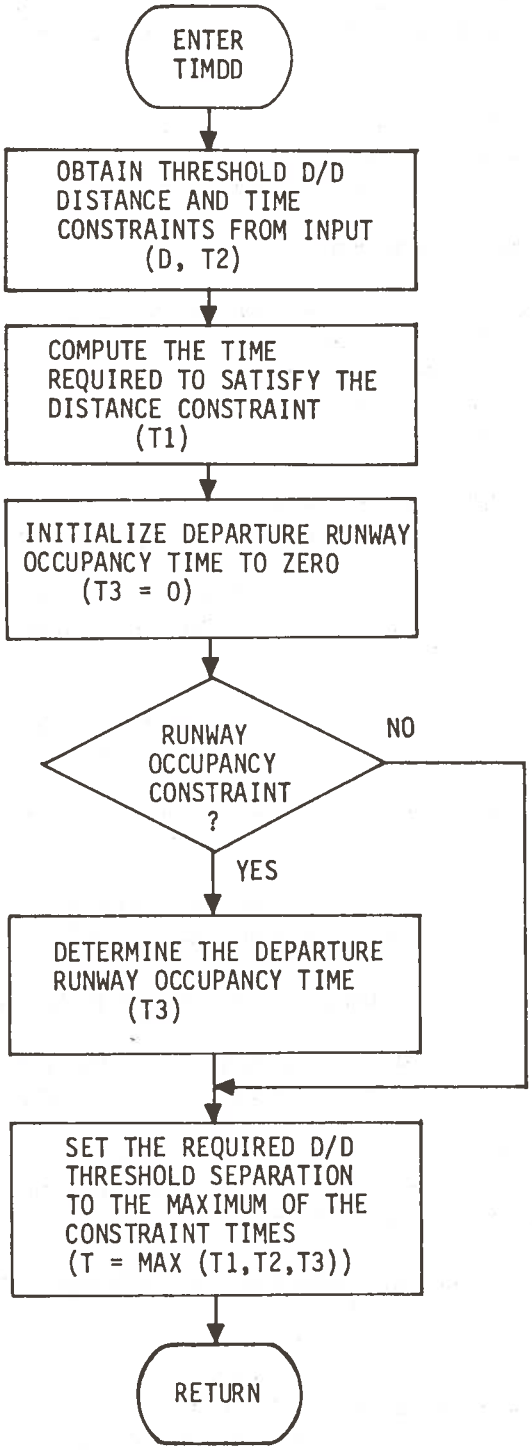


FIGURE 4-11.—DEPARTURE-DEPARTURE SEPARATION TIME CONSTRAINT DETERMINATION

speed/path profiles from the IAF to the outer marker, separation exists in the entire near-terminal area.

As the scheduled landing time is within the scheduling window, the final task is then to generate a conflict-free RTP from the entry fix to the IAF. This RTP must make good the IAF time projected from the scheduled landing time.

4.1.5 RTP Generation Considerations

The route-time profile (RTP) generation function determines the waypoints and times through which the airplane must sequence in order to achieve the scheduled landing time. In addition, this function must ensure that the RTP ensures adequate separation (i.e., is conflict free) during execution. Figure 4-12 shows the logical flow at the macrolevel for the RTP generation function.

In generating the RTP, the wind, temperature, aeroperformance limits, and geometry must be considered simultaneously. The process involves the following steps:

1) Determine the time required for the airplane to transition from the outer marker to the threshold by consideration of the outer marker speed and distance and the planned approach speed.

2) Determine the IAF to outer marker time by consideration of the path geometry, the common speed profile, and the environmental conditions.

3) Establish a target IAF time by subtracting the above times from the scheduled landing time.

4) Determine a target time to transition from the outer terminal area (i.e., entry fix to IAF) by differencing the estimated entry fix time and the target IAF time.

5) Choose a velocity schedule consistent with the airplane performance window.

6) Make a trial letdown to determine the outer terminal area transition time, considering geometry, wind, temperature, and aeroperformance limits.

7) Compare the target and trial IAF times. If they are not equal, adjust the velocity profile and iterate (on steps 5, 6, and 7) until the times agree. When agreement is reached, an RTP has been generated.

8) Test the RTP from step 7 against the airplane ahead on the trial path for conflicts.

9) If a conflict exists, step to another parallel path and return to step 5. If no conflict exists, the RTP generated in step 7 is completed by adding the near-terminal area common path waypoints and times and is assigned to the airplane.

Specific detail for accomplishing this function is included in volumes III and IV. Some general comments on the technique are provided below.

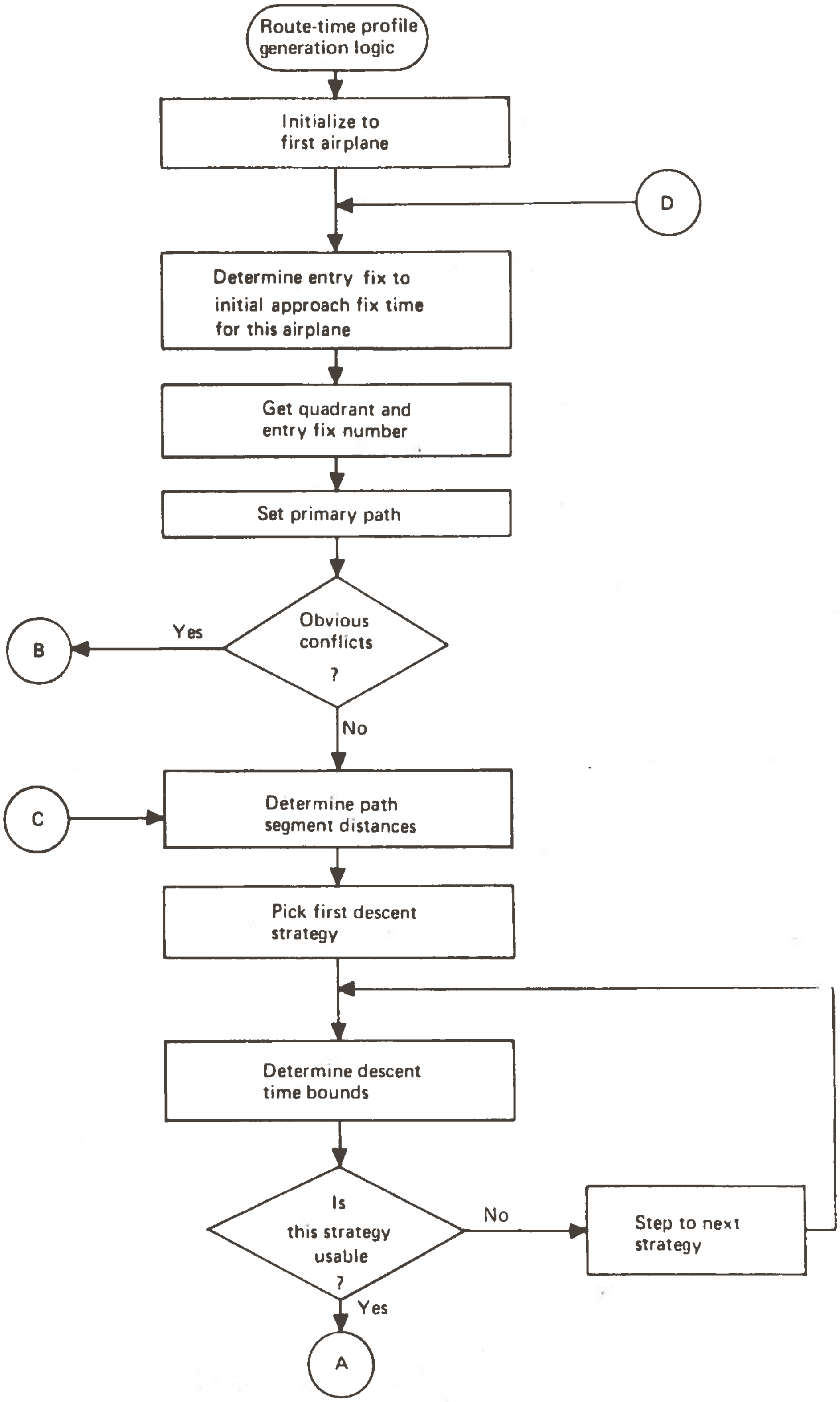


FIGURE 4-12.—ROUTE-TIME PROFILE GENERATION LOGIC

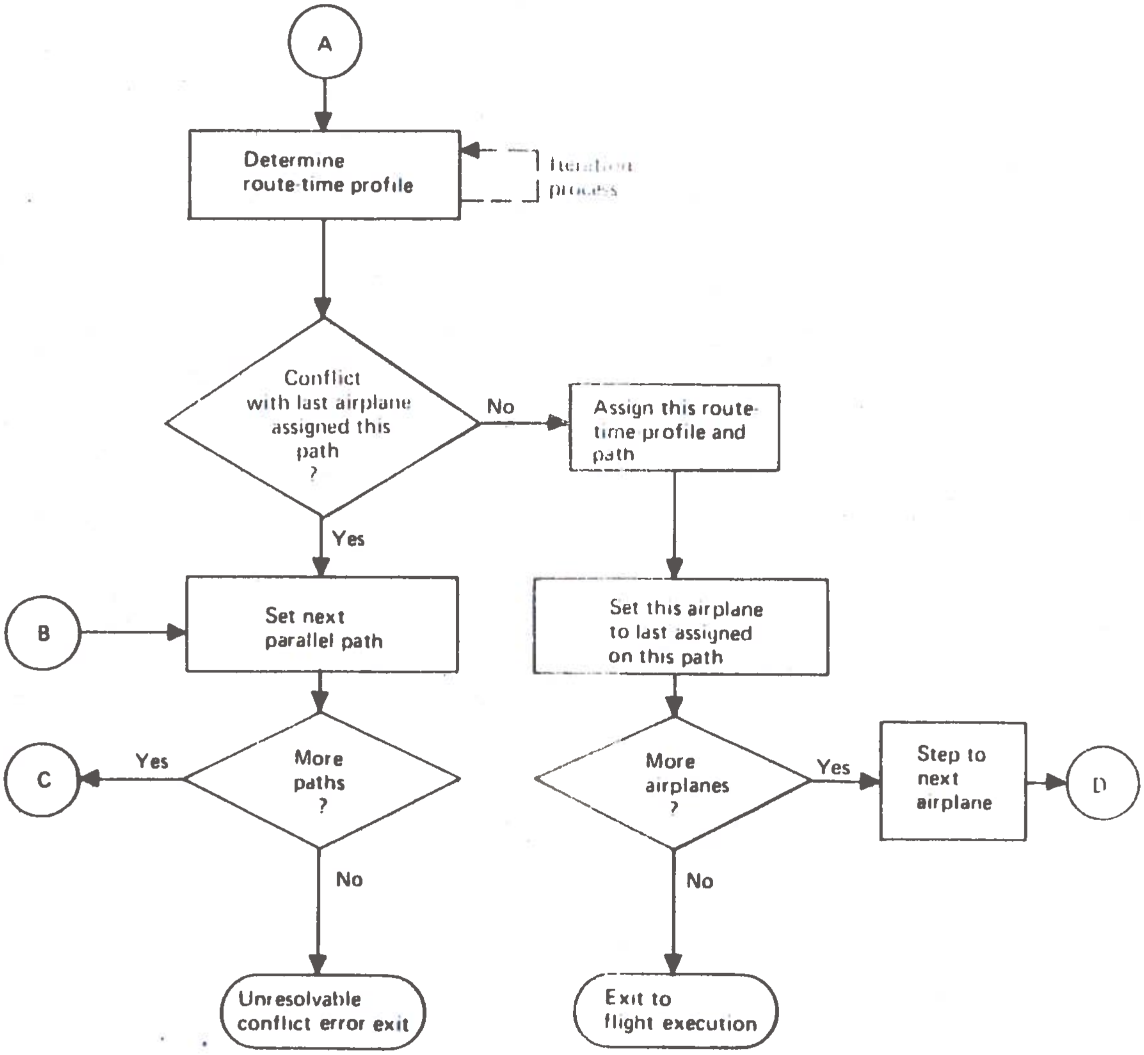


FIGURE 4-12.–CONCLUDED

Figure 4-13 shows the macrologic for the conflict detection strategy. Basically, this process overlays the RTPs for two successive airplanes on a path and does a point-by-point comparison to ensure that separations are not violated. Figure 4-14 shows the process graphically and steps required.

The process for determining RTP generation strategies is shown in figure 4-15. This figure indicates the relationships between the aeroperformance boundaries and the letdown trial velocity profiles.

Figure 4-16 shows the overall relationships between the input traffic demand, the sequencing function, the scheduling function, the RTP generation function, and the evaluation model flight execution routine.

Table 4-1 shows the form of data generated for a single route-time profile.

TABLE 4-1.—TYPICAL ROUTE-TIME PROFILE OUTPUT FORMAT

Index number	Altitude (feet)	Distance from entry fix (nautical miles)	Ground speed (knots)	Clock time (seconds)	Control point indicator
1	32,681	0	455	18	1 (entry fix)
2	32,681	39	423	340	0
3	27,340	61	427	521	0
4	22,000	82	432	700	0
5	16,000	106	392	910	0
6	10,000	130	356	1141	0
7	10,000	140	287	1253	2 (initial approach fix)
8	10,000	145	273	1325	3 (turn fix)
9	4,800	161	238	1541	4 (merge fix)
10	2,400	169	185	1685	5 (final approach fix)
11	1,500	172	179	1757	6 (outer marker)
12	0	177	131	1877	7 (threshold)

4.2 RUNWAY REVERSAL CONSIDERATIONS

The problem of runway reversal was considered only qualitatively in this study. The following discusses possible mechanizations and impact on the algorithm.

The principal difficulty in accomplishing a runway reversal is that all airplanes that already have an RTP assignment must obtain a resequence, reschedule, and RTP modification. This reallocation of resources need not be done simultaneously, but rather each airplane in turn must receive a new RTP prior to reaching some critical point in the system.

As the IAF geometry is roughly symmetrical about the runway, this point would make a likely candidate for the system changeover point. In addition, all airplanes fly a common

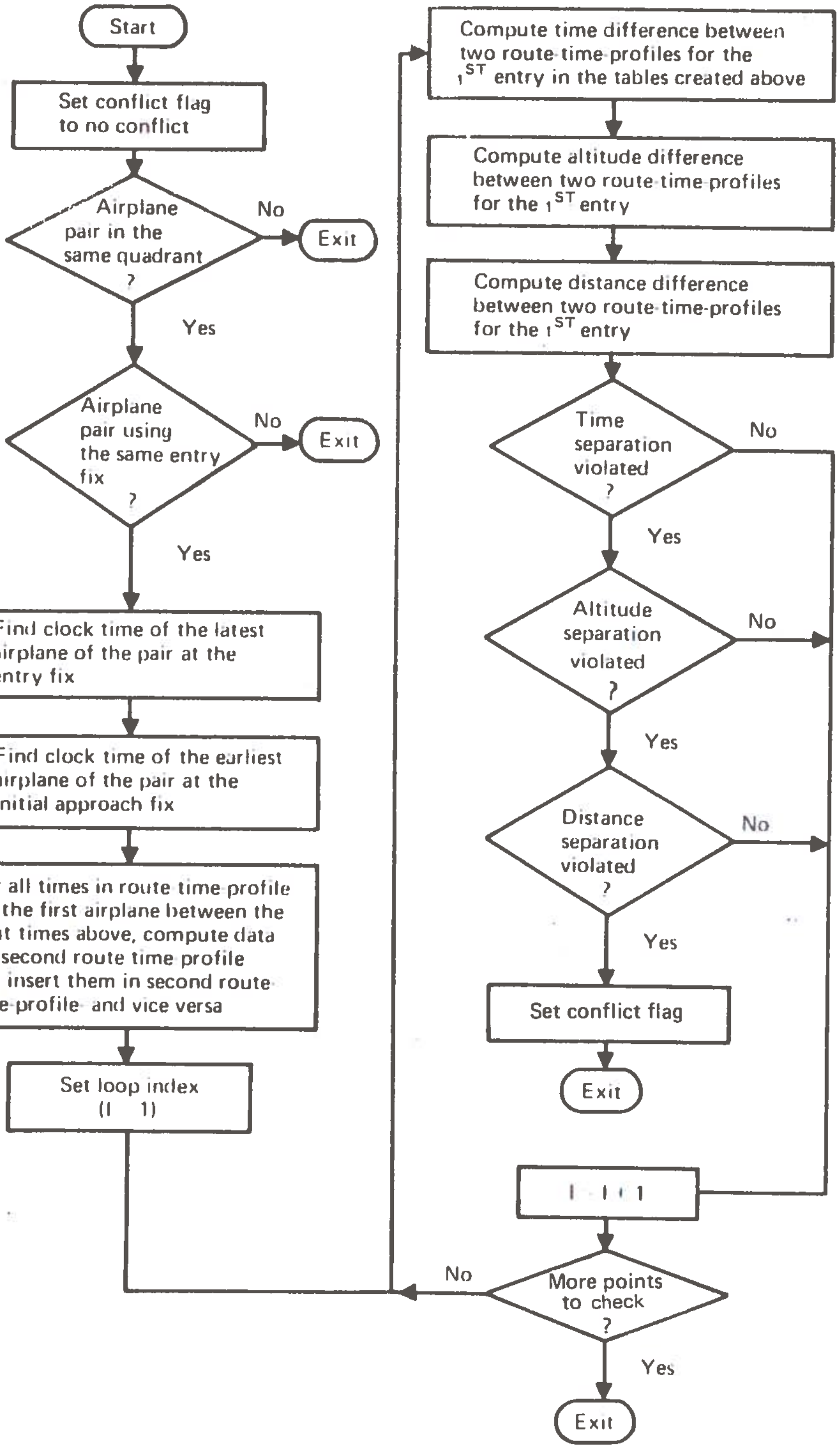
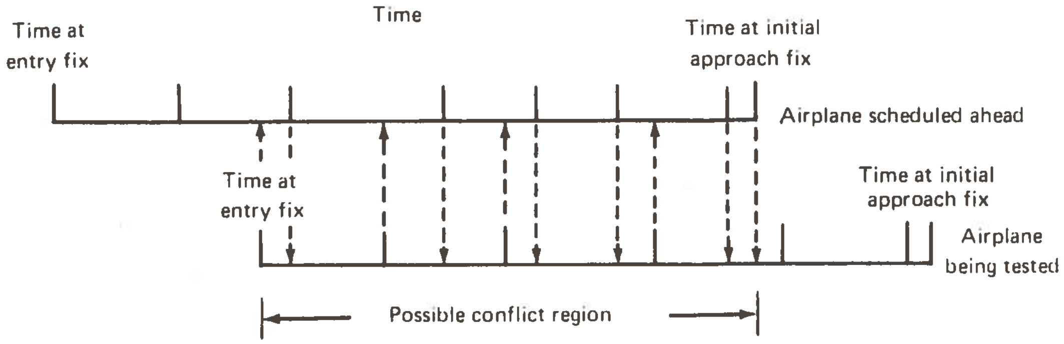


FIGURE 4-13.—CONFLICT DETERMINATION FLOW CHART

① Merge airplane waypoint times in both lists.



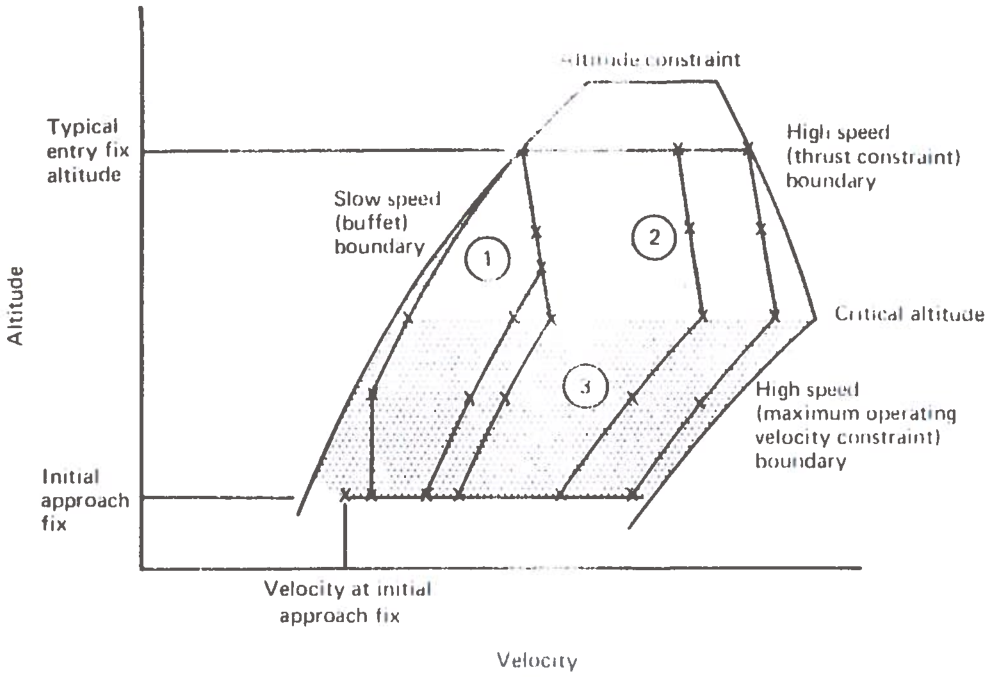
② Compute distance, velocity and altitude for added points in each list.

③ Determine if distance, time or altitude constraints violated at any point in the list pertaining to the airplane being added.

④ If constraints are violated, a conflict exists and a new trial path must be selected for the airplane being tested.

⑤ If contraints are not violated, the tested route-time profile is assigned to the airplane.

FIGURE 4-14.—CONFLICT DETERMINATION PROCESS



① Mach/calibrated airspeed* letdown via low speed aero boundary and computed altitude breakpoint

② Mach/calibrated airspeed* letdown via critical transition altitude

③ Calibrated airspeed* letdown for airplanes arriving below critical altitude

*The route time profile is generated in terms of groundspeeds which are piecewise linear approximations to constant Mach and/or calibrated airspeeds and reflect appropriate wind and temperature corrections.

FIGURE 4-15.—ROUTE-TIME PROFILE GENERATION STRATEGIES

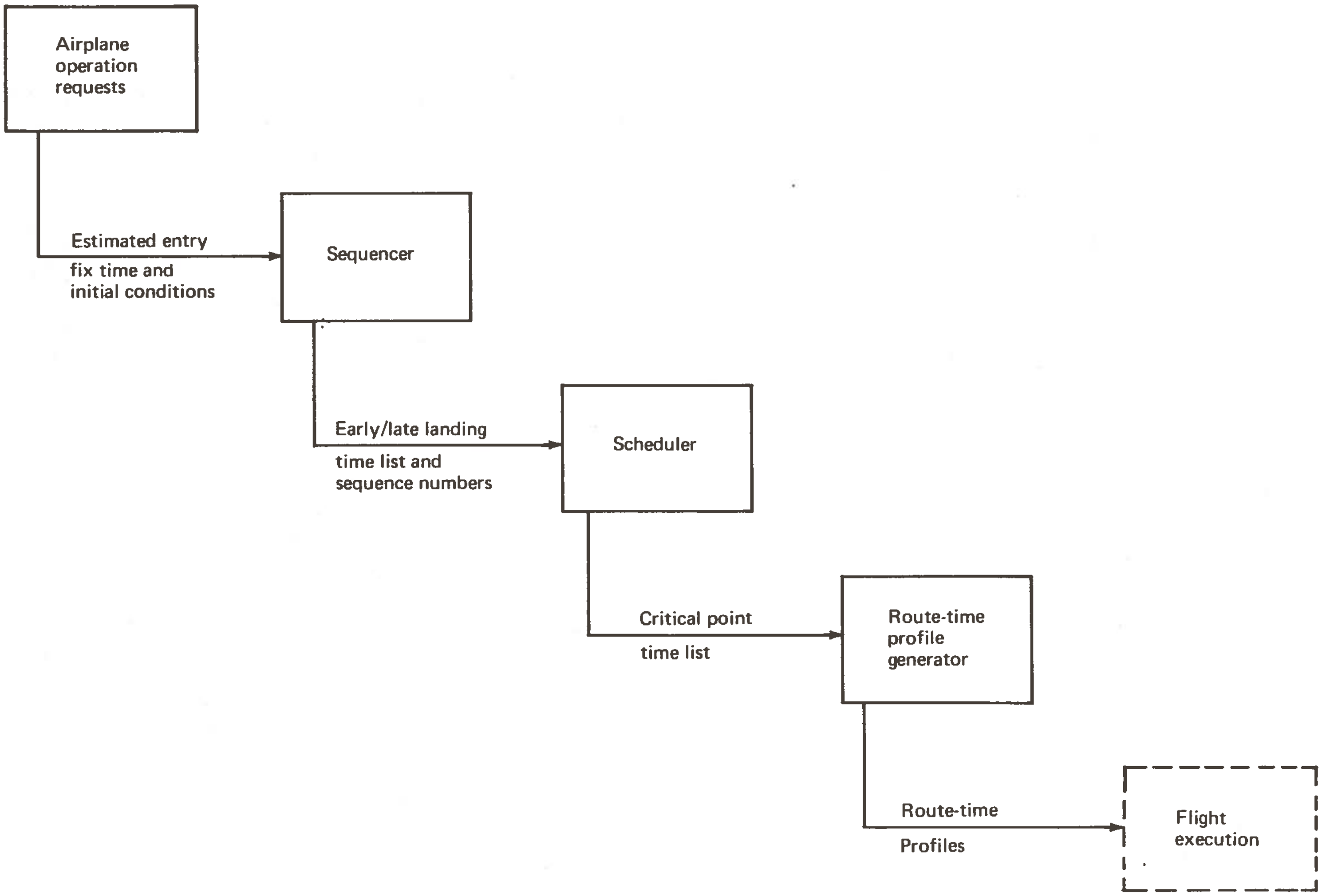


FIGURE 4-16.—SIMPLIFIED ALGORITHM STRUCTURE

speed profile inside this point, and hence the computer burden required for a dynamic reallocation is much easier. The stream arriving at the IAFs on their original schedule would be broken and all successive arrivals would be diverted to the new near-terminal geometry, which terminates on the reversed thresholds. In general, the path lengths from a particular IAF would change as a result of a runway reversal. If this is the case, a new runway sequence and schedule list would have to be computed.

As the last airplane assigned to the old runway must have time to clear the runway and must have a clear missed approach path, a buffer time during changeover must be provided. This time might be achieved in several ways. One method would be to reverse on a natural void in the arrival stream. If such a natural time buffer was not available, a general reduction in the common speed profile could be made until a void was available to reestablish the normal profile. Similarly a reversal path assignment that was longer than normal might be employed until a suitable void in traffic would allow a return to the normal path for the new runway direction.

The details of mechanizing a runway reversal strategy appear to be tractable to analysis and the potential computer burden should be relatively insignificant due to the low frequency of occurrence. The communications load is increased due to the retransmission of partial RTPs.

4.3 PARALLEL INDEPENDENT RUNWAY CONSIDERATIONS

The algorithm geometry discussed in section 4.1 is capable of accommodating either single or parallel runways. To preclude interaction between the two streams (and hence scheduling interaction) it is necessary to have a separate IAF structure feeding each runway. This is most easily accomplished by allowing the two feeder fixes that feed one merge fix to handle one runway and the IAFs and merge fixes on the other side to handle the traffic for the opposing runway. It is also possible to channel three IAFs through a single merge point in the case of an unbalanced demand.

From a scheduling and sequencing point of view, each runway needs to have an independent list of traffic but the scheduling and sequencing programs as well as the RTP generation program could be time shared between the two runways.

Since each runway has a unique final approach fix and outer marker, the final approach course intercepts for the two streams can be at different distances from touchdown. In addition, the final approach course glide slope angles can be different. By choice of outer marker and final approach fix position and required altitude, two segment descent profiles can be accommodated.

4.4 PARALLEL DEPENDENT RUNWAY CONSIDERATIONS

The discussion in section 4.3 above is also pertinent to parallel dependent runway operation. The principal difference is that the scheduling of one runway is dependent upon the other runway schedule. This dependence is in the form of additional constraints imposed by the operation rules. The nature of the possible operational scenarios and the constraining parameters are discussed in section 3.2.2.

5.0 EVALUATION MODEL

This section describes the model developed to simulate strategic terminal area operation for developing and evaluating the basic strategic control arrival algorithm. Evaluation model results discussed include algorithm design verification and sensitivities.

The strategic algorithm evaluation model is a digital simulation of an airport terminal area, the strategic control algorithm, and the airplane operating under the strategic control authority. The model is written in Fortran IV and is operational on the CDC 6600 computer.

During the strategic algorithm development program the model has been applied to the study objectives of:

- Testing the algorithm and iterating its design
- Developing requirements for strategic control
- Determining sensitivities of the concept
- Evaluating system performance

To expedite these objectives an experiment plan has been formulated and performed. Data generated indicate the strategic concept is viable as an operational tool for use in an advanced ATC system.

The following discussion consists of a description of the evaluation model (sec. 5.1), the experiments performed using the model (sec. 5.2), and the supporting analyses and data required (secs. 5.3 and 5.4).

5.1 EVALUATION MODEL DESCRIPTION

The following description of the strategic control evaluation model is a summary of the basic functional elements of the model. A detailed description of the evaluation model is provided in volume IV, the strategic algorithm evaluation model computer program document.

Figure 5-1 indicates the basic information flow components of the model. Input data include traffic characteristics, a wind and a temperature model, geometry/configuration data, an aeroperformance data bank, ATC rules, and avionics performance. Model outputs include summary data, statistical data, and detailed histories. The model logic flow is divided into five primary functions: data input, algorithm preprocessing, algorithm representation, flight simulation, and data reduction and output.

Figure 5-2 shows the strategic algorithm evaluation model macroflow. The vertical column represents the main calling sequence with other primary subroutine calls shown to

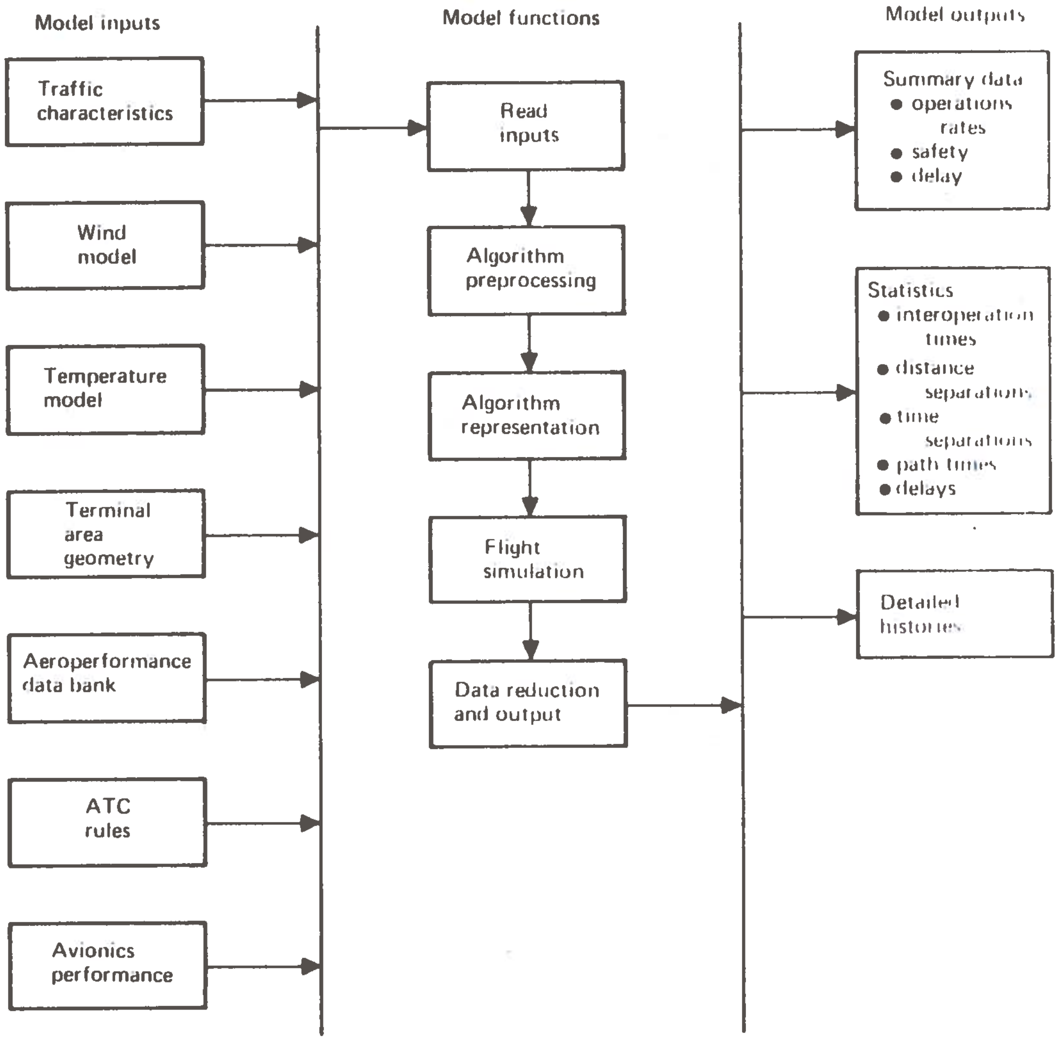
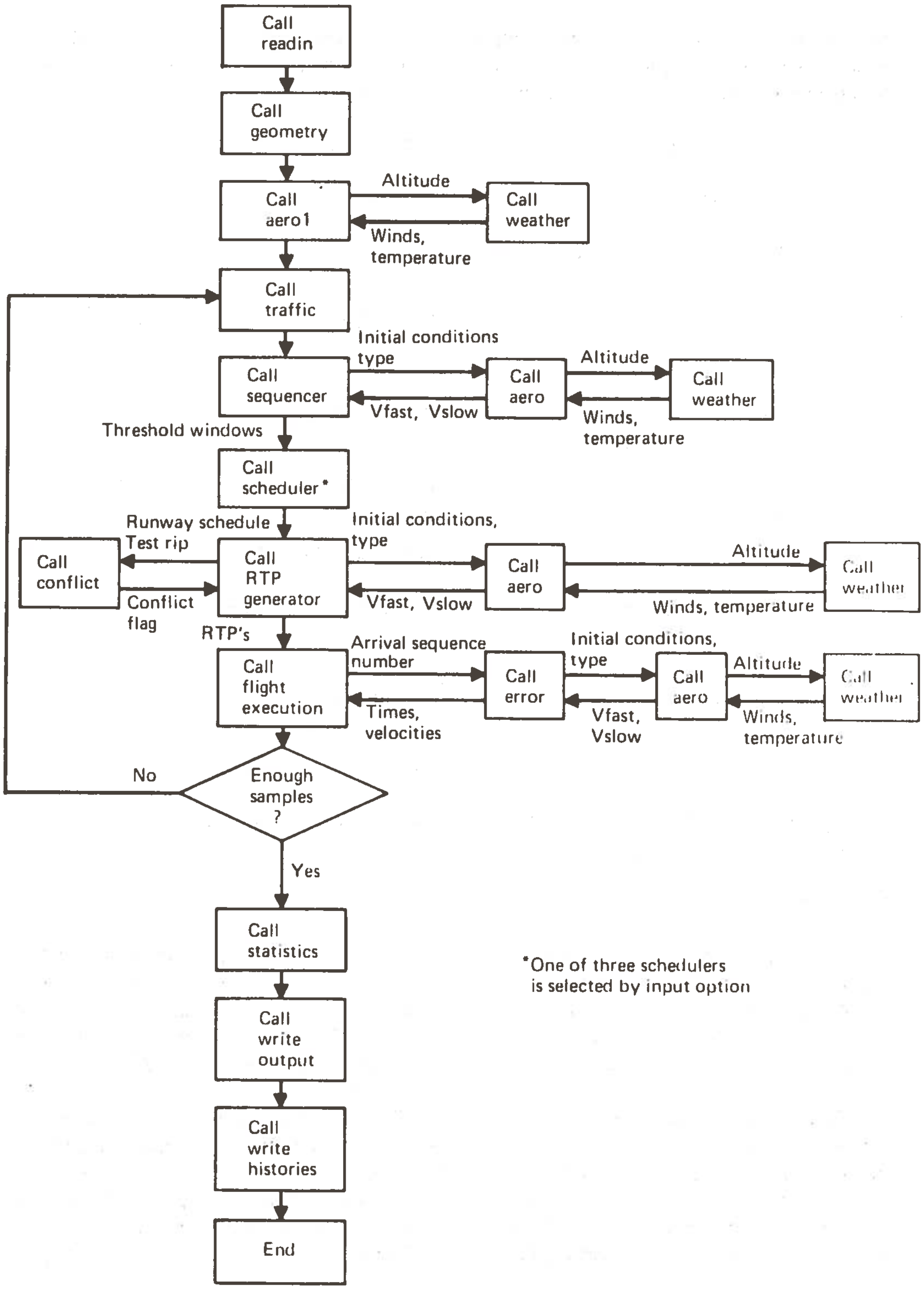


FIGURE 5-1.—STRATEGIC ALGORITHM EVALUATION MODEL INFORMATION STRUCTURE



*One of three schedulers is selected by input option

FIGURE 5-2.—STRATEGIC ALGORITHM EVALUATION MODEL MACRO FLOW the left or right. A data sampling loop to generate operational statistics is indicated. The subroutines shown represent the basic subroutine elements of the model and may be grouped under the five primary functions discussed above as:

Functions	Subroutines
1) Data input	READIN
2) Algorithm preprocessing	GEOMETRY AERO1 WEATHER TRAFFIC
3) Strategic algorithm	SEQUENCER AERO SCHEDULERS RTP GENERATOR CONFLICT CHECK
4) Flight simulation	FLIGHT EXECUTION ERROR
5) Data reduction and output	STATISTICS WRITE OUTPUT WRITE HISTORIES

The following five sections (5.1.1-5.1.5) discuss each of these functions as performed by the model.

5.1.1 Data Input

The initialization of the evaluation model occurs when the subroutine READIN is called. This subroutine reads the input data, stores the data in the appropriate common blocks, and writes the input report. Seven input categories are defined. They involve specifying the traffic, weather, terminal area configuration, aeroperformance limits of the airplane fleet, ATC rules, avionics performance data, and output write controls.

The traffic data contain a switch to control the discrete/distribution traffic option. When the discrete option is being used, a list of arrivals and departures is input. In addition, statistical perturbation data (errors in entry fix times, velocities, etc.) may be input. If the distribution option is selected, a random number generator creates the input traffic based on input distribution characteristics. Current model options allow for the selection of uniform, normal, or Erlang-distributed times, weights, and velocities.

The weather input consists of wind and temperature profiles. The wind profile is comprised of north and east components. These profiles are input as a function of altitude. Wind and temperature forecast errors are also input.

Terminal area configuration data consist of specifying a terminal area approach path structure. These paths together with the runways and control fixes are located in a three-dimensional reference frame for use by the algorithm. The Los Angeles International Airport terminal area path structure for a strategic control system was input to the model.

The aeroperformance data involve specifying the velocity bounds of various airplane types as a function of approach weight and altitude. Additional data such as maximum cabin pressure differential are also input by airplane type.

ATC options involve the specification of scheduling priorities and constraints at the runway (runway occupancy, time, or distance-separation criteria) and conflict criteria for use in generating route-time-profiles by the strategic algorithm. Avionics performance data input specifies the navigation and control system error distributions associated with the airplanes flying the route-time profiles. These data are used in the flight simulation to measure the system safety and efficiency in expediting the strategic algorithm instructions.

The statistic control inputs set up the critical time and distance separation criteria to measure conflict levels and the critical delay times. The statistics controls also set up the probability table entry values for which the operational statistics are output. In this way the user can select the range of values (initial values, step size, and number of steps) in the output tables.

Data sets used in running the strategic control evaluation model are discussed in section 5.4.

5.1.2 Preprocessing for Algorithm

The algorithm preprocessing in the evaluation model consists of the initial data processing to set up the geometry, wind, temperature, and traffic information required by the algorithm. In addition, the traffic independent portions of the geometry/schedule are determined. Four major subroutines are required: GEOMETRY, AERO1, WEATHER, and TRAFFIC. The first two subroutines are executed once per data set. The WEATHER subroutine is called from several places in the program. The TRAFFIC subroutine is called once per data sample to generate traffic lists.

The GEOMETRY subroutine requires x, y, z coordinates of the control points, radii of turn circles, and parallel offset (lateral) distances. The control points are assumed as exits of turn circles. The subroutine then computes turn circle centers and entrance points and calculates path distances and headings (for straight segments) for use in scheduling, sequencing, and the generation of RTPs.

The subroutine AERO1 determines velocities and time durations for airplanes flying in the strategic control system from the initial approach fix (IAF) to the outer marker. These nominal times and velocities are assigned within the performance bounds of all airplanes in the traffic set. Path segment distances and angles are input from GEOMETRY. Calibrated airspeed at control fixes from the initial approach fix to the threshold are input data. Based on forecast winds and temperature, the calibrated airspeeds are converted to groundspeeds and path time durations calculated. These data provide the initial approach fix to runway times for use in constructing route-time profiles (RTPs).

The WEATHER subroutine is called from AERO1, AERO, SEQUENCER, RTP, and ERROR subroutines. It is called at a specific altitude and returns wind, temperature, density, and pressure ratio data. A switch may be set so that the weather data returned are forecast or actual. The strategic algorithm subroutines call WEATHER to obtain forecast data while the flight simulation (ERROR) portion of the model calls WEATHER to obtain actual weather data.

The TRAFFIC subroutine is called at the beginning of each data sample. The basic traffic option allows a discrete data set to be input (specifying nominal times, velocities, and weights as well as entry fix and airplane type) or a distribution input to create these parameters. Options available to the user include uniform, normal, and Erlang-distributed random variables (created by a random number generation process). The traffic input set provides the lists of arriving and departing airplanes that must be sequenced, scheduled, and provided with route-time profiles (RTP).

These four preprocessing functions provide data with which the algorithm can carry out its required computations.

5.1.3 Algorithm Representation

The strategic algorithm is represented in the evaluation model by five primary subroutines: SEQUENCER, AERO, SCHEDULER, RTP GENERATOR, and CONFLICT. The primary information flow for these subroutines is shown in figure 5-3. The basic algorithm is located within the data sampling loop of the model. It follows the traffic generation and precedes the flight simulation. The SEQUENCER, SCHEDULER, and RTP GENERATOR are called once per sample. The AERO subroutine is called for each airplane and the CONFLICT subroutine at least once per each RTP generated.

The SEQUENCER determines the earliest and latest runway time for each arrival of the traffic list. It combines the outer marker to threshold time (utilizing VREF data generated in the traffic list) and the initial approach fix to outer marker time (from AERO1 for the particular approach path) and computes a fast and slow speed letdown from the entry fix (at en route altitude) to the initial approach fix. These time considerations generate the threshold window for each arrival. Cabin repressurization constraints are also applied. When all arrival airplanes have been assigned an estimated earliest landing time (EELT) and an estimated latest landing time (ELLT) the arrival list is reordered by EELT. The sequence for scheduling is then based on this computed first threshold capability.

The above determination of fast and slow letdowns is based on data provided for each arrival by the AERO subroutine. For each arriving airplane, AERO is supplied with type and initial conditions (position, velocity, and weight data). AERO then uses the input data stored for each airplane performance type to derive (for the particular airplane weight,

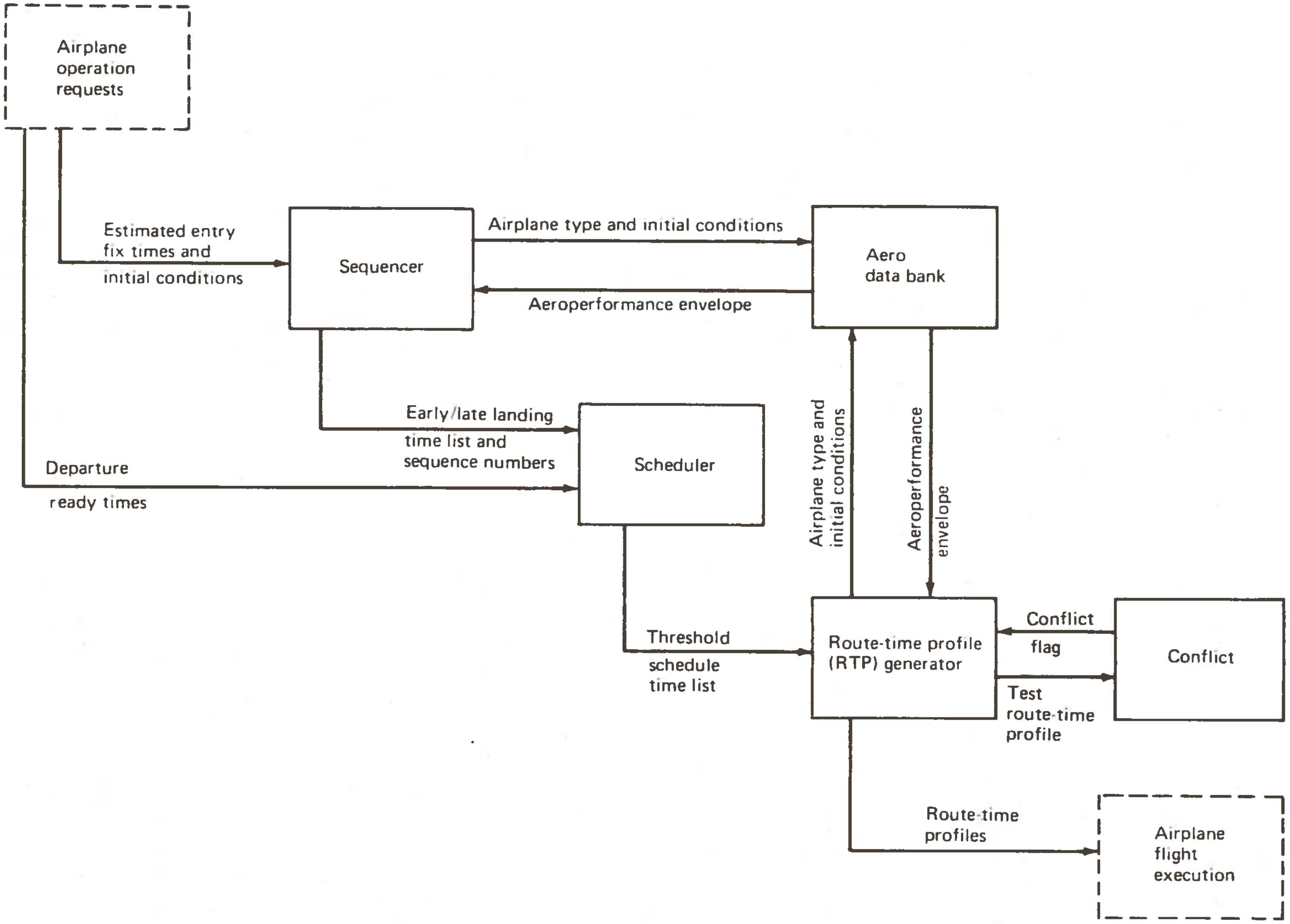


FIGURE 5-3.—STRATEGIC ALGORITHM STRUCTURE

speed, and location) a set of fast and slow speed boundaries as a function of altitude. These speeds are based on a call by AERO to WEATHER to obtain forecast or actual winds and temperatures. The output speeds are groundspeeds. When AERO is called by the algorithm subroutines, the forecast weather data are applied. When AERO is called within the flight simulation, true winds and temperatures are applied (modifying the resultant speed constraints).

The SCHEDULER is called after the SEQUENCER. The SCHEDULER assigns runway times to arrivals (in the sequenced order) and to departures. The SCHEDULER logic allocates runway time based on various safety criteria (distance, time, or runway occupancy criteria may be applied). Three arrival/departure priorities are available in scheduling and selection is controlled by program input.

The RTP GENERATOR utilizes the schedule threshold time, traffic-generated entry-fix time, and fixed path structure from GEOMETRY to create a route-time profile for each arrival airplane. The airplane altitude, distance, speed, and time are determined for various critical locations (designated waypoints) along the fixed-track structure. Waypoint locations that are common to all arrivals are further designated control points. The evaluation model monitors position, velocity, and separation data at control points for outputs.

For each airplane in the arrival traffic list, the RTP GENERATOR "solves" the airplane letdown problem along the fixed geometry and within the AERO constraints in such a way as to arrive at the runway at the scheduled time. An iterative solution technique is used to find the velocity letdown strategy for which the scheduled threshold time is achieved. Typical route-time profile generation strategies that have been implemented include various combinations of Mach and calibrated airspeed letdowns.

Once a route-time profile has been generated, the CONFLICT subroutine is called to ensure that the airplane schedule is free of conflicts with previously scheduled arrivals. The time, altitude, and distance separations of successive airplanes along a particular path are compared. If a conflict is determined, a flag is set and the program returns to RTP. The airplane may be assigned an alternate path (parallel offsets are provided for entry fix to initial approach fix paths). A new route-time profile will be generated for the new path and CONFLICT again called. If all paths should be exhausted with a conflict still present, the program will assign a route-time profile but note the existence of a scheduled conflict.

Once the route-time profiles have been generated, the algorithm function is completed. The model will now simulate the airplanes attempting to execute these control instructions within the strategic control terminal area.

5.1.4 Strategic System Simulation

The strategic system simulation takes the traffic set generated and the route-time profiles from the control algorithm and represents the airplanes moving through the terminal area as they attempt to fly the profiles generated. Two major subroutines represent the flight simulation logic—the FLIGHT EXECUTION and the ERROR subroutines. The FLIGHT EXECUTION routine is called once per sample and collects data for output as airplanes move through the system. The ERROR subroutine is called once for each arrival airplane in each data sample. The ERROR subroutine generates navigation and control errors encountered by the airplanes in attempting to execute the route-time profiles.

The FLIGHT EXECUTION subroutine processes all arrivals and departures in the traffic list. FLIGHT EXECUTION computes runway interoperation times, distance and time separations for successive arrivals through control fixes, path duration times for arrivals, and delays associated with arrivals and departures. The data compiled in this subroutine when processed provide the resultant model output report.

The ERROR subroutine generates the navigation and control errors associated with each arrival airplane and represents the airplane control law as the arrivals attempt to fly the route-time profile. Velocity bounds are modified based on weather forecast errors and attempts to speed up or slow down to achieve the route-time profile are modeled. The error generation process and airplane control process represented in the model are discussed in section 5.3.

5.1.5 Data Reduction and Output

The data reduction and output section consists of the primary subroutines STATISTICS, WRITE OUTPUT, and WRITE HISTORIES. Each of these subroutines is called once per run. The STATISTICS subroutine reduces all the data collected within the FLIGHT EXECUTION subroutine. The WRITE OUTPUT formats and prints the summary and operational statistics. The WRITE HISTORIES subroutine formats and prints the detailed schedule data for selected samples. Up to five samples (detailed histories) can be requested for output. Typical model outputs include probability distributions for interoperation times, time and distance separations, and delays.

5.2 EXPERIMENTS

The evaluation model experiments consist of collections of data sets run in the model to test the algorithm design under various postulated operational conditions. The model measures the strategic system safety and efficiency as the airplanes expedite the control instructions. The specific experiment objectives for the algorithm development program are set forth in section 5.2.1. The experiment plan (discussed in sec. 5.2.2) is the program of data generation formulated to meet the objectives. Results and conclusions of the experiments are detailed in sections 5.2.3 through 5.2.5.

5.2.1 Objectives, Methodology, and Criteria

The objectives of the experiments are:

- To test the algorithm and iterate its design

- To develop requirements for strategic control

- To determine sensitivities of the concept
- To evaluate the system performance

The strategic algorithm is tested for arrivals only at a single runway, mixed arrivals and departures at a single runway, and mixed operations on a dual-lane runway. Requirements for the level of navigation and guidance performance of airplanes in a strategic control environment are determined. The strategic control concept sensitivities to changes in terminal area configuration and schedule are investigated. Finally, an evaluation of the concept at a typical airport is conducted. To achieve these objectives a list of experiments has been defined for evaluation by the model.

The purpose of the experiment plan is to determine the specific uses of the evaluation model in the study. Experiments are defined as one or more data sets that will be run with the strategic algorithm in the evaluation model. A data set is a collection of parameter values required to run the model. These values (a data set) define the terminal area configuration, input traffic characteristics, and ATC procedures and performance to be used in testing the strategic algorithm concept. The resulting system performance is measured in terms of various evaluation criteria to be specified.

Figure 5-4 shows the methodology used to derive the experiment plan. The specific objectives are first determined to achieve the study goal of the iteration and evaluation of the algorithm. A list of 10 experiments is determined. In all, 25 data sets are defined. Next, evaluation criteria are defined. These criteria are measured in terms of model parameters and related to the various experiments.

The criteria by which the experiments are evaluated include: safety, airspace, capacity, delay, and resource utilization. In terms of the evaluation model these criteria are measured for the following list of parameters:

- Conflict frequency
- Number of tracks required
- Throughput (in operations per hour)
- Expected delay
- Runway utilization (time schedule/time available for scheduling)

The experiments are evaluated for one or more of the criteria (in terms of the model output parameters). Table 5-1 shows the criteria/experiment matrix, which represents those criteria applicable to each experiment. A discussion of each of the 10 experiments follows.

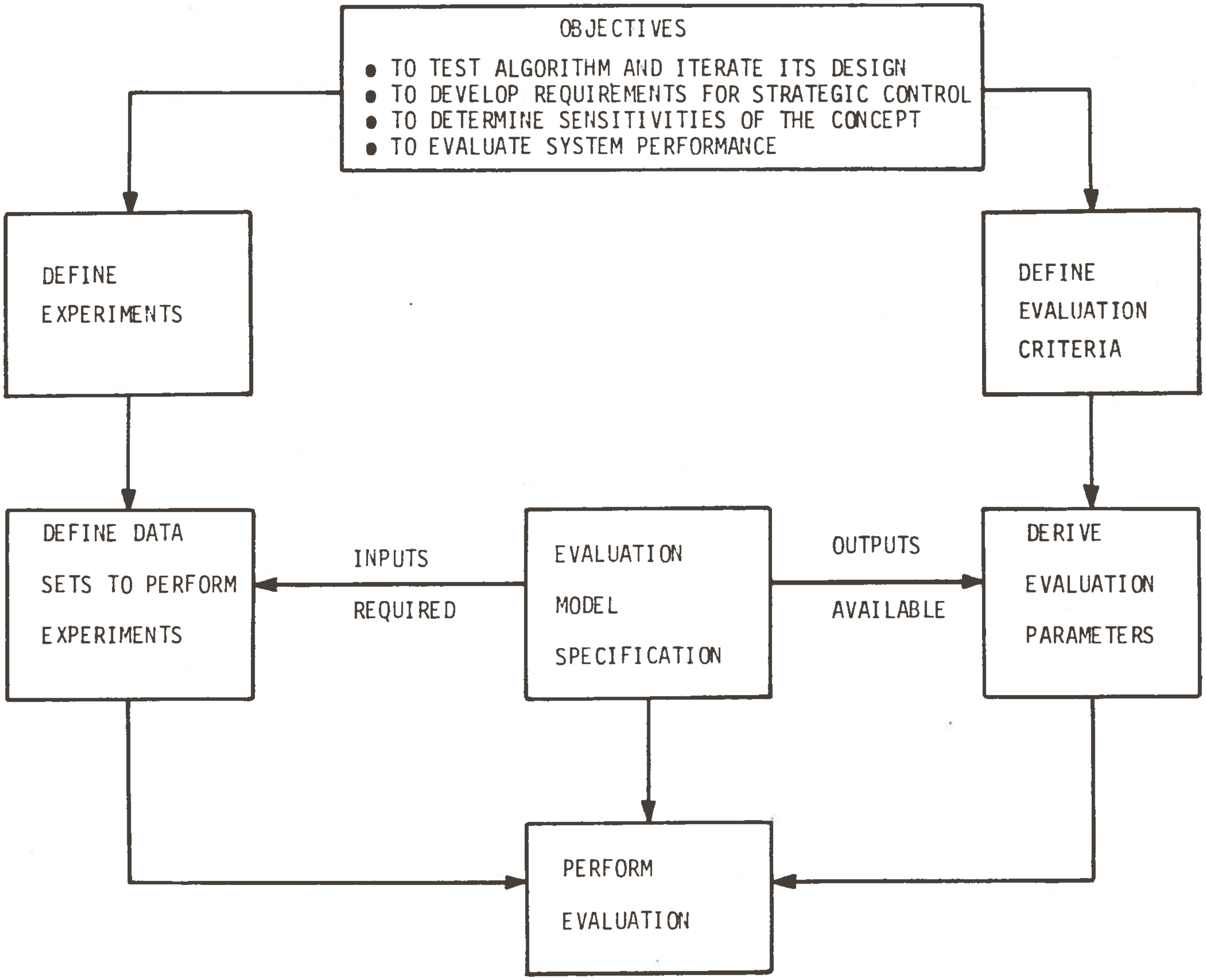


FIGURE 5-4.—EXPERIMENT PLAN DEFINITION INFORMATION FLOW ELEMENTS

TABLE 5-1.—EXPERIMENT/CRITERIA MATRIX

Experiments	Criteria				
	Safety (conflict level)	Airspace (number of tracks)	Capacity (through-put)	Delay (expected delay)	Utilization (runway scheduling)
Debug algorithm — single runway, arrivals only	X	X		X	X
Navigation/guidance accuracy requirements	X				
Schedule-keeping accuracy				X	X
Control radius sensitivity		X		X	X
Throughput sensitivity		X	X	X	
Debug algorithm — single runway, mixed operations	X	X		X	X
Departure scheduling strategy				X	X
Debug algorithm — dual runway, mixed operations	X	X		X	X
Future Los Angeles International operations		X	X	X	
General aviation impact	X		X	X	X

5.2.2 Experiment Plan

Ten experiments have been defined to provide an initial test of the strategic control algorithm. These experiments begin with the simplest operational situation, an arrivals-only traffic stream to be scheduled to a single runway, and proceed to a representation of the complexities of the Los Angeles International Airport terminal area. The 10 experiments that have been defined are:

1) Debug algorithm—single runway, arrivals only

2) Navigation/guidance accuracy requirements

3) Schedule-keeping accuracy

4) Control radius sensitivity

5) Throughput sensitivity

6) Debug algorithm—single runway, mixed operations

7) Departure scheduling strategy

8) Debug algorithm—dual runway, mixed operations

9) Future Los Angeles International Airport operations

10) General aviation impact

The experiments are represented in table 5-2 as a collection of data sets. Each input data set is represented as a vertical line. The model input values to be used for each data set are indicated by the circled positions on the line. Twenty-five data sets (10 experiments) are shown.

The first experiment is to debug the arrivals-only, single runway algorithm. For this experiment two data sets are defined. The first set tests the strategic algorithm at today's operation levels and spacings. It assumes a nominal 3.0-nautical-mile threshold spacing and a 2.0-nautical-mile conflict distance. A corresponding traffic load is assumed with a within-hour-schedule distribution representative of current operations. The second data set represents a future operation level. A 60-second nominal separation and a 40-second conflict interval are used. A corresponding greater traffic demand is input with an analogous within-hour distribution. Other parameter values, common to both data sets, include a 120-second (one sigma) schedule-keeping accuracy, a 175-nautical-mile control radius, and zero navigation and control errors. Conflicts, number of tracks, delay, and runway utilization are the evaluation parameters.

The second experiment uses the verified algorithm from the first experiment and parametrically varies the values of the navigation and guidance error parameters to establish requirements for the strategic control algorithm with both today's traffic level and separation criteria and the future traffic and separation values as used in the first experiment. Five data sets are defined representing:

1) Today's traffic and separations with 0.5-nautical-mile navigation and 10-second guidance errors (all values one sigma).

2) Today's traffic and separations with 0.1-nautical-mile navigation and 5-second guidance errors.

3) Today's traffic and separations with 0.05-nautical-mile navigation and 2-second guidance errors.

4) Future traffic and separations as in the first experiment with 0.1-nautical-mile navigation and 5-second guidance errors.

5) Future traffic and separations with 0.05-nautical-mile navigation and 2-second guidance errors.

The evaluation criterion used to set the navigation/guidance requirements is safety measured in terms of the rate at which conflicts occur in the system.

TABLE 5-2.—EXPERIMENT/DATA SET MATRIX

EXPERIMENTS

ALTERNATIVE PARAMETER VALUES	1. Debug Algorithm		2. Navigation/ Guidance Accuracy Requirements					3. Schedule Keeping Accuracy					4. Control Rad Sensitivity		5. Today's Arrival Throughput Sensitivity		6. Debug Algorithm		7. Departure Scheduling Strategy			8. Debug Algorithm (Dual Runway)		9. Future Los Angeles Operations	10. General Aviation
Configuration																									
Single runway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0
Dual runway																						0	0	0	
Navigation error																									
0.5 nautical miles (1σ)			0					1	1	1	1	1	1	1	1	1			1	1	1			1	1
0.1 nautical miles (1σ)				0		0																			
0.05 nautical miles (1σ)					0		0																		
0.0 nautical miles (1σ)	0	0															0	0				0	0		
Guidance error																									
10 seconds (1σ)			0					2	2	2	2	2	2	2	2	2			2	2	2			2	2
5 seconds (1σ)				0		0																			
2 seconds (1σ)					0		0																		
0 seconds (1σ)	0	0															0	0				0	0		
Control radius																									
150 nautical miles													0												
175 nautical miles	0	0	0	0	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0
200 nautical miles														0											
Separation criteria																									
3.5/2.5 nautical miles	0		0	0	0								0	0	0	0	0		0	0	0	0			0
60/40 seconds		0				0	0	0	0	0	0	0						0					0	0	
Traffic set																									
Today's (arrivals)	0		0	0	0								0	0	3	3									4
Today's (mixed)																	0		0	0	0	0			
Future (arrivals)		0				0	0																		
Future (metered arrivals)								0	0	0	0	0													
Future (mixed)																		0					0	0	
Arrival schedule keeping																									
300 seconds (1σ)	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0
120 seconds (1σ)									0																
30 seconds (1σ)										0															
10 seconds (1σ)											0														
0 seconds (1σ)												0													
Departure strategy																									
Opportunity																	0	0	0						
Arrival/depart. ratio						Not applicable														0		0	0		
Departure schedule																					0				
Departure schedule keeping																									
300 seconds (1σ)																	0	0	0	0		0	0		
30 seconds (1σ)																					0				

Key: 0. Parameter value used from list of alternatives.
1. Navigation errors as determined in experiment 2.
2. Control errors as determined in experiment 2
3. Input arrival rate varied.
4. General aviation airplanes input.

The third experiment determines the impact on strategic control operations of schedule-keeping accuracy. A uniform within-hour schedule is assumed for two demand levels and the schedule-keeping error is varied for 300, 120, 30, 10, and zero seconds (one sigma). The single runway, 175-nautical-mile terminal configuration is assumed. The future demand level and separations are used. The navigation/guidance errors determined in the second experiment are used. The sensitivity is measured in terms of delay and scheduling efficiency.

A control radius sensitivity study constitutes the fourth experiment. The model is run assuming a single runway, the required navigation/guidance values, today's demand level and separation values, and a 300-second (one sigma) scheduling-keeping accuracy. Two control radius values selected to be run are based on the algorithm performance of the first experiment set (150 and 200 nautical miles). Evaluation is with respect to the airspace, delay, and runway utilization parameters.

The fifth experiment measures today's arrival throughput sensitivity. A statistical within-hour demand distribution and spacing are assumed, but the number of arrivals per hour is run for two alternate throughput levels. Other assumptions include the single runway, experiment 2 determined navigation/guidance values, 175-nautical-mile control radius, and a 300-second (one sigma) schedule-keeping accuracy. Evaluation is made for the airspace required, the system capacity measured in terms of throughput, and the delays incurred.

The next experiment is to debug the single runway, mixed operations algorithm. Two data sets are run with parameter values as in experiment 1 (except that the traffic sets will include departures). The departure scheduling strategy is based on opportunity runway time assignments and the assumed departure schedule-keeping value is 120 seconds (one sigma). As in the first experiment, the evaluation criteria are safety, airspace volume, delay, and runway utilization.

The seventh experiment looks at alternative departure scheduling strategies. The objective of this experiment is to determine the best way to incorporate departures with the arrival scheduling logic. Three data sets are run representing opportunity scheduling, arrival/departure ratio scheduling, and departure slot scheduling. The traffic set and separations represent today's operations. Other model values include the required navigation/control performance, a 175-nautical-mile control radius, and a 300-second (one sigma) arrival schedule-keeping error. Alternative departure scheduling strategies are evaluated in terms of delay and runway scheduling parameters.

The eighth experiment is to debug the dual runway algorithm. All parameter values are as in the sixth experiment (to debug the single runway, mixed operations algorithm). Again the algorithm is tested against two data sets, one representing today's operations and the other future operations. Safety, airspace volume, delay, and runway utilization are the evaluation criteria.

The ninth experiment evaluates the strategic algorithm applied to an operational environment representative of Los Angeles International Airport. Two dual-lane runways and the Los Angeles runway configuration are also assumed. A future (1995) Los Angeles terminal configuration is used. Arrival and departure scheduling is represented. The navigation/guidance system values are those derived in the second experiment. The 175-nautical-mile control radius and 300-second (one sigma) arrival schedule-keeping accuracy are used. Departures are scheduled based on the experiment 7 scheduler recommendation with appropriate departure schedule-keeping accuracy. The evaluation is based on the airspace volume required, the system throughput, and the delays.

The last experiment looks at the impact of general aviation airplanes on the strategic control concept. A single data set is run incorporating general aviation airplanes into the input data set. Arrivals are represented. The required navigation/guidance system performance, 175-nautical-mile radius, and 300-second (one sigma) schedule-keeping accuracy values are used. Evaluation is in terms of safety, capacity, delay, and utilization.

The performance of this experiment set provides an initial test of the strategic control algorithm, its feasibility and possible benefits. Many additional experiments can be defined to refine the strategic control concept but are beyond the scope of this effort (to develop a basic strategic control algorithm).

The following discussion of experiment results is divided into three sections: algorithm design verification (sec. 5.2.3), strategic control requirements (sec. 5.2.4), and sensitivities and evaluation (sec. 5.2.5). The design verification experiments are 1, 6, and 8. These experiments provide a detailed examination of the strategic algorithm applied to a single arrivals-only runway, a single mixed operations runway, and a dual-lane mixed operations runway. The development of system requirements for the strategic control algorithm is the objective of the second, third, and seventh experiments. Strategic control sensitivities are examined in experiments 4 and 5. Experiments 9 and 10 evaluate the Los Angeles terminal area application and the unequipped airplane experiment.

5.2.3 Algorithm Design Verification

Experiments 1, 6, and 8 all address the primary study objective of testing the algorithm and iterating its design. These three experiments apply to a single runway with arrivals only, a single runway with mixed operations, and multiple (dual-lane) runways with mixed operations.

5.2.3.1 Single Runway, Arrivals Only (Experiment 1)

Results of the first experiment indicate the strategic algorithm developed during the study is a valid concept for the control of arrival airplanes from en route altitude through runway touchdown. Tables 5-3 and 5-4 summarize the traffic demand and path assignment for the 1972 LAX traffic input and a projected 1995 LAX traffic input. Paths on three of the four available quadrants were used.

For the low demand level 8 primary paths, three first offsets and one second offset were used in scheduling conflict-free traffic from the entry fix through the initial approach fix. For the high demand level 8 primary paths, seven first offsets, four second offsets, and one third offset were required. Figure 5-5 summarizes the relative frequency of use of the offsets.

TABLE 5-3.—PERCENT PATH ASSIGNMENT (LOS ANGELES INTERNATIONAL 1972 TRAFFIC)

	NORTHEAST QUADRANT			NORTHWEST QUADRANT			SOUTHEAST QUADRANT		
PERCENTAGE OF TRAFFIC	55			33			12		
ENTRY FIX DESIGNATIONS	11	12	13	21	22	23	41	42	43
Primary Path	12	21	7	5	16	7	2	10	
First Offset	2	9			5				
Second Offset		4							
Third Offset									
Fourth Offset									

TABLE 5-4.—PERCENT PATH ASSIGNMENT (LOS ANGELES INTERNATIONAL 1995 TRAFFIC)

	NORTHEAST QUADRANT			NORTHWEST QUADRANT			SOUTHEAST QUADRANT		
PERCENTAGE OF TRAFFIC	58			28			14		
ENTRY FIX DESIGNATIONS	11	12	13	21	22	23	41	42	43
Primary Path	9	16	6	4	11	2	3	9	
First Offset	6	10	1	1	5	1		2	
Second Offset	2	6			3	1			
Third Offset		2							
Fourth Offset									

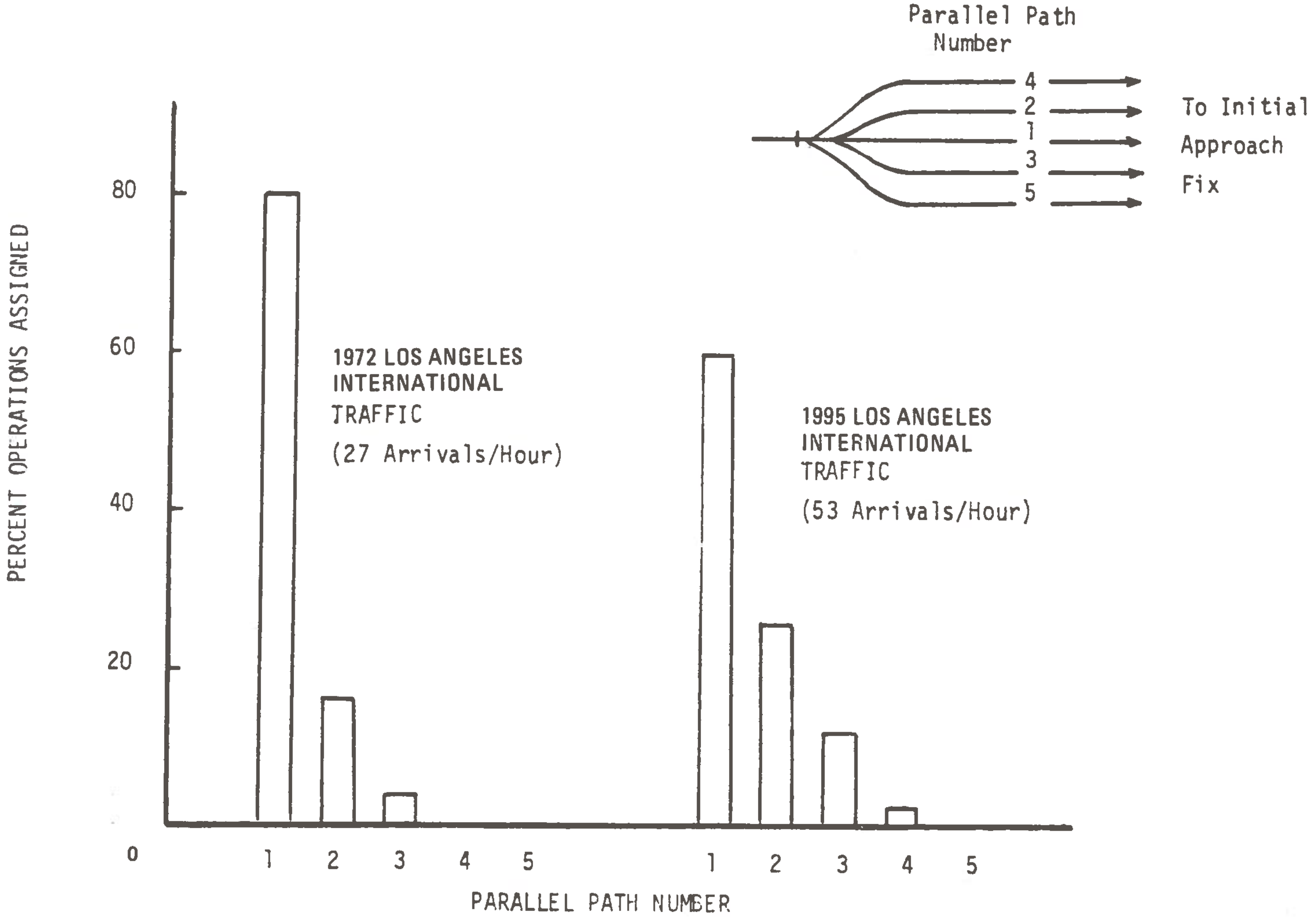


FIGURE 5-5.—PATH ASSIGNMENT SUMMARY

The distribution of assigned path times (from the entry fix to threshold) is shown for the two demand levels in figure 5-6. The high demand path duration curve reflects considerable speed controlling as the runway approaches saturation. Note all path times lie between 30 and 40 minutes, reflecting a runway threshold window of between 6 and 10 minutes (depending on the airplane type and path assigned). The path lengths in the geometry input vary from 175 nautical miles (straight-in) to almost 215 nautical miles.

The distribution of assigned threshold separations is shown in figures 5-7 and 5-8. The 1972 traffic was scheduled with a 3-nautical-mile runway separation constraint. Over 60% of the arrival pairs were scheduled between 3 and 3.5 nautical miles apart. Greater threshold spacing reflects "gaps" in the traffic demand. The 1995 threshold separation probabilities are plotted versus threshold separation time. As the input scheduling constraint is 60 seconds, over 90% of all arrival pairs are scheduled between 60 and 90 seconds. The high demand precludes any large threshold gaps.

The scheduled landing time excess over the earliest threshold capability is shown plotted for the two demand levels in figure 5-9. As expected, the 1995 traffic level requires considerable speed control applied to arrivals. Figure 5-10 shows the probability that arrivals would be required to hold at entry to the strategic control system. For the 1995 arrival traffic scheduled onto a single runway, approximately one airplane in four required an entry fix hold. No 1972 schedule traffic required entry fix holds.

5.2.3.2 Single Runway, Mixed Operations (Experiment 6)

The sixth experiment adds departures to the traffic list. The algorithm then schedules departures as well as arrivals at the runway. The initial scheduling concept provides absolute priority for arrivals over departures (i.e., if both an arrival and a departure can use the runway over some time interval, the arrival will be scheduled). Experiment 7 (discussed in sec. 5.2.4.3) considers alternative scheduling strategies.

The ATC-imposed constraints on interoperation scheduling (as input to the evaluation model) may use any combination of time, distance, and/or (no) joint runway occupancy. Input constraints imposed for the 1972 traffic set included:

First operation	Second operation	Constraint
Arrival	Arrival	3 nautical miles
Arrival	Departure	Runway occupancy
Departure	Arrival	2 nautical miles
Departure	Departure	60 seconds

Input ATC constraints for scheduling the 1995 traffic set included:

First operation	Second operation	Constraint
Arrival	Arrival	60 seconds
Arrival	Departure	Runway occupancy
Departure	Arrival	Runway occupancy
Departure	Departure	Runway occupancy

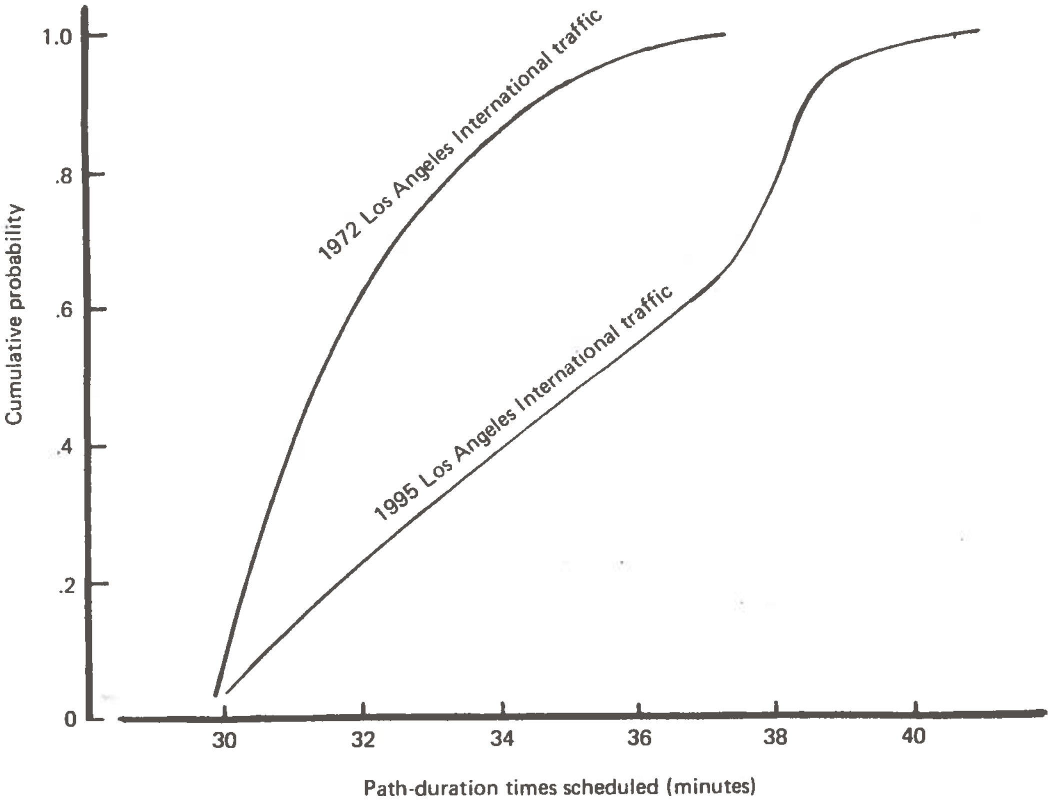


FIGURE 5-6.–PATH DURATION TIMES SCHEDULED

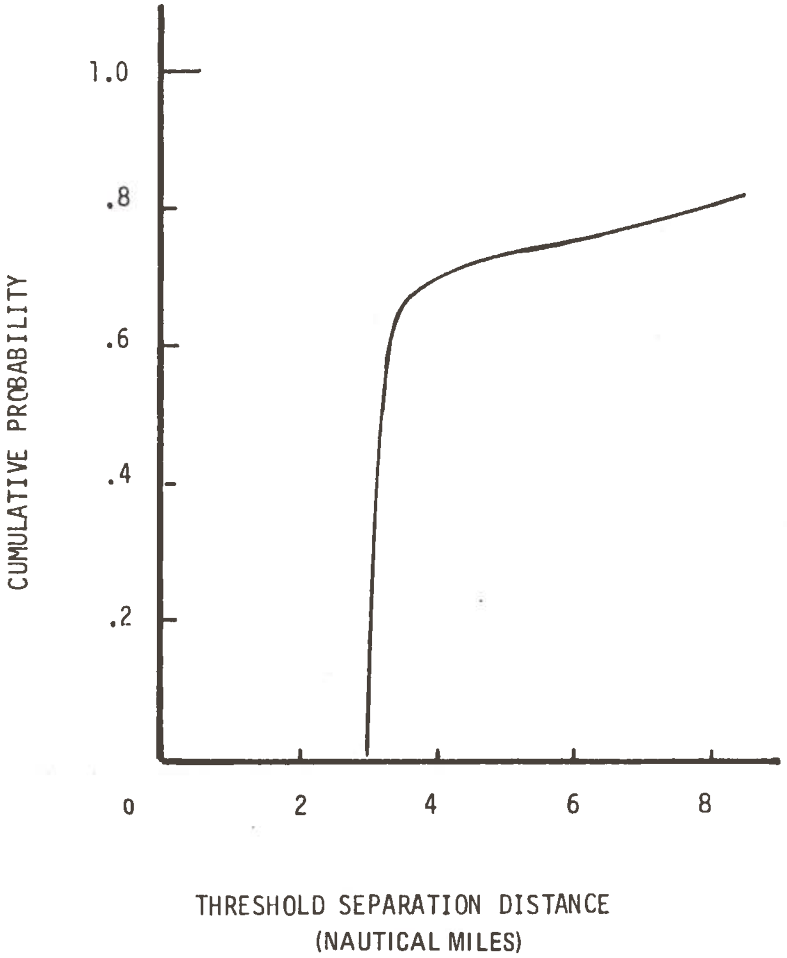


FIGURE 5-7.—THRESHOLD SCHEDULED SEPARATION; 1972 LOS ANGELES INTERNATIONAL TRAFFIC

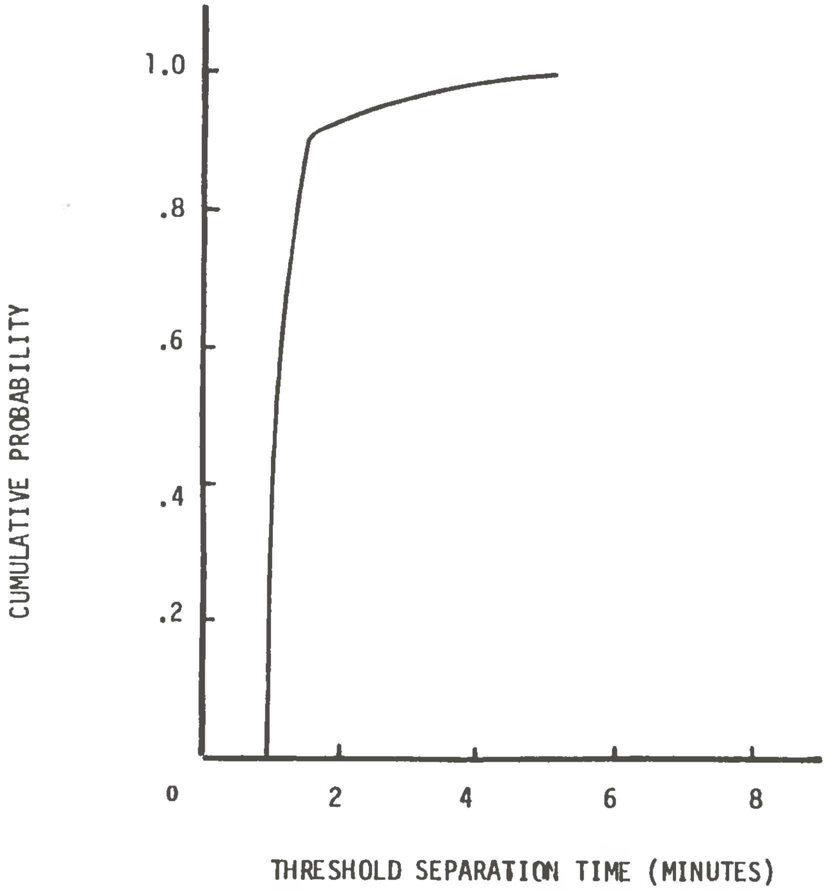


FIGURE 5-8.—THRESHOLD SCHEDULED SEPARATION; 1995 LOS ANGELES INTERNATIONAL TRAFFIC

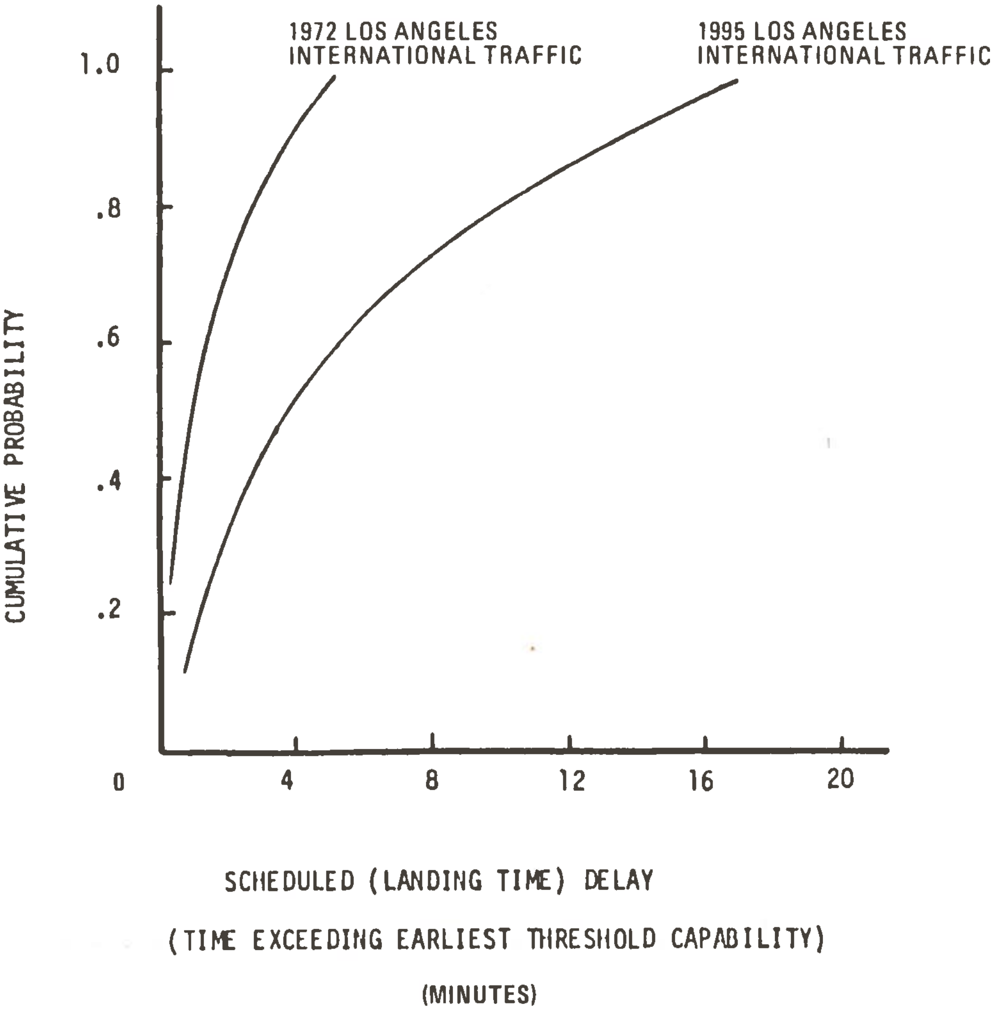


FIGURE 5-9.–SCHEDULED DELAY FOR BASIC ALGORITHM

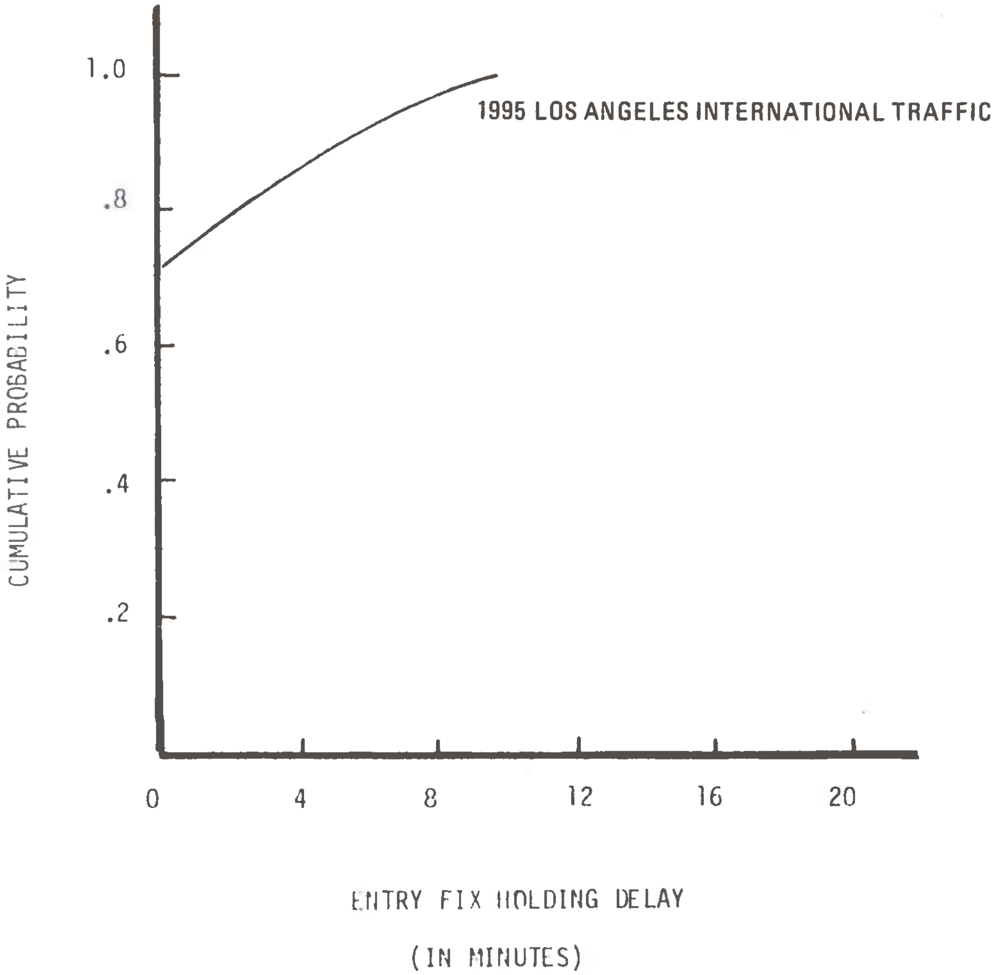


FIGURE 5-10.—HOLDING DELAY FOR BASIC ALGORITHM

Figure 5-11 illustrates the scheduling over a typical segment of time by the strategic algorithm. Departures are shown from system entry (schedule ready) time to scheduled takeoff time (indicated by the inverted triangle on the chart). Arrival operations are shown from estimated earliest landing time to estimated latest landing time. The scheduled landing time is also indicated (by the triangle on the chart). For arrivals and departures, time shown to the left of the schedule triangle is delay imposed by the algorithm. Schedule gaps reflect periods of slack demand. Minimum schedule intervals are imposed by the ATC rules governing the various operational sequences (arrival following arrival, arrival following departure, departure following arrival, and departure following departure).

As indicated in figure 5-11, the departures incur substantially larger scheduling delays than arrivals. For the period of time shown (3000 to 5000 seconds after 1700 hours for the 1972 traffic mix) most arrivals are scheduled at or near the beginning of the schedule window. Departures occur clustered at certain times (e.g., at 3600 seconds). A schedule break occurs between 3100 and 3300 seconds. Otherwise, interoperation times scheduled are close to the minimums.

The arrival scheduling priority results in route-time profiles generated in experiment 6 being identical with those derived in the first experiment. Thus the path utilization, path duration, and in-air separation statistics presented in figures 5-5 through 5-8 are applicable here.

Figure 5-12 shows the distribution of arrival following arrival, arrival following departure, departure following arrival, and departure following departure interoperation times at the runway for the 1972 schedule. The cumulative distribution function for arrivals followed by arrivals peaks sharply at about 80 to 90 seconds corresponding to the schedule minimum (3 nautical miles at approximately 120 knots) and is similar for departure-departure and arrival-departure interoperation times (with their corresponding constraint minimums). The departure followed by arrival distribution is less peaked and reflects the random input demand rather than constraint minimums. Similar results are shown plotted in figure 5-13 for the 1995 traffic demand.

Delay data associated with the baseline algorithm are shown in figure 5-14 where the cumulative probability distributions are plotted versus delay in minutes for the 1972 arrivals, 1995 arrivals, 1972 departures, and 1995 departures. Note the substantially greater departure delay for comparable demand levels (reflecting scheduling priorities). The 1995 departure delay levels (50% exceed 8 minutes) appear unacceptable for an operational system.

5.2.3.3 Dual-Lane Runway, Mixed Operations (Experiment 8)

The eighth experiment applies the strategic algorithm to a dual-lane runway airport. The traffic demand and airspace configuration are assumed as in the previous experiments. A close-spaced parallel runway pair is available for scheduling arrival and departure operations. The dual runway configuration provides no increase in capacity for arrival-arrival, departure-arrival, or departure-departure operations under current (IFR) rules. In the arrival-departure case (by using one runway for arrivals and the adjoining runway for departures), the runway occupancy constraint can be dropped. A departure may be released as an arrival touches down.

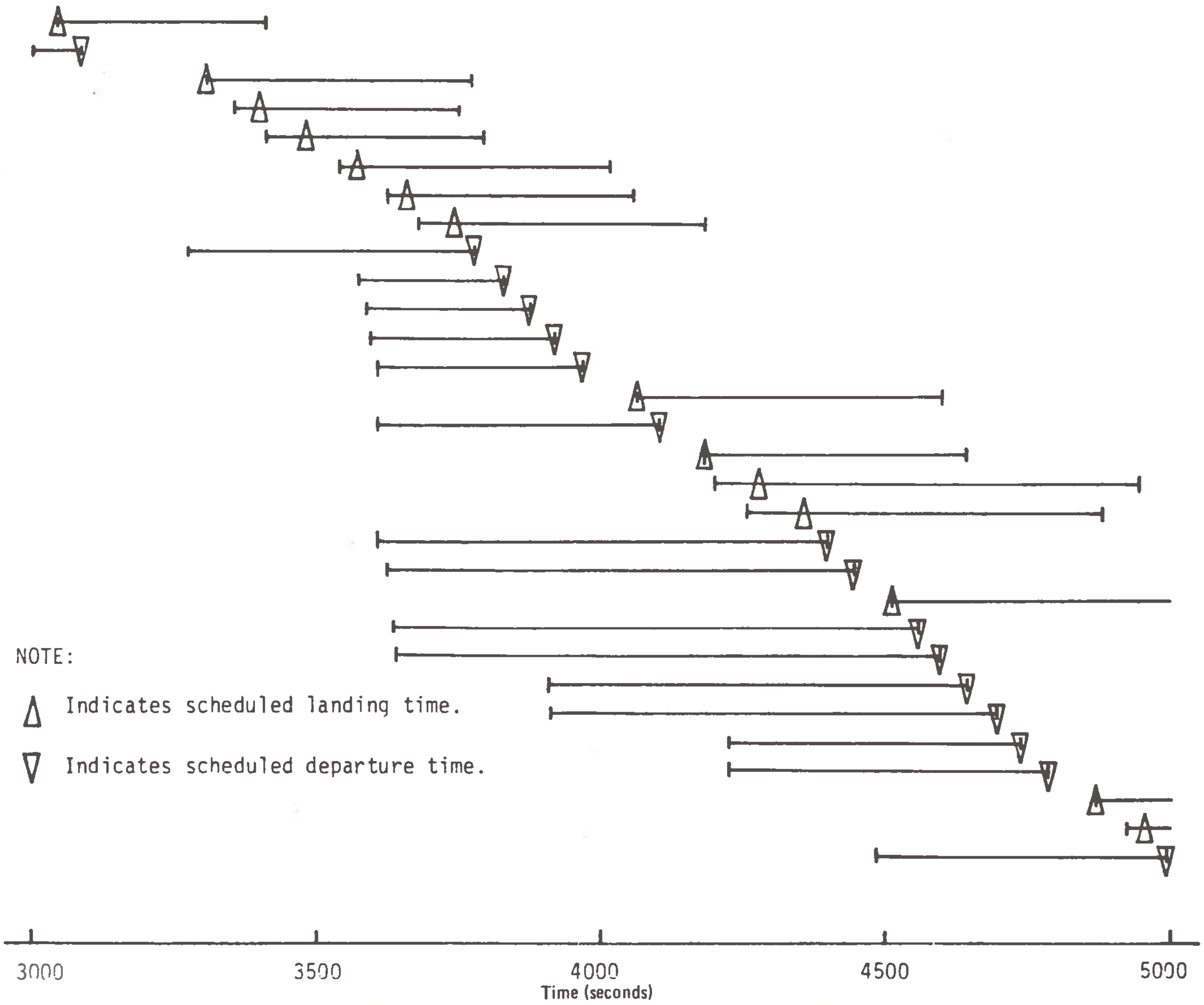


FIGURE 5-11.—TYPICAL RUNWAY SCHEDULE WINDOWS

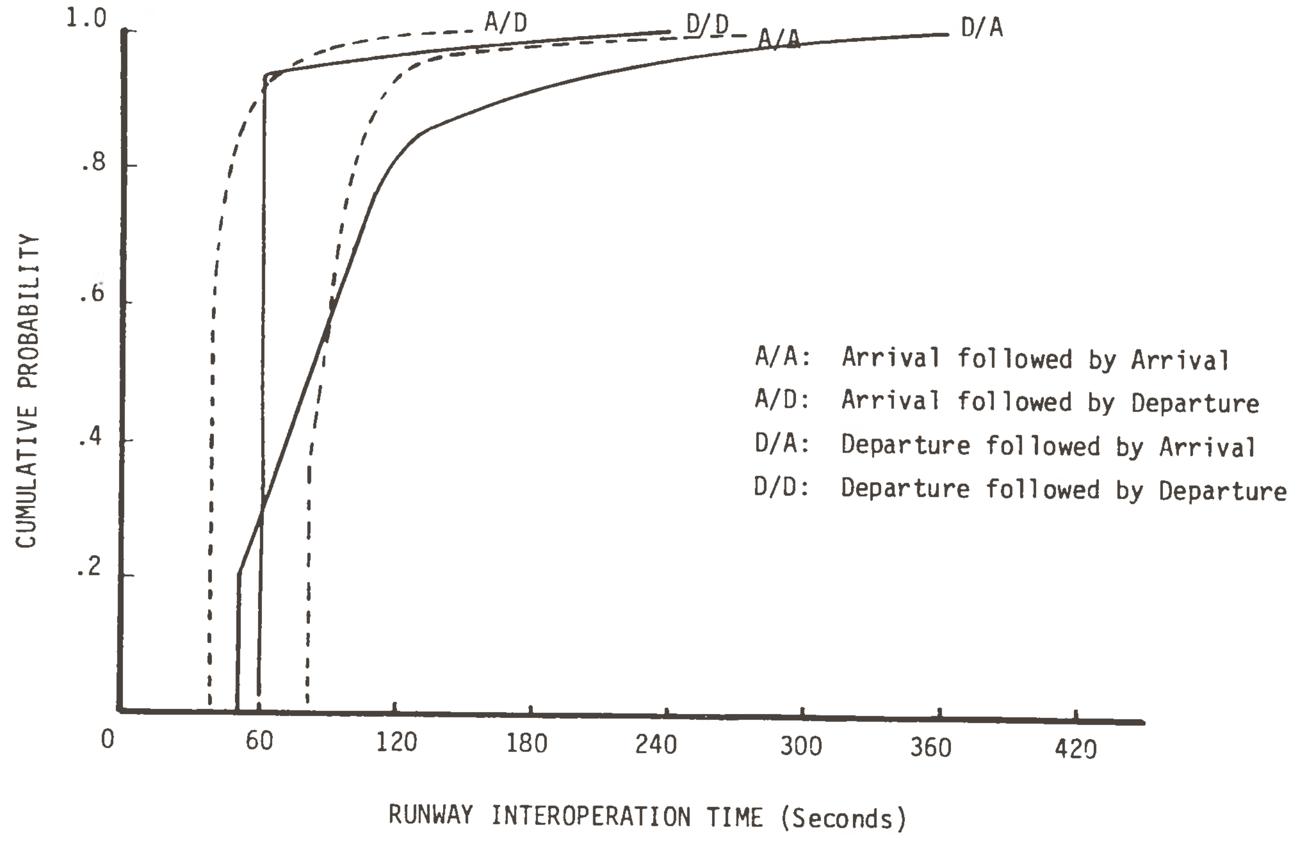


FIGURE 5-12.—INTEROPERATION TIME DISTRIBUTIONS FOR 1972 TRAFFIC

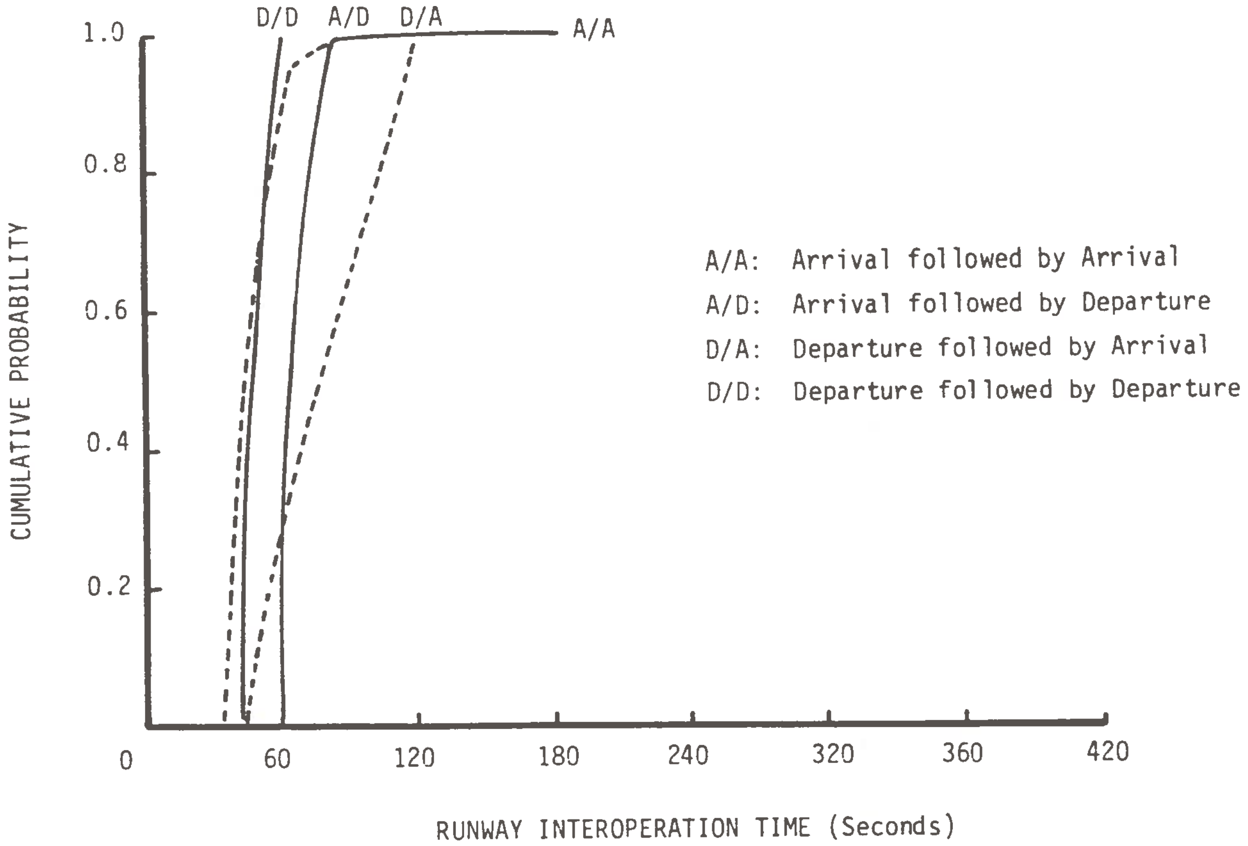


FIGURE 5-13.—INTEROPERATION TIME DISTRIBUTIONS FOR 1995 TRAFFIC

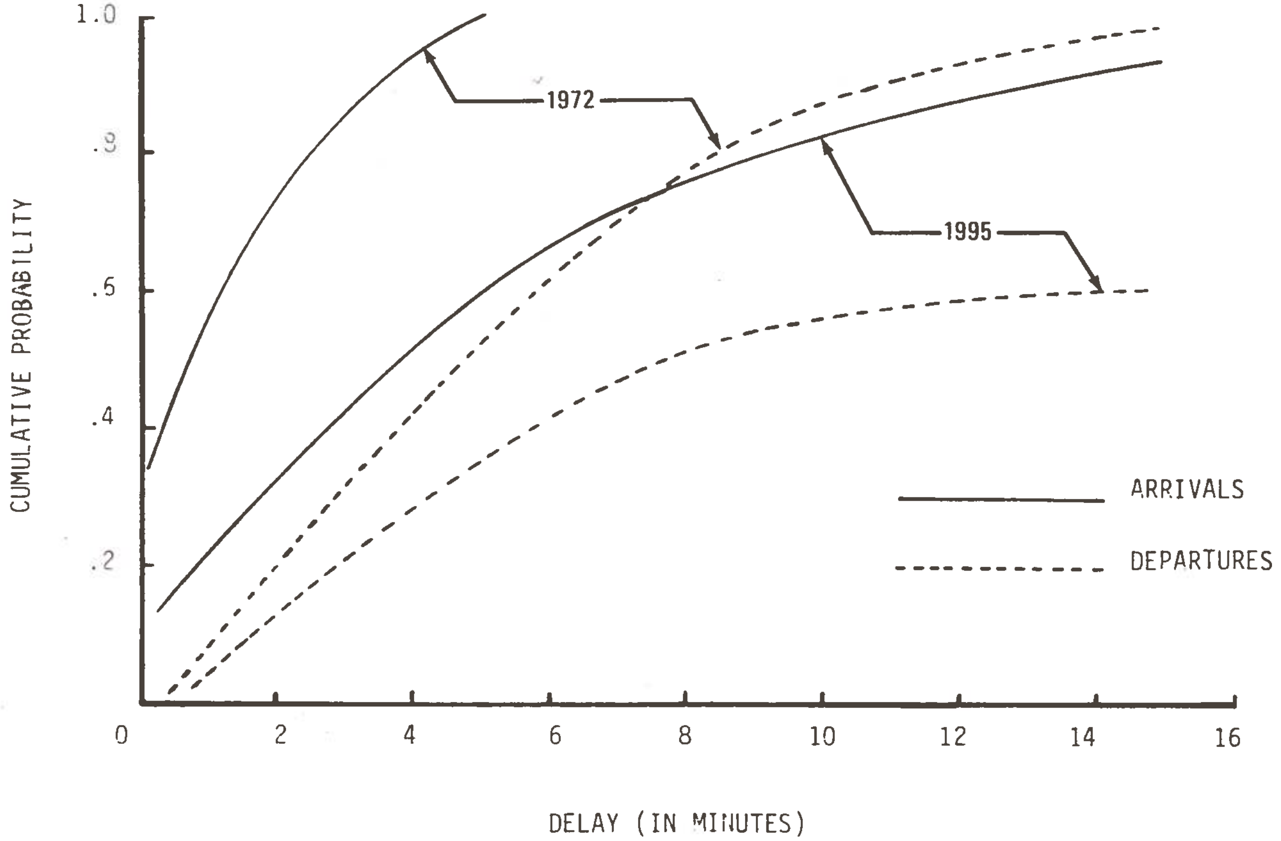


FIGURE 5-14.—SCHEDULED DELAY FOR ARRIVALS AND DEPARTURES

The corresponding interoperation time distributions for arrival-arrival, departure-arrival, and departure-departure pairs are not significantly changed (from the results reported previously in experiment 6). Only the arrival-departure interoperation time distribution is altered, as shown in figure 5-15. Note that about three-fourths of the departures in the 1972 traffic set were scheduled to depart immediately upon arrival landing for the dual-lane runway.

Since the arrival scheduling and RTP generation are unchanged from the arrivals-only (experiment 1) and mixed operations (experiment 6) algorithms, the previous arrival results (path utilization, in-air separation, and path-duration distributions) reported in this section apply to the dual runway algorithm. The significant evaluation parameter that is changed is the departure (and total operations) delay.

Departure delay distributions for the 1972 traffic demand are shown in figure 5-16. Delay probability is plotted for the single and dual-lane runways. A substantial reduction in departure holding is indicated by employing the dual-lane runway. Figure 5-17 shows analogous data plotted for the 1995 demand. The delay reduction for the 1995 traffic demand is even more dramatically affected. For the single runway, departure delay in excess of 16 minutes occurs for over 40% of the departures. For the dual-lane runway, no departures exceeded 6 minutes' delay.

5.2.4 Strategic Control Requirements

The development of system requirements for strategic control is the objective of the second, third, and seventh experiments. The second experiment sets the navigation and control performance requirements associated with the user airplanes. The third experiment considers the degree of accuracy with which arrivals must be delivered from the en route system. The seventh experiment examines desirable runway scheduling techniques.

5.2.4.1 Navigation/Controls (Experiment 2)

Figure 5-18 shows, for a typical airplane in the 1972 traffic set, the altitude/groundspeed profile generated by the algorithm and the flight simulation profile output for three levels of avionics (combined navigation and controls) performance. The performance levels are summarized as:

Low performance:	Navigation error	0.5 nautical mile (one sigma)
	Controls error	10 seconds (one sigma)
Medium performance:	Navigation error	0.1 nautical mile (one sigma)
	Controls error	5 seconds (one sigma)
High performance:	Navigation error	0.05 nautical mile (one sigma)
	Controls error	2 seconds (one sigma)

The error modeling is discussed in section 5.3. Figure 5-19 shows an example for a single arrival of the airplane clock errors and "true clock" time as a function of the distance from threshold.

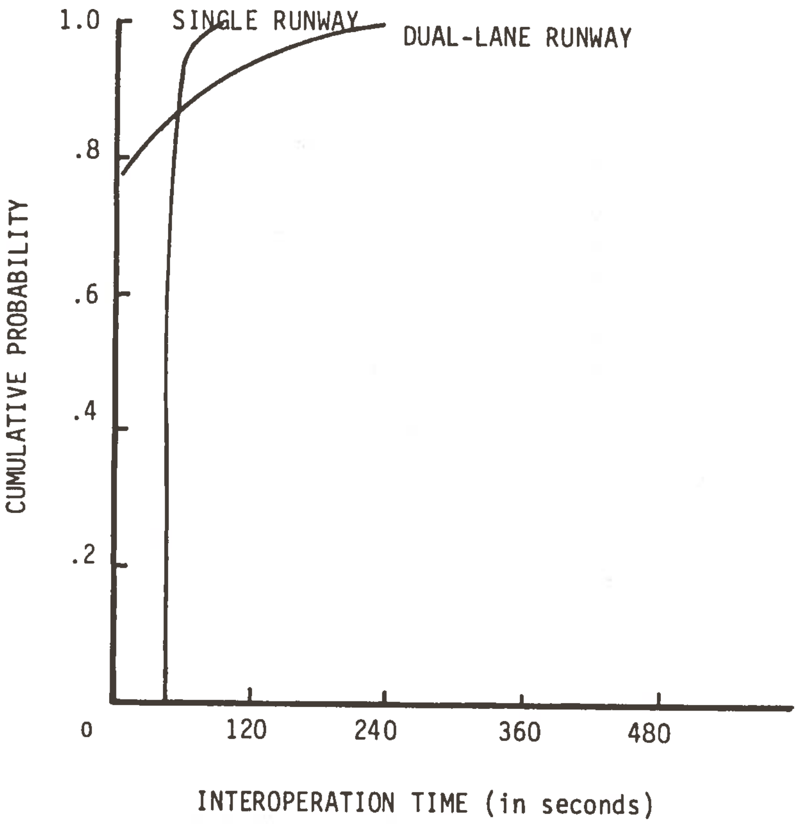


FIGURE 5-15.—ARRIVAL/DEPARTURE INTEROPERATION TIME DISTRIBUTION

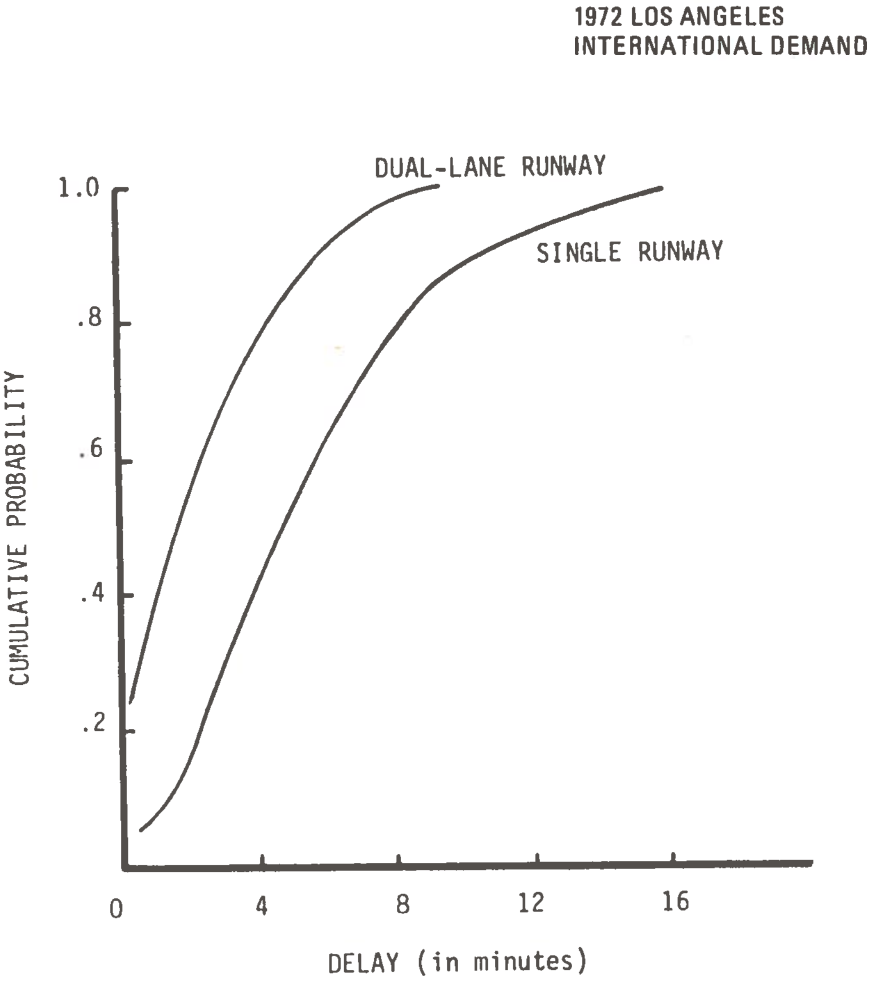


FIGURE 5-16.—DEPARTURE DELAY DISTRIBUTION FOR 1972 TRAFFIC

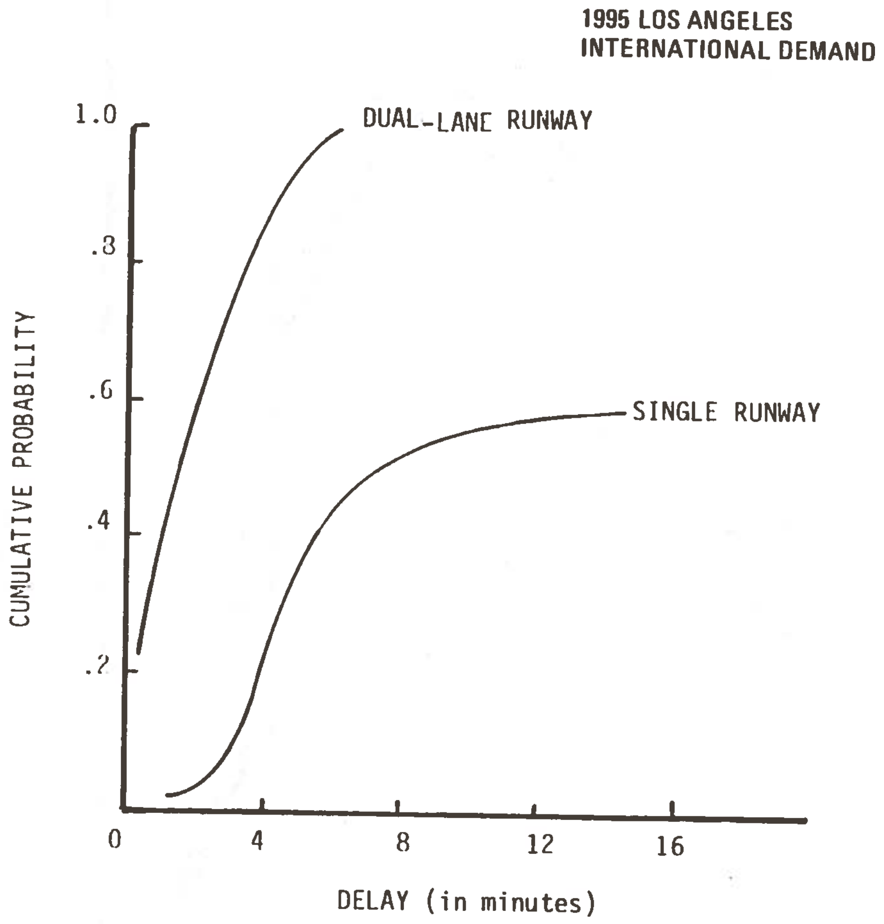


FIGURE 5-17.–DEPARTURE DELAY DISTRIBUTION FOR 1995 TRAFFIC

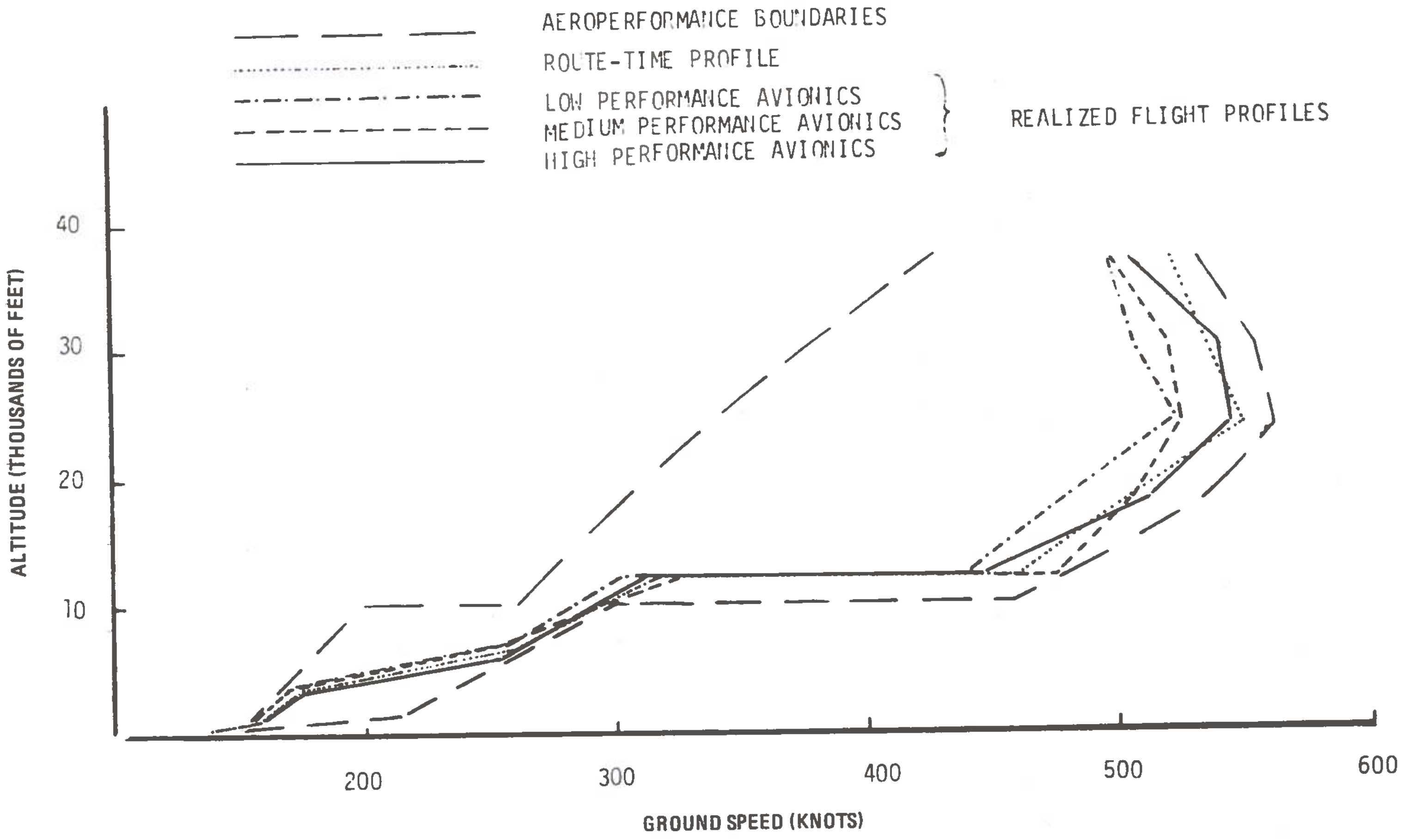


FIGURE 5-18.—FLIGHT SIMULATION PROFILE

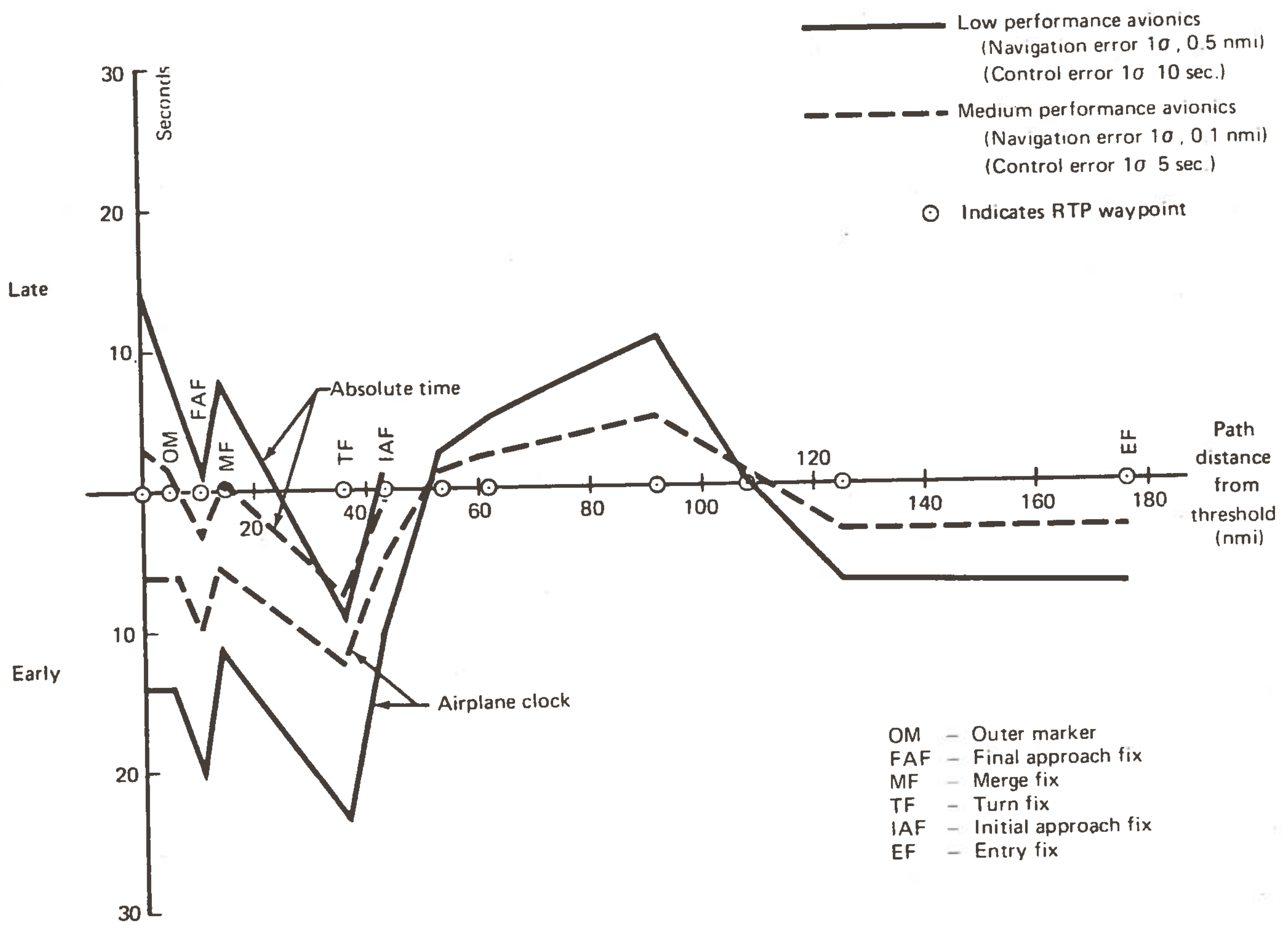


FIGURE 5-19.—SIMULATION SCHEDULE-KEEPING

The resultant threshold spacings are shown plotted in figure 5-20 for the 1972 demand and the three avionics performance levels. Note that the lower performance results in close spacings for some approach pairs. When this spacing drops below some critical value, a potential conflict (safety hazard) exists. Setting a 2-nautical-mile conflict level for the 1972 traffic and a 40-second conflict level for the 1995 traffic, we plot (fig. 5-21) probability of conflict on final approach versus a parameter combining navigation and controls errors.

For a 1% conflict criteria, the resultant navigation and controls requirements are:

1972 traffic level:	Navigation error	0.2 nautical mile (one sigma)
	Controls error	6 seconds (one sigma)
1995 traffic level:	Navigation error	0.1 nautical mile (one sigma)
	Controls error	3 seconds (one sigma)

The implication of navigation and controls errors on the airplane control system ability to accommodate velocity change commands is illustrated in figure 5-22. The evaluation model outputs control flags at waypoints when the RTP-required waypoint velocity exceeds velocity or acceleration bounds (see the discussion of the error models, sec. 5.3). The figure shows the percentage of flags at waypoints as a function of navigation and controls errors for the 1972 traffic demand.

5.2.4.2 En Route Schedule-Keeping (Experiment 3)

The third experiment determines the required schedule-keeping accuracy (delivery from the en route system into the strategic control system). The determination is made for the 1972 and 1995 demand levels. The evaluation criteria involve the permissible delay levels.

For experiment 3, the total operations per hour for the respective demand levels are placed nominally at regular arrival intervals. These nominal arrival times are then perturbed by adding random variates sampled from a distribution representing the en route system arrival schedule-keeping accuracy. A normal distribution was used with mean interarrival time at the scheduled time and standard deviation varied parametrically from 300 seconds down to 0 seconds.

The navigation and controls errors are those derived in the second experiment. For the 1972 demand a navigation error of 0.2 nautical mile (one sigma) and a control error of 6 seconds (one sigma) were used. For the 1995 demand a navigation error of 0.1 nautical mile (one sigma) and a control error of 3 seconds (one sigma) were used.

Path utilization results of the evaluation model are shown in figure 5-23 for the high demand level. Percent utilization of the primary path and the four offsets are shown as a function of the en route schedule-keeping uncertainty. The figure indicates the increasing use of the primary path with increasing schedule-keeping accuracy (and corresponding decrease in the use of the parallel offsets). Similar results apply for the low demand level, but with less sensitivity of path usage to schedule-keeping accuracy.

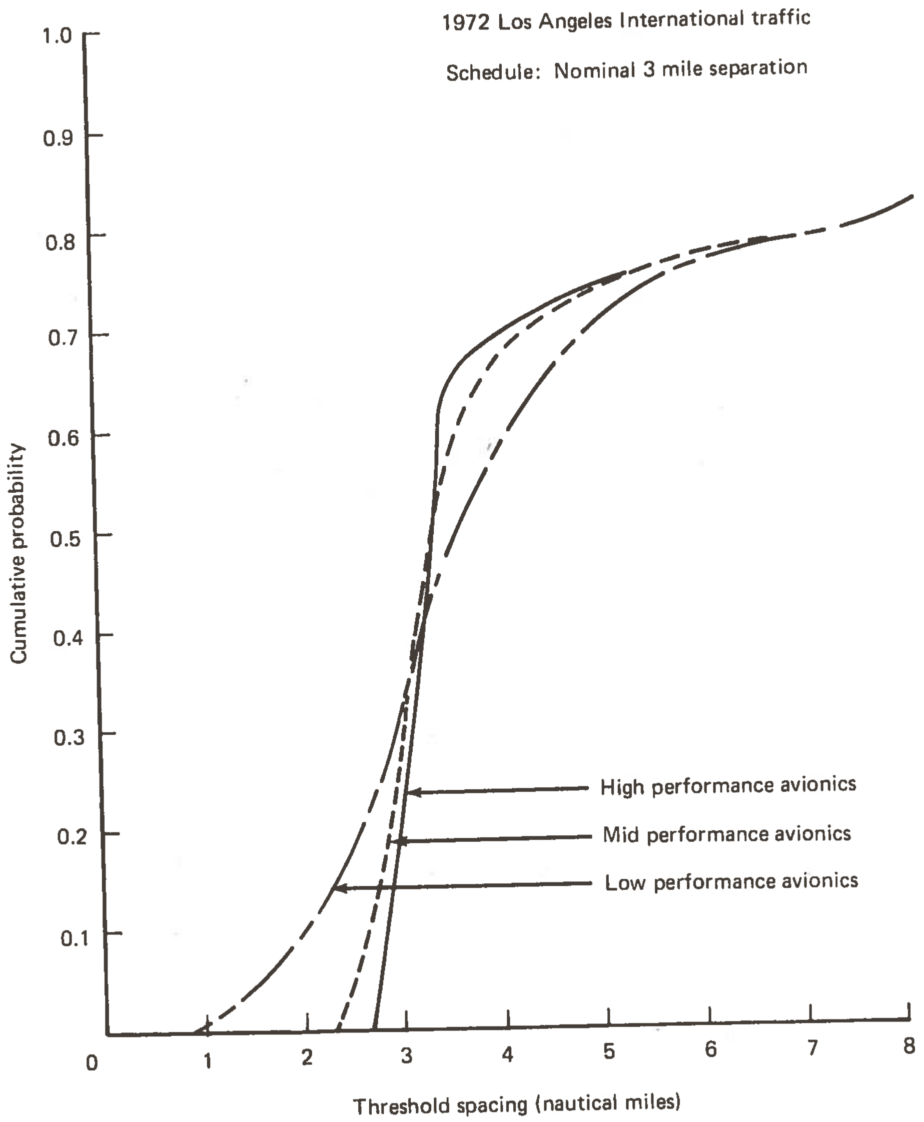


FIGURE 5-20.—THRESHOLD SEPARATION DISTRIBUTIONS

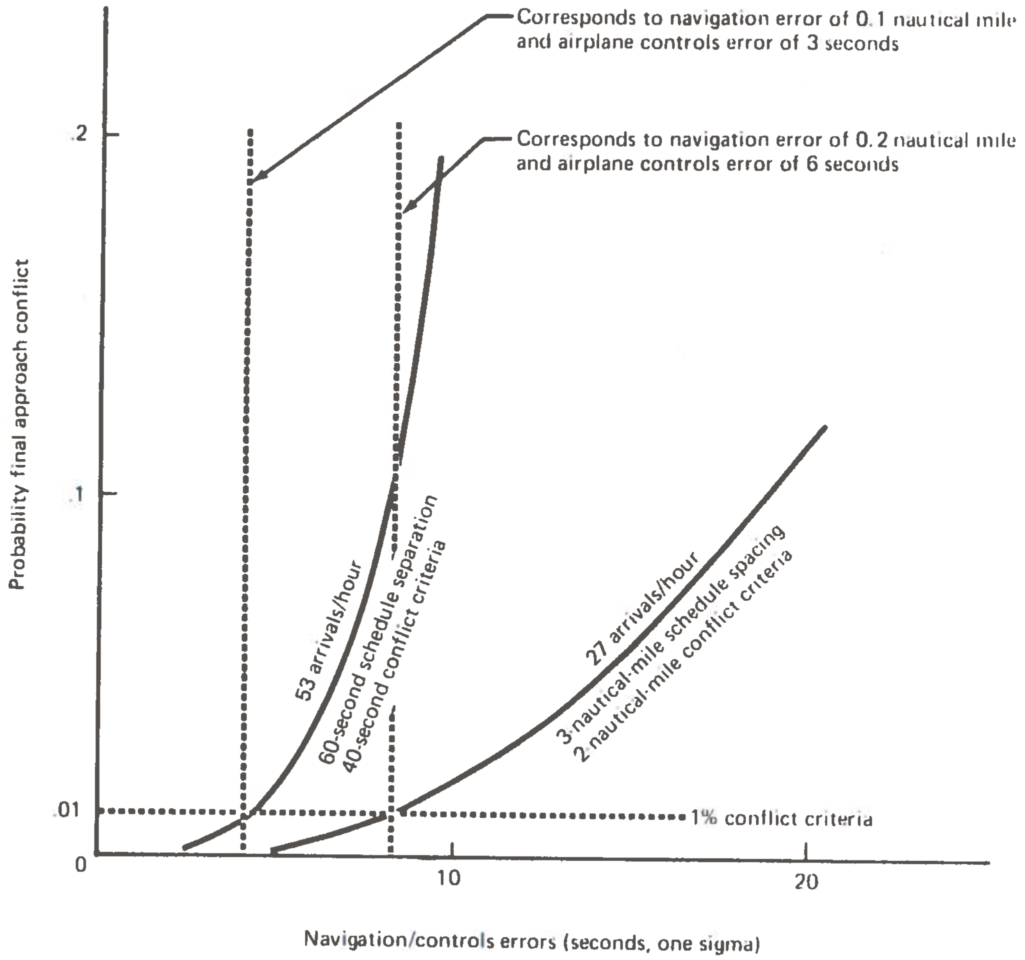


FIGURE 5-21.—NAVIGATION/CONTROLS REQUIREMENTS

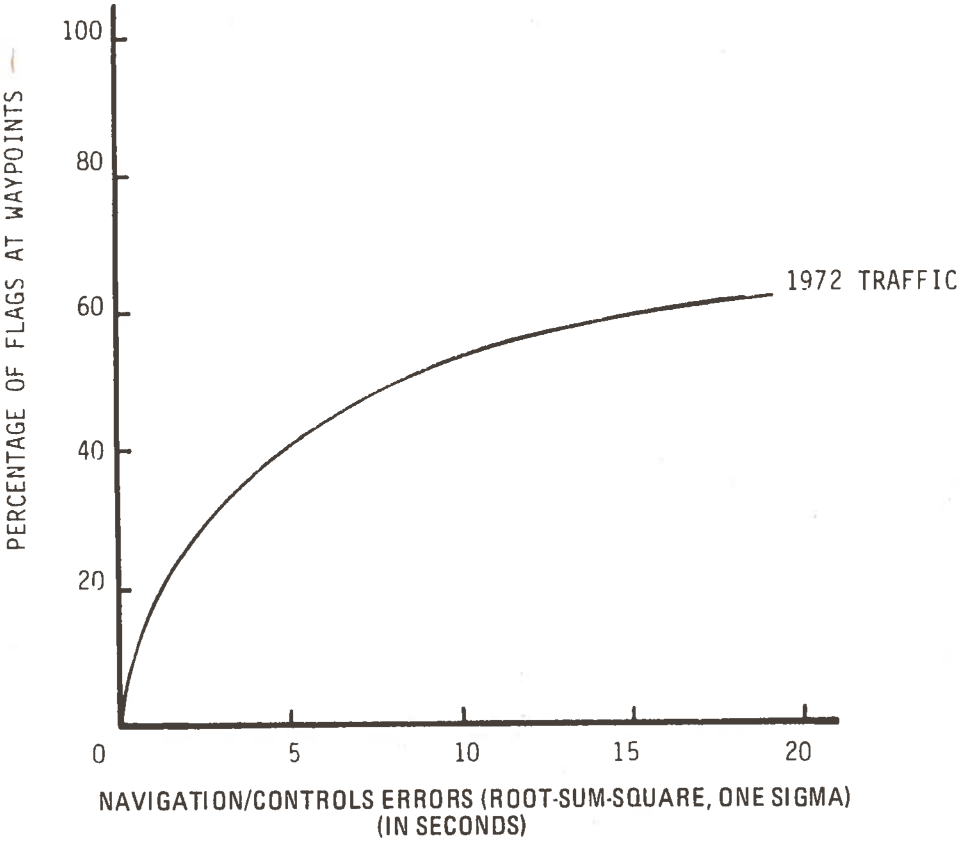


FIGURE 5-22.—AIRPLANE VELOCITY CONTROL CONSTRAINTS

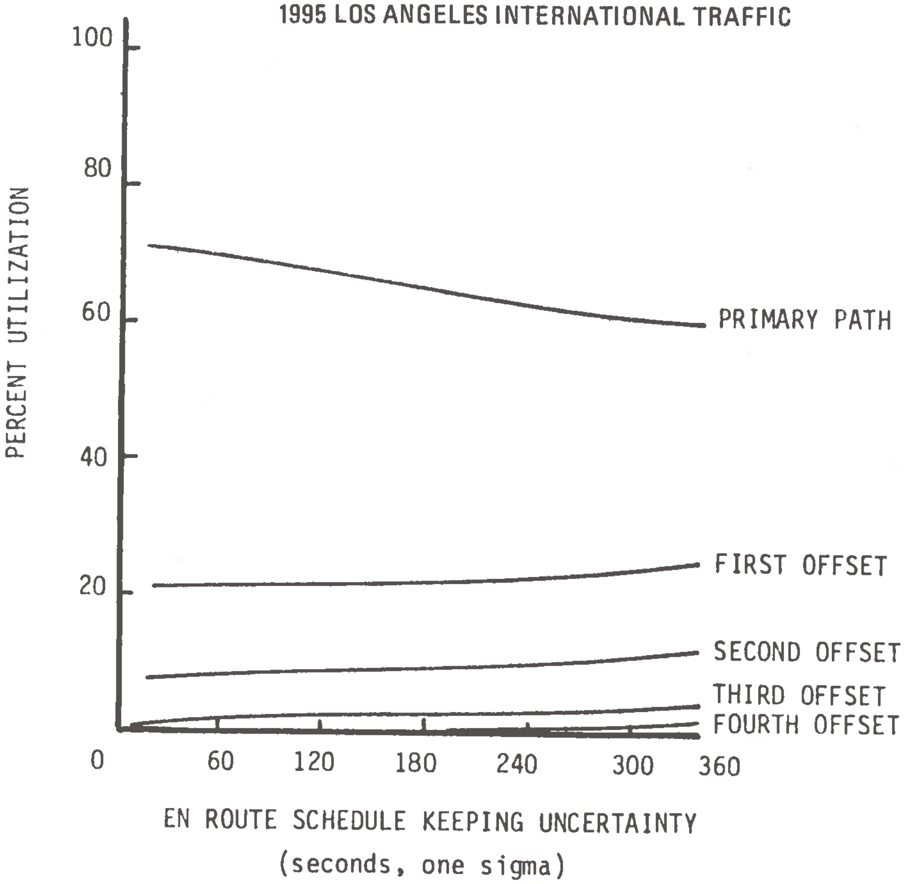


FIGURE 5-23.—AIRSPACE SENSITIVITY TO EN ROUTE DELIVERY ACCURACY

The primary effect of schedule-keeping uncertainty is measurable in terms of scheduled delays incurred by airplanes within the strategic control authority. Figure 5-24 shows the cumulative probability of delay for 300-, 120-, and 30-second (one sigma) en route schedule-keeping uncertainty for the 1972 and 1995 traffic levels. Substantially higher delay levels are indicated for the high traffic demand.

Delay criteria (as cited in the benefits analysis, sec. 8.2.2) for an advanced ATC system include:

1) Daily average—less than 3 minutes

2) Busy-hour average—less than 6 minutes

3) 90% delay—less than 15 minutes (daily)

4) 99.9% delay—less than 30 minutes (daily)

As indicated in figure 5-24, the 3-minute daily average criterion is exceeded only for the 300-second (one sigma) arrival accuracy case with 1995 demand. Figure 5-25 shows the average (50%), 90%, and 99.9% delay levels for the 1972 and 1995 demands. Again, the only criterion imposing a system constraint is the 3-minute average delay. For the high demand level, an en route schedule-keeping accuracy of 160 seconds (one sigma) is required.

5.2.4.3 Runway Scheduling (Experiment 7)

The seventh experiment examines alternate runway scheduling algorithms for use in the strategic control system. Three scheduling techniques assign variable arrival and departure priorities. The first scheduler is that employed in experiment 6 (discussed in sec. 5.2.3). Arrivals have absolute priority over departures. Departures are scheduled only when runway time slots of sufficient length are available. Scheduler two gives arrivals priority over departures (assigning arrival slots prior to departures) but increases the arrival-arrival spacing to allow for a departure insertion; the departure will be inserted if an airplane is available for takeoff at the time slot. The third scheduler assigns departure as well as arrival slots in advance (30 minutes) of the operations. The departure scheduling assumes the airplane can make good the scheduled departure time with some error distribution.

The scheduling runs assume the 1972 Los Angeles traffic mix and ATC constraints as in the sixth experiment (sec. 5.2.3). The navigation/controls errors and arrival schedule-keeping accuracies are assumed as previously determined in this section. A departure schedule-keeping accuracy of 30 seconds, one sigma, is also assumed for the third scheduler.

The primary evaluation parameter sensitive to alternate scheduling strategies is the system delay. The arrival delay distributions for the three schedulers are shown in figure 5-26. The minimum arrival delay is imposed by the first scheduler with slight increases in delay for the second and third schedulers. In all cases, the total arrival delay is under 7 minutes. Delay is defined here as the actual time at the runway minus the earliest possible runway time. Figure 5-27 shows the corresponding departure delay data for the three

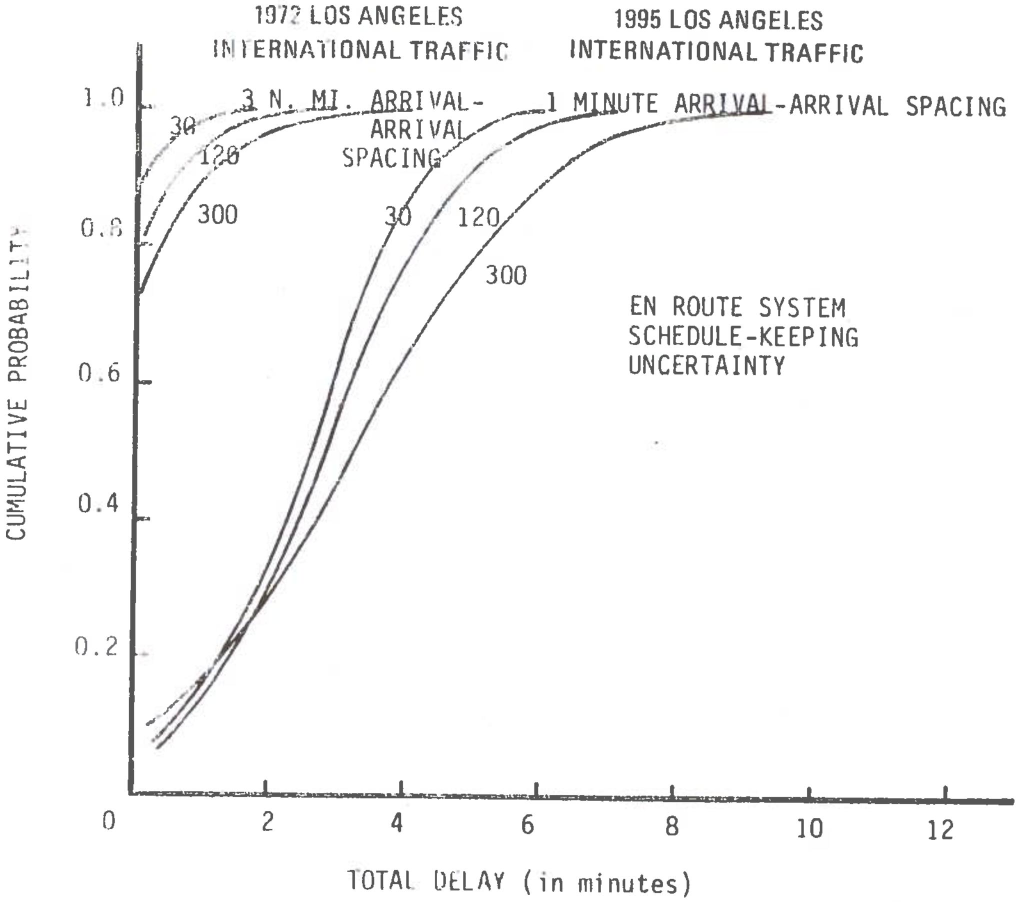


FIGURE 5-24.—DELAY DISTRIBUTION FOR VARIOUS EN ROUTE DELIVERY ACCURACIES

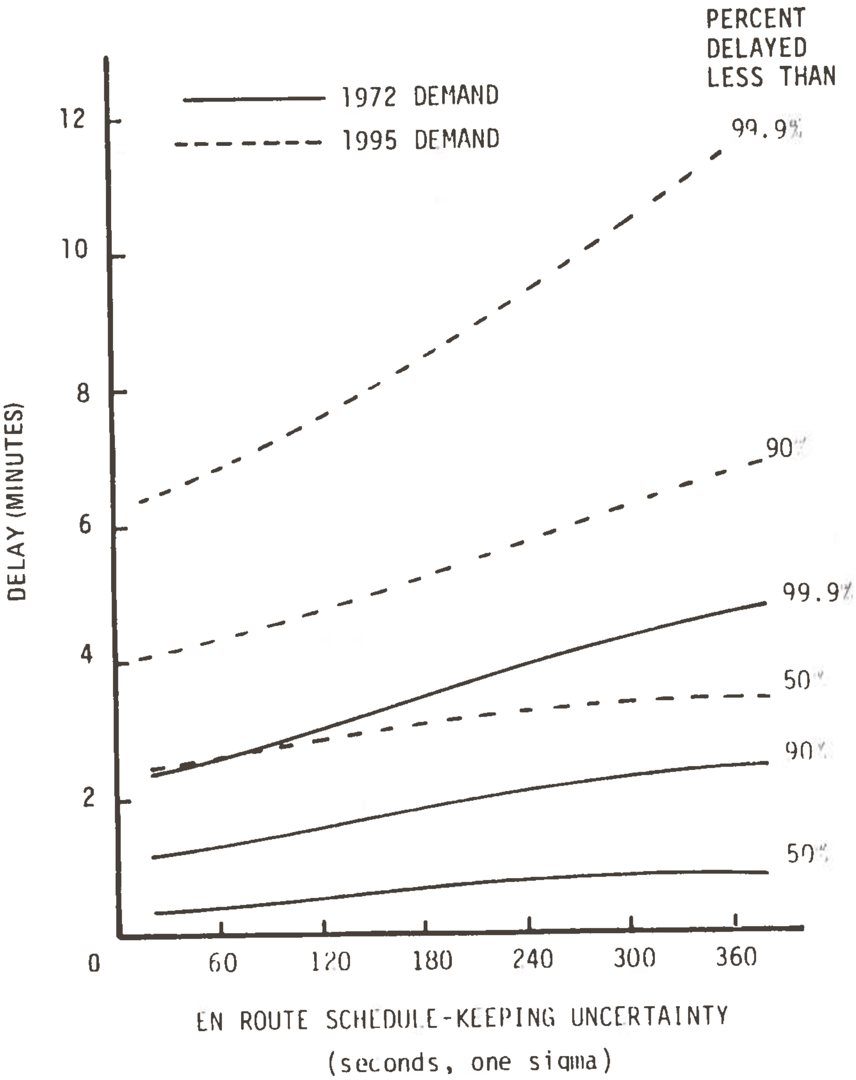


FIGURE 5-25.—DELAY SENSITIVITY TO EN ROUTE DELIVERY ACCURACY

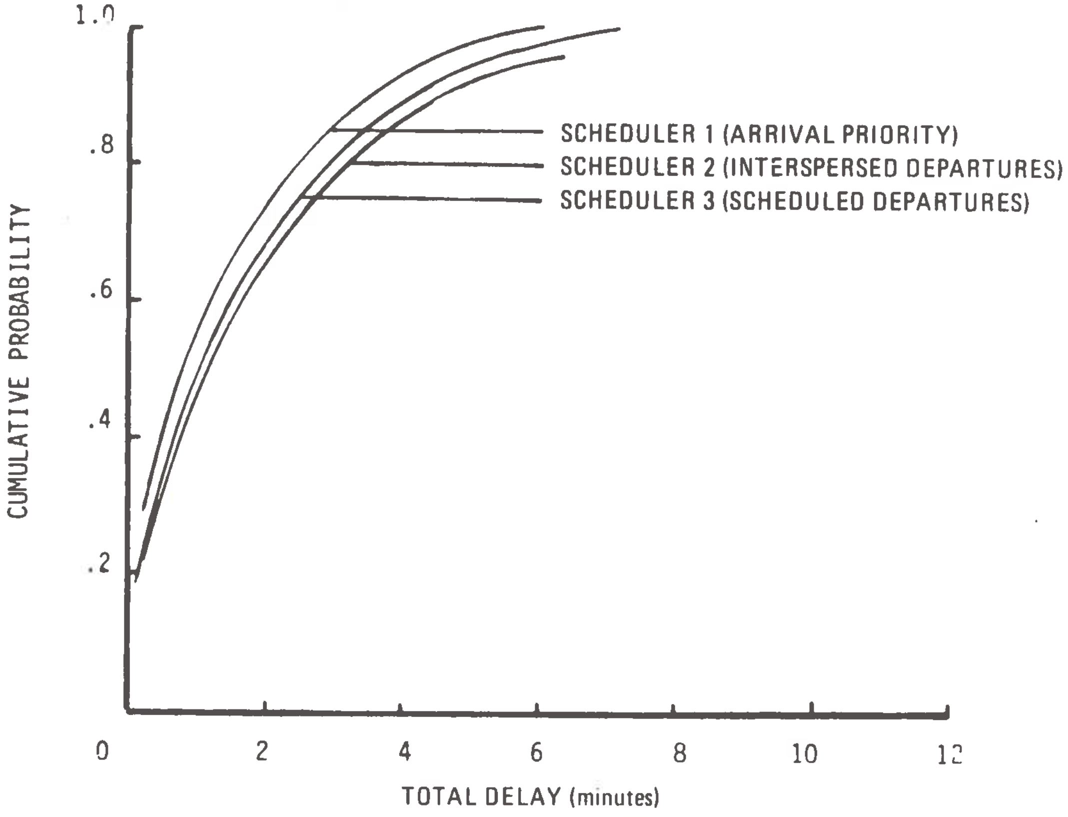


FIGURE 5-26.—ARRIVAL DELAY DISTRIBUTIONS

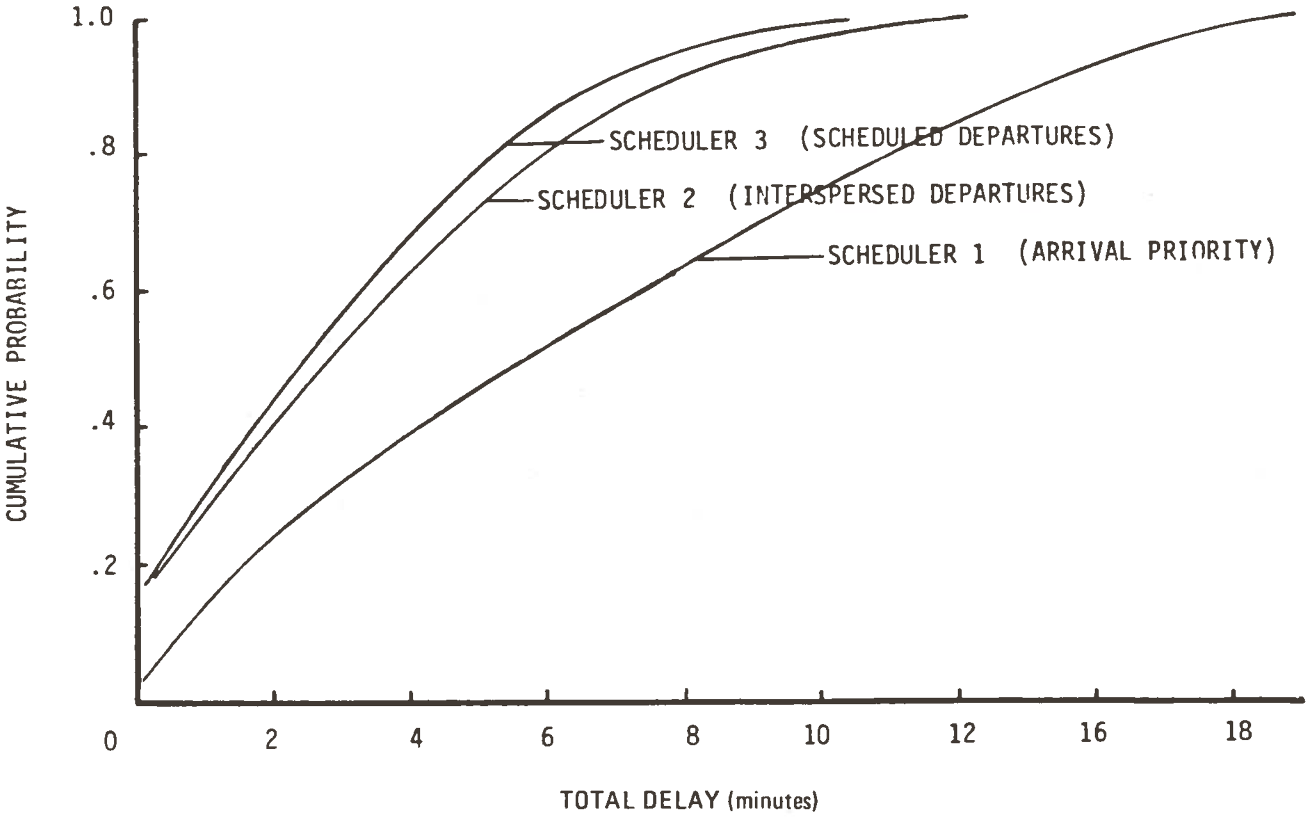


FIGURE 5-27.—DEPARTURE DELAY DISTRIBUTIONS

schedulers. For departures, scheduler three provides minimum delay followed closely by scheduler two. The departure delay for the first scheduler shows a substantial increase.

The mean delay and standard deviation for total operations are summarized in figure 5-28. Mean delay for arrivals and departures is about 3.5 minutes for scheduler one, 2.4 minutes for scheduler two, and 2.2 minutes for scheduler three. Based on these delay results and consideration of schedule-keeping requirements imposed on departures for the third scheduling algorithm, the recommended scheduling concept for the 1972 traffic levels and ATC constraints is the arrival priority with separation intervals widened to allow a departure insertion (scheduler two). This concept requires arrival scheduling at entry to the strategic system and departure scheduling at departure-ready time. Therefore no departure schedule-keeping requirement is imposed.

5.2.5 Sensitivities and Evaluation

Strategic control sensitivities are examined in experiments 4 and 5. Experiment 4 determines the effect of varying the control radius between 150 and 200 nautical miles. Experiment 5 assesses the control concept sensitivity to changes in traffic demand levels (interoperation times) for arrivals. Experiment 9 evaluates the strategic control concept at a representative terminal area (Los Angeles International was selected). Experiment 10 assesses the impact of general aviation airplanes on the operation of the strategic control algorithm.

5.2.5.1 Control Radius (Experiment 4)

Experiment 4 examines the strategic algorithm sensitivity to assumptions of the control radius (distance of the entry fixes to runway). A nominal value of 175 nautical miles was selected. The rationale for the selection of this distance is detailed in volume III, section 2, Geometry Considerations. The selection involves three basic factors: (1) the range of en route cruise altitudes to be expected in the traffic list, (2) the en route transition region descent rate to be assigned in the RTP generation, and (3) the fixed (near-terminal) geometry region radius.

For this experiment, a minimum radius of 150 nautical miles was run together with an increased terminal area geometry whose radius was assumed 200 nautical miles. The lower value is close to the algorithm lower limit (given the assumptions listed in the above paragraph). A radius greater than 200 nautical miles could be considered, although such an expanded terminal area would require careful consideration of the impact on en route traffic passing over the area and on nearby airports. Other experiment assumptions included the use of the 1972 Los Angeles arrival traffic list, the Los Angeles geometry (as in the other experiments) from the initial approach fix to the runway, and the current rules and procedures. The navigation/controls values are those determined in the second experiment.

Figure 5-29 shows the effect on algorithm path assignment of control radius variation. The longer the control radius, the greater the probability of assignment to the primary path with corresponding decrease in use of the first offset. The use of the second offset is approximately constant over the range of values assumed. While the trends are apparent, the sensitivity over the range of values considered is not great.

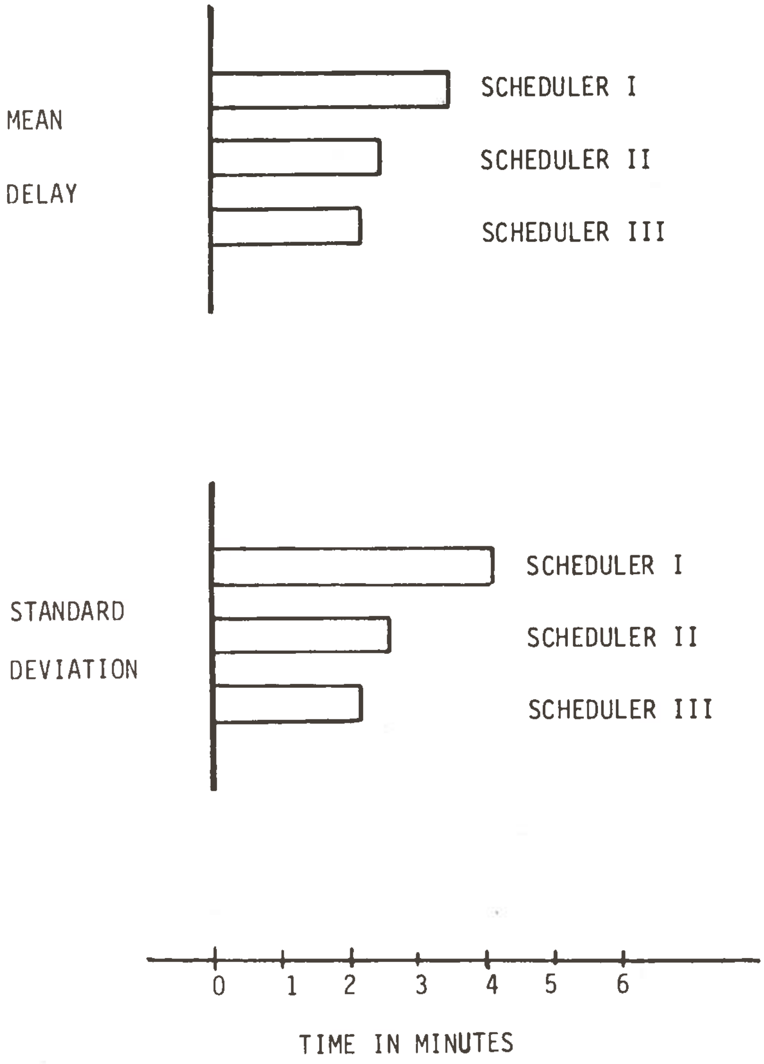


FIGURE 5-28.–DELAY SUMMARY

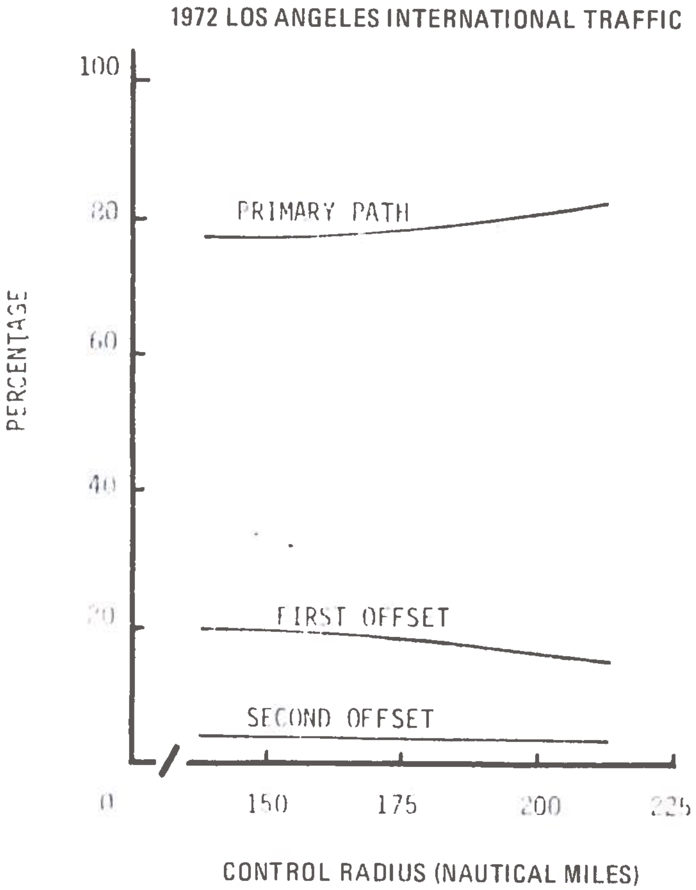


FIGURE 5-29.—PATH ASSIGNMENT SENSITIVITY TO CONTROL RADIUS VARIATION

Figure 5-30 shows the delay (for 50%, 90%, and 99.9% of arrival airplanes) in minutes plotted as a function of control radius. For all delay criteria, increased control radius results in reduced delay. As with the path assignment considerations, the sensitivity appears small. Other evaluation parameters (separation time and distance distributions) are not affected by changes in control radius. Experiment 4 data indicate the strategic algorithm control concept basic results will be valid over the range of control radii assumed.

5.2.5.2 Throughput Sensitivity (Experiment 5)

Experiment 5 considers the sensitivity of the control concept to changes in the throughput rate. Throughput is here defined as the number of arrivals processed per hour. For this experiment, the baseline Los Angeles terminal area geometry is assumed together with the (experiment 2) required navigation/surveillance accuracies and the current ATC separation rules. The arrival traffic input is assumed to have a normally distributed interoperation time as in experiment 3. The mean values of the interoperation time distribution used in the experiment were 90, 110, and 132 seconds.

Figure 5-31 shows the path assignment sensitivity to the throughput rate variation. As indicated, the percentage utilization of the primary path decreases as the interarrival time decreases (representing an increased demand level). The corresponding offset utilization increases. Path assignment results are not highly sensitive to the demand variation.

The delay distribution effects for various throughput assumptions are indicated in figure 5-32. The cumulative probability of delay is shown plotted for the 132-, 110-, and 90-second mean interarrival times. A 60-second case is also shown from experiment 3 for comparison. The 60-second interarrival time utilizes a runway threshold spacing constraint of 60 seconds (3 nautical miles is assumed for the other values). As indicated, the delay parameters are sensitive to throughput rate, especially as the mean interarrival time parameter approaches the runway spacing constraint; but the low airspace sensitivity results (fig. 5-31) indicate the adequacy of the strategic control concept with the airspace and safety separations assumed.

5.2.5.3 Future LAX Operations (Experiment 9)

Experiment 9 is an evaluation of the strategic control algorithm applied to future (1995) operations at the Los Angeles International Airport. The configuration assumption was that two sets of dual runways (four runways total) would be operating. The 1995 traffic input was used with departures divided approximately equally between the two runway pairs. Arrival traffic from the northeast and southeast (quadrants one and four) were scheduled onto runway pair 25. Traffic from the northwest and southwest (quadrants two and three) were scheduled onto runway pair 24. A 60-second arrival-arrival threshold scheduling constraint was applied. The high traffic demand navigation/control required performance levels (from experiment 2) were also applied.

Figure 5-33 shows the Los Angeles runway operations rates output for experiment 9. Operations per hour over the traffic sample interval are shown output for runways 25R, 25L, 24R, and 24L. The composite rate is slightly over 100 operations per hour.

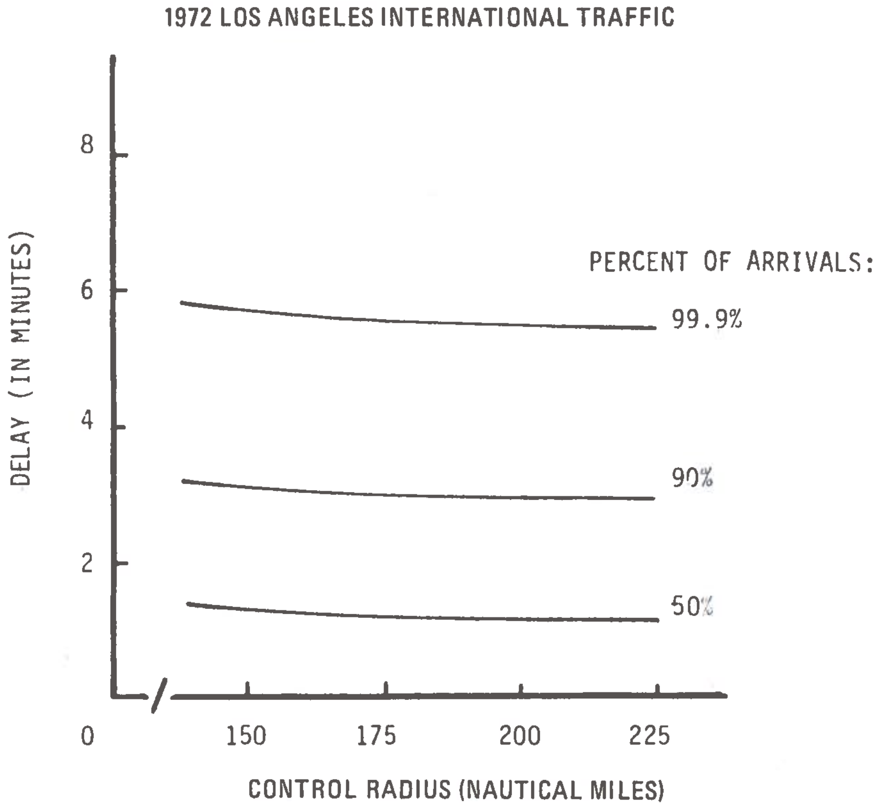


FIGURE 5-30.—DELAY SENSITIVITY TO CONTROL RADIUS VARIATION

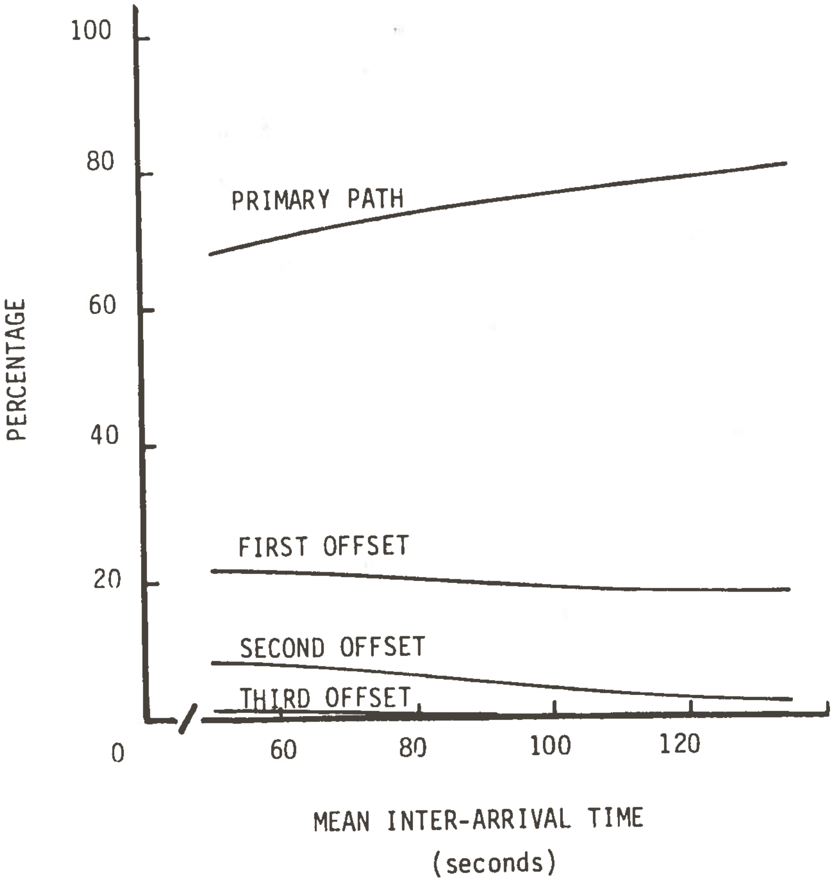


FIGURE 5-31.—PATH ASSIGNMENT SENSITIVITY TO THROUGHPUT RATE VARIATION

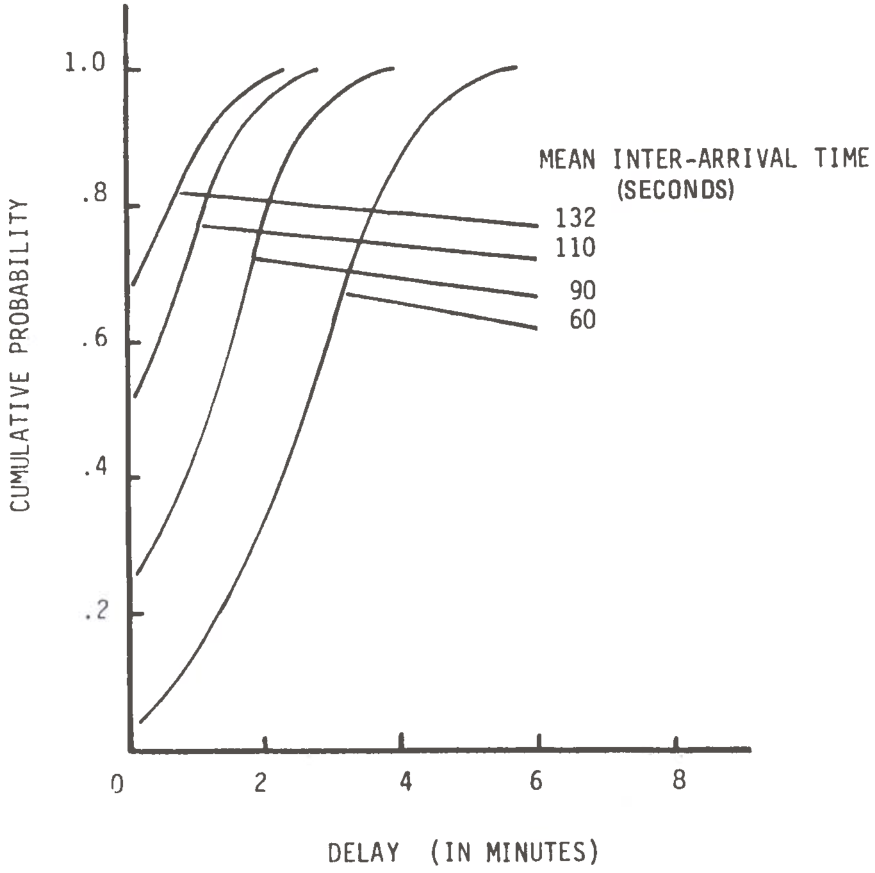


FIGURE 5-32.—DELAY SENSITIVITY TO THROUGHPUT RATE VARIATION

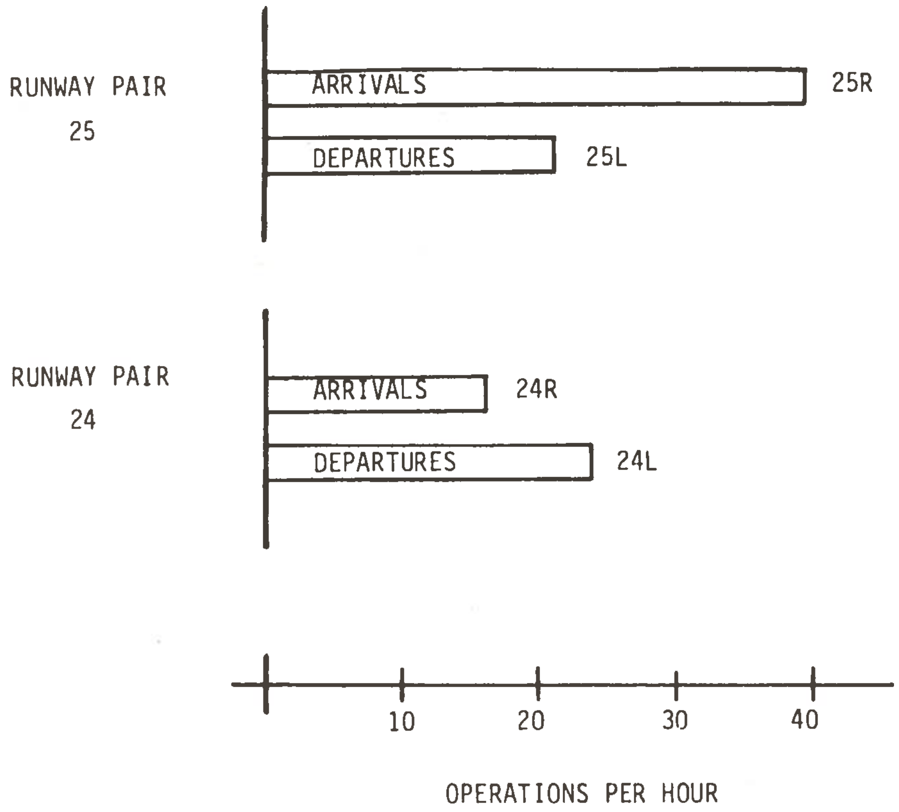


FIGURE 5-33.– LOS ANGELES INTERNATIONAL RUNWAY OPERATIONS RATES FOR 1995 DEMAND

Results of the Los Angeles evaluation indicate eight entry fixes and 20 parallel offsets are required to safely route and schedule the input arrival traffic. These figures agree with the experiment 1 arrivals-only data for the high demand level. The in-air and runway threshold separation statistics indicate safety levels better than the experiment 2 criteria: arrival-arrival pair spacing should be 40 seconds or greater 99% of the time. Experiment 9 results indicate the 40-second separation criteria was met 99.7% of the time for runway 25 arrival pairs and 100% of the time for runway 24.

Delay data indicate a reduction in arrival and departure delay for the LAX configuration. Arrival delay data are shown in figure 5-34. A substantial arrival delay reduction is indicated by utilizing the two dual-lane runways as compared to a single dual-lane runway or a single runway for the same traffic input (from experiments 6 and 8 as discussed in sec. 5.2.3). Departure delay distributions for the three runway assumptions are compared in figure 5-35. Again, delay reduction occurs in going from one dual-lane runway to a pair of dual-lane runways. The total delay results are summarized in figure 5-36. For the three runway configurations, the mean delay, the 90% delay level, and the 99.9% delay level are plotted. These delays are compared to the delay criteria discussed in section 5.2.4 (experiment 3). The Los Angeles strategic control algorithm meets all delay requirements.

5.2.5.4 General Aviation Impact (Experiment 10)

The tenth experiment evaluates the effects of unequipped (nonstrategic) airplanes being scheduled at a strategic control airport. For this experiment, the 1972 Los Angeles arrivals-only traffic set was used. Five unequipped airplanes were added (at random times) into the traffic set. The Los Angeles geometry and current ATC separation rules were assumed. The experiment 2 derived navigation/controls values were also used.

The algorithm assumptions in handling the unequipped airplanes for this experiment include:

1) The nonstrategic users are not routed over the fixed-track structure (but merged near the runway threshold).

2) The nonstrategic users notify the control system of intent to land 30 minutes before landing.

3) The nonstrategic users can make good a 60-second threshold window (i.e., they can achieve the scheduled threshold time with an error less than ±30 seconds).

Experiment 10 results indicate the capability to incorporate a moderate number of unequipped airplanes into the strategic arrival stream (subject to the above assumptions) for the 1972 Los Angeles traffic demand. Results indicate no significant safety degradation. Probability of exceeding a 2-nautical-mile in-air constraint (the safety criteria input) was 1.3% with unequipped airplanes versus the 1% value determined in experiment 2 for the same traffic mix less the unequipped airplanes. The major impact of the introduction of unequipped airplanes into the strategic system is the increased arrival delay level.

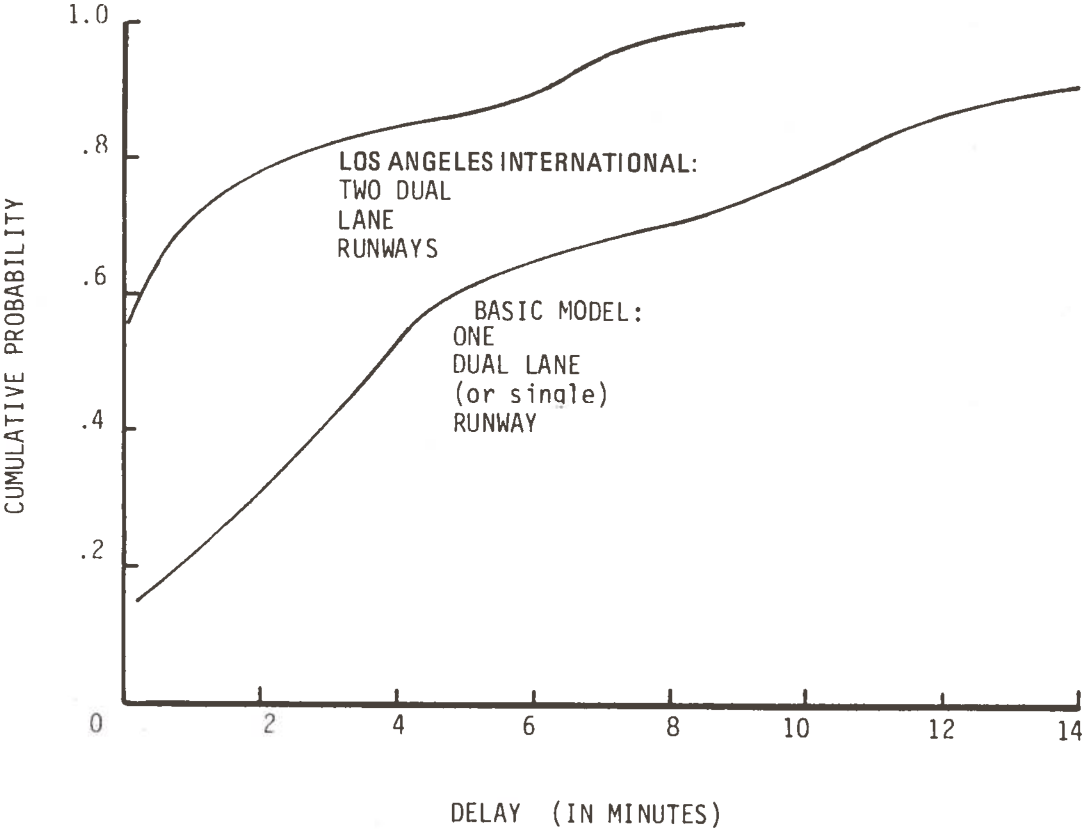


FIGURE 5-34.—ARRIVAL DELAY DISTRIBUTIONS FOR VARIOUS RUNWAY ASSUMPTIONS

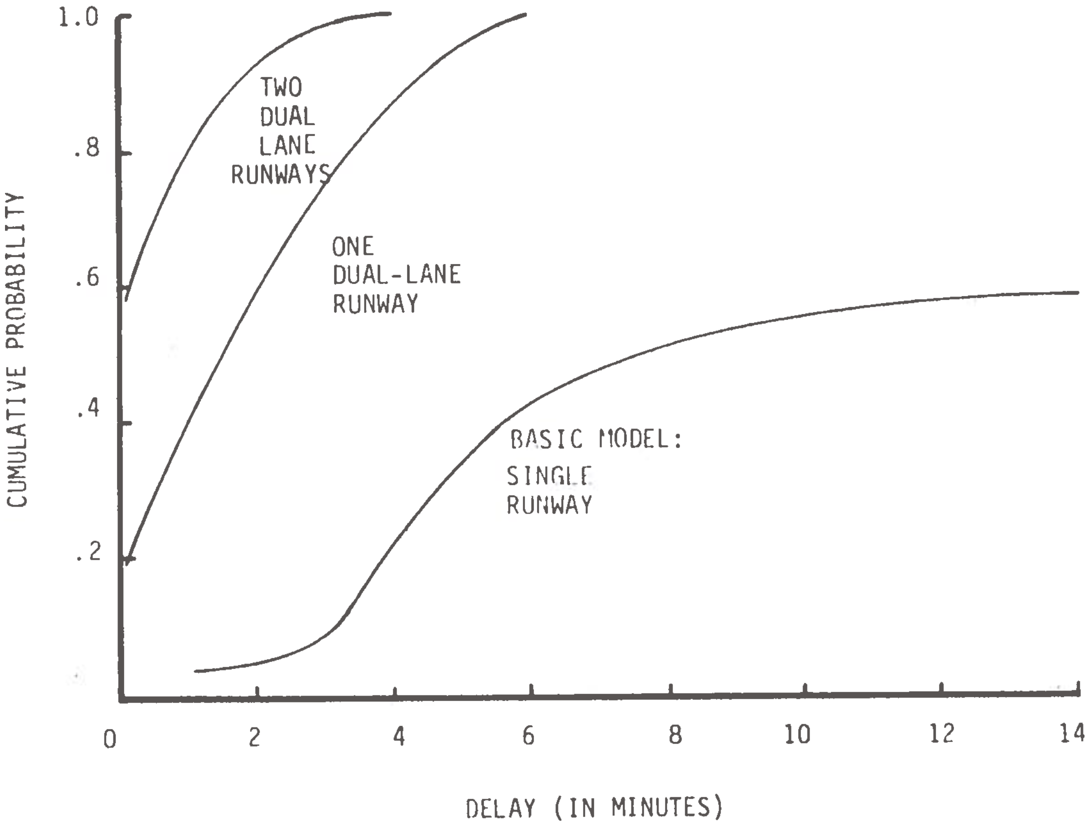


FIGURE 5-35.—DEPARTURE DELAY DISTRIBUTIONS FOR VARIOUS RUNWAY ASSUMPTIONS

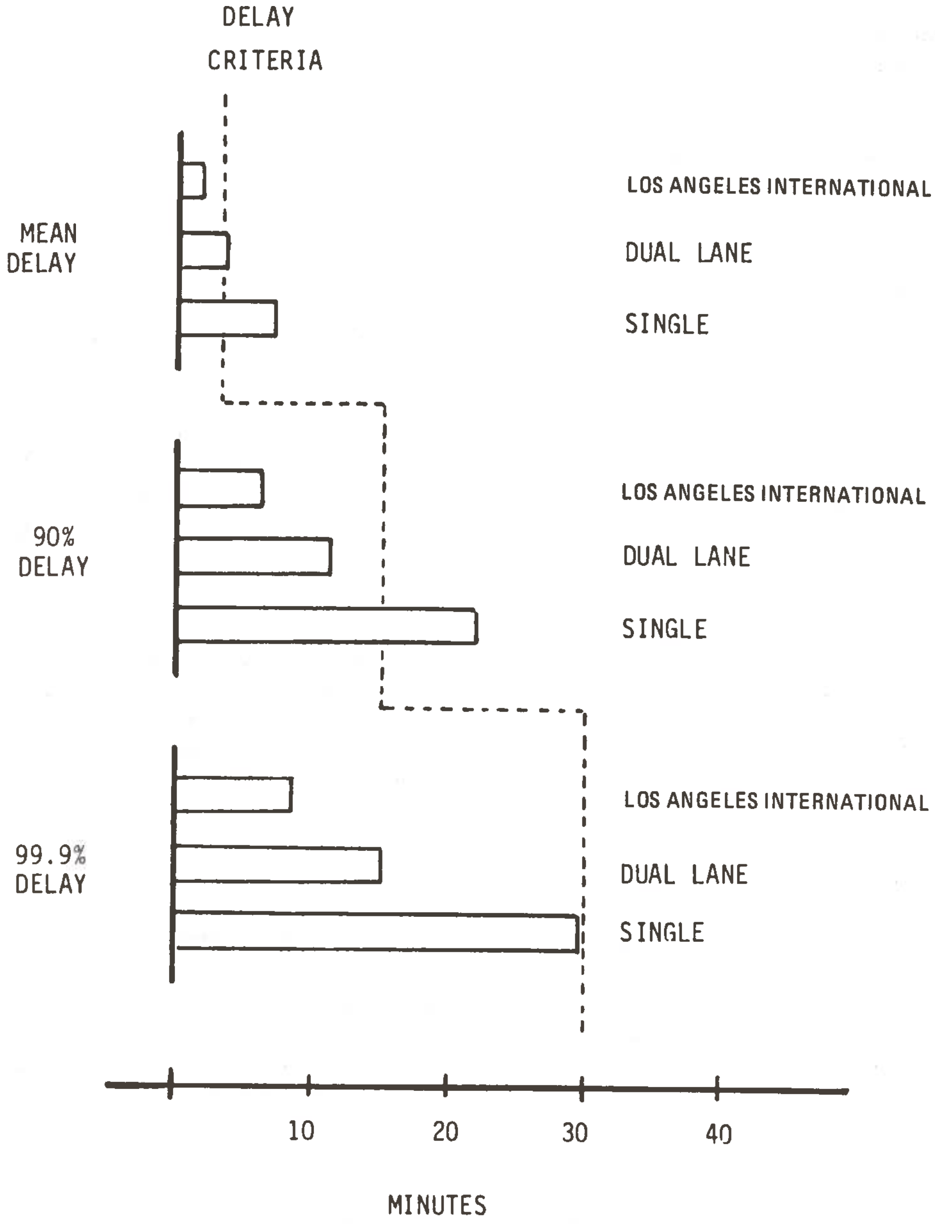


FIGURE 5-36.–DELAY SUMMARY FOR VARIOUS RUNWAY ASSUMPTIONS

Figure 5-37 shows the cumulative probability of delay for the 1972 traffic with and without the unequipped airplanes. The mean delay increased from 1.2 minutes to 2.3 minutes with the additional airplanes. This value is still well within the delay criteria value (3 minutes average). The impact of unequipped airplanes on systems with higher demand levels might be more significant, but at the 1972 traffic level the effect appears minimal.

For higher demand levels, alternative techniques to merge the unequipped airplanes with strategically controlled airplanes might be necessary.

5.3 ERROR MODEL

This section contains a technical discussion of the route-time profile error analysis used in the strategic control algorithm evaluation model. The error model simulates the flight of each arriving airplane in the strategic control area from entry fix to threshold based on the specified navigation and guidance accuracies and airplane performance capabilities consistent with the prevailing meteorological conditions. The data obtained from the realized route-time profiles are used by the evaluation model to generate statistical information required to establish measures of strategic control system effectiveness under various operating assumptions.

The model employs the concept of groundspeed control to compensate for the arrival time errors at the various waypoints along flight trajectory arising from the control errors (inability to maintain assigned velocity-distance profile). Revised velocity-time profiles are computed taking into account the position (navigation) errors and control errors consistent with the airplane performance-imposed speed constraints (corrected for variations in temperature and wind conditions).

5.3.1 Strategic Control Configuration Assumptions

A plan view of a generally applicable strategic control airspace geometry is illustrated in figure 5-38. The flight trajectories associated with different entry points and the notation used to identify the control fixes are shown in the figure. Although the geometrical layout of the fixes depends on the particular airport considered, all tracks are constructed in sequential order (the entry fix, initial fix, turn fix, merge fix, final approach fix, outer marker, and threshold). A path segment between two fixes contains either a straight-line section or a straight-line section and a circular arc (turn circle arc). A segment may contain one or more intermediate waypoints in addition to the fixes on either end. The total number of waypoints and the identifying number of the fixes are specified.

The strategic control algorithm takes the traffic input and assigns to each airplane a conflict-free route-time profile. The route-time profile of each airplane contains a series of waypoints. To each waypoint correspond: 1) altitude, 2) groundspeed, 3) arrival time, 4) distance to next waypoint, 5) control fix identifier, and 6) speed constraints (maximum and minimum groundspeeds). These and the flightpath angles (subtended by the straight-line section of the flight segment in the xy plane between two successive control fixes) form the input to the ERROR model. The flightpath angles are computed in the GEOMETRY subroutine. The speed constraints at each waypoint altitude are computed in the model from the speed-altitude envelope, which is an output of the AERO subroutine.

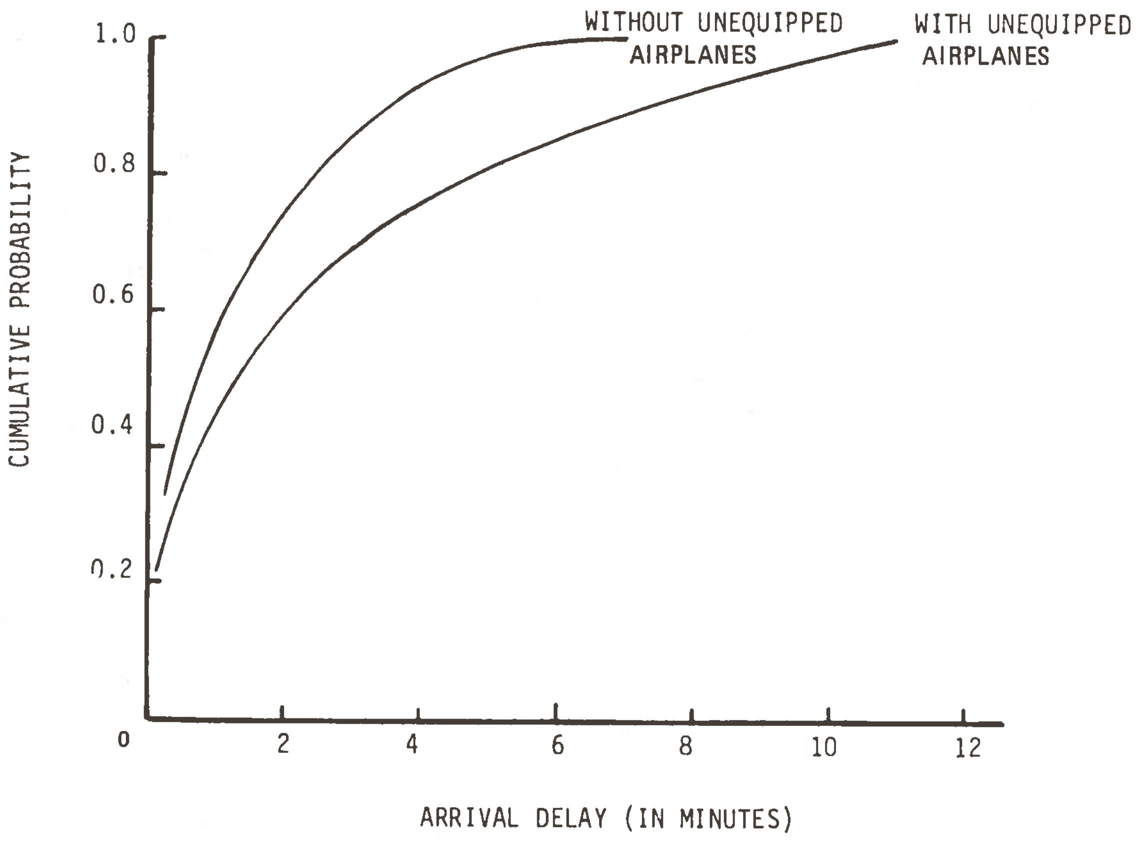


FIGURE 5-37.—IMPACT OF UNEQUIPPED AIRPLANES ON DELAY

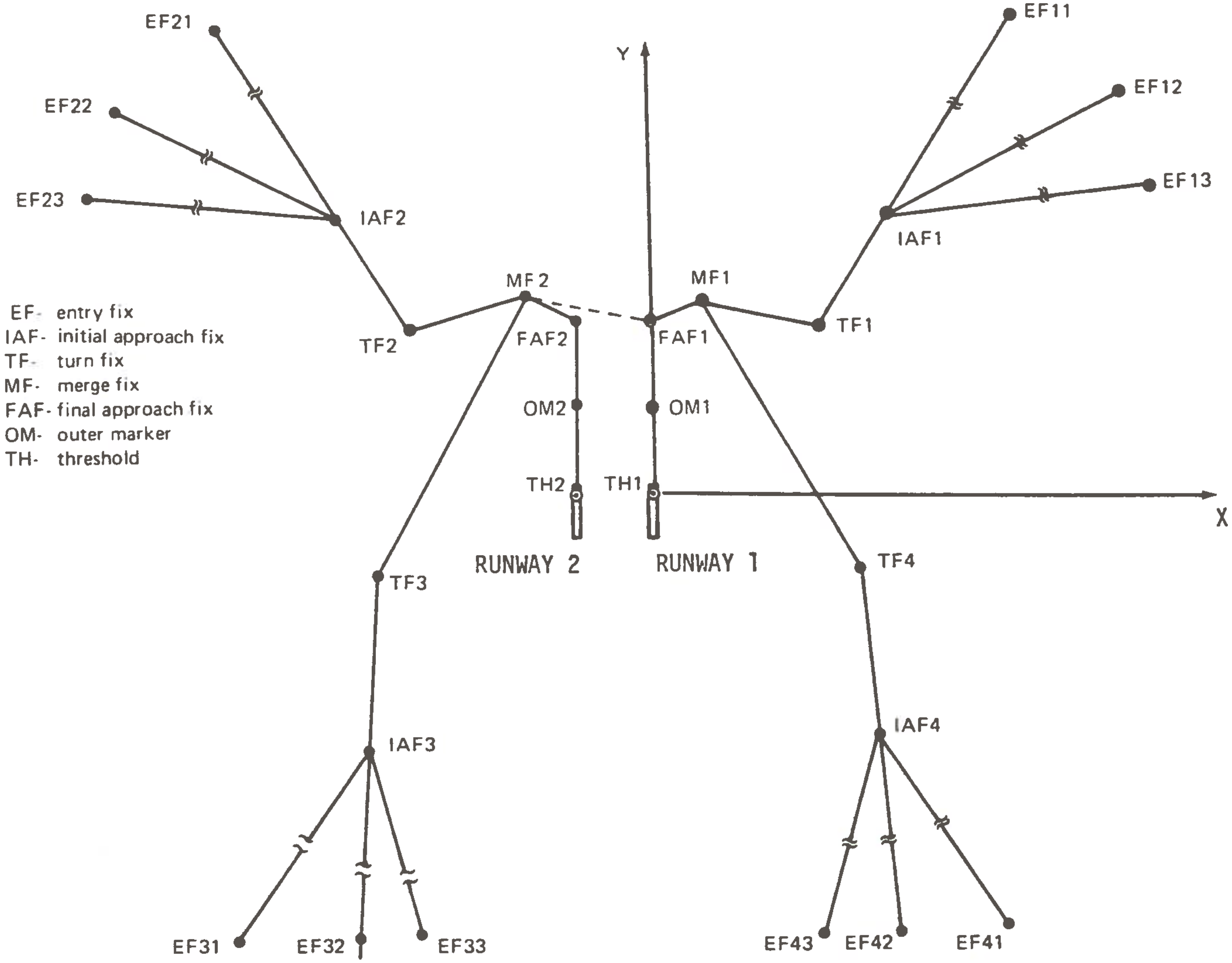


FIGURE 5-38.—STRATEGIC CONTROL GEOMETRY

5.3.2 Error Sources

The model considers four major sources of error. These are:

- Navigation errors
- Control errors
- Variations in forecast winds
- Variations in forecast temperature

5.3.2.1 Position Errors at Control Points

Each airplane arriving at an entry fix is assumed to have initial position errors in the along-track and cross-track directions. These errors are the result of accumulated en route navigation errors. The model considers the contribution of along-track errors in computing the arrival time errors at the control points. Figure 5-39 schematically illustrates the actual position of the airplane at the entry fix. The coordinate system used is also shown. Point A represents the entry fix and P the actual position at the assigned arrival time at A. Vector $\overline{AQ}$ is the straight section of the segment (in horizontal plane) between the entry fix and the initial approach fix. $\overline{AP}$ is the position error vector. The random variable ρ representing the magnitude of the radius vector $\overline{AP}$ is assumed to be distributed normally about A. The angle ϕ subtended by $\overline{AP}$ and the positive y-axis (positive when measured clockwise from positive y-axis) is assumed to be distributed uniformly between 0 and 2π radians. The modeled navigation errors are assumed to remain unchanged (both in magnitude and direction) throughout the flight in the strategic control area. The position error vector at any point along a flight trajectory (or for any one flight) will have the same magnitude and direction.

Denoting the angle subtended by the straight line AQ with positive y-axis by θ_1, the angle ψ_1 between the vectors $\overline{AP}$ and $\overline{AQ}$ (see fig. 5-39) can be expressed as

$$\psi_1 = \phi - \theta_1$$

The along-track error component ξ_1 at the entry fix is given by

$$\xi_1 = \cos (\phi - \theta_1)$$

Similarly the along-track error at any fix i can be obtained as

$$\xi_i = \cos (\phi - \theta_i) \quad i = 1, 2, \ldots . 7$$

where θ_i is the angle made by the straight-line section of the flightpath between waypoints i and i + 1 with the positive y-axis. Altitude navigation errors are not considered in the model.

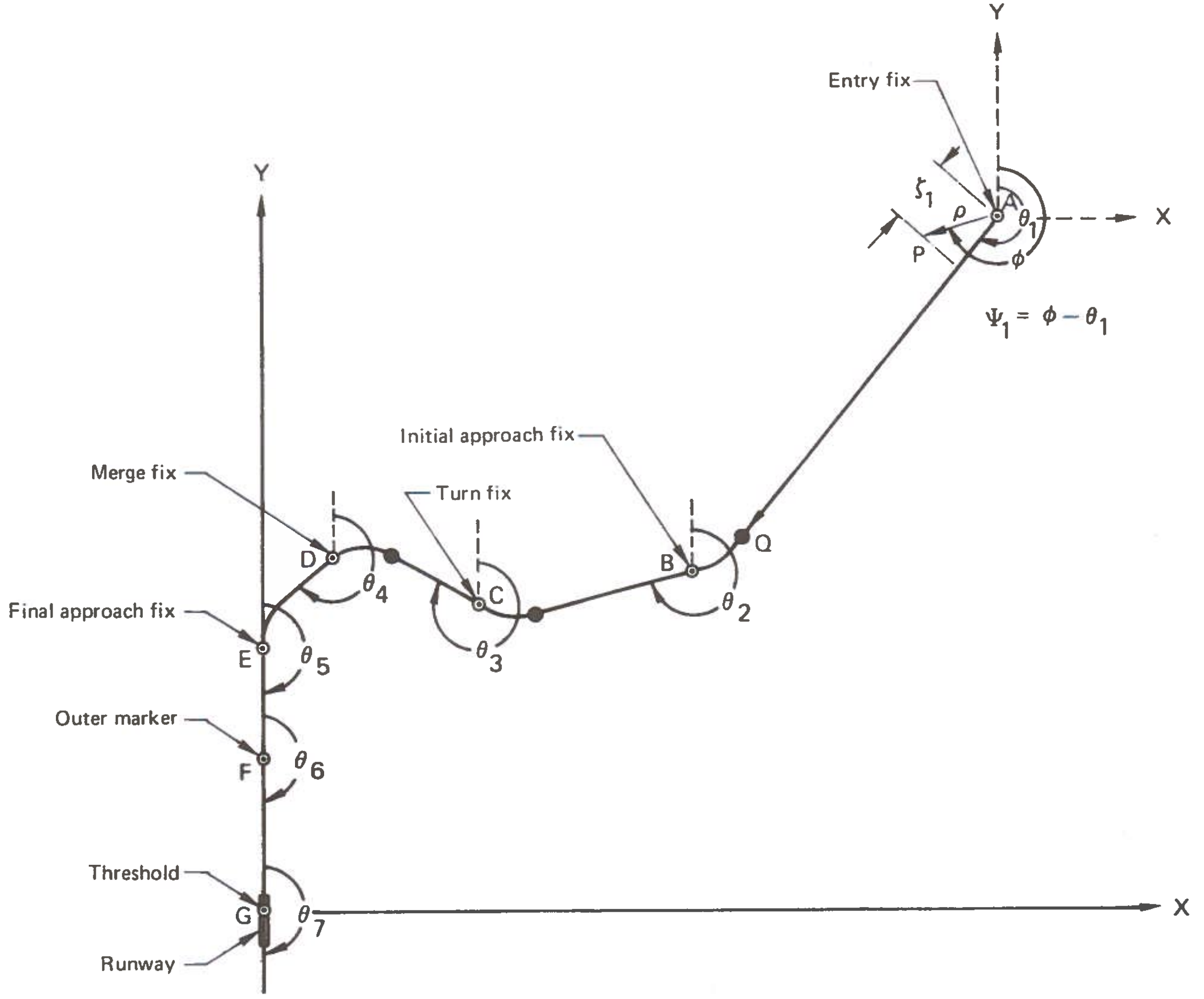


FIGURE 5-39.– TYPICAL FLIGHTPATH SHOWING POSITION ERROR

5.3.2.2 Control Errors

The deviations in arrival time from the assigned arrival time at any waypoint occur due to imprecision in controlling the airplane on the assigned speed-distance profile. The control errors in time units at any waypoint i are represented by the random variable τ_i. The modeling of these errors is done by assuming the τ_is to be independent, with identical distributions at all waypoints.

5.3.2.3 Wind and Temperature Variation Effects

The ability of an airplane to control speed while maintaining desired altitude depends on the thrust and drag characteristics (braking and control capabilities of aerodynamic surfaces). The margin of available speed control under standard day and no-wind condition will be constrained by configuration-imposed limitations. These limitations determine the speed control margin at any given altitude H by maximum and minimum permissible speeds V_{max} (H) and V_{min} (H), respectively. Under nonstandard day conditions and in the presence of wind, the speed control margins will have to be modified to take into account uncertainties in wind and temperature.

5.3.3 Control Algorithm

The route-time profile algorithm assigns to each airplane a route and a schedule containing the desired arrival times at the successive waypoints along the route. Because of the inability to control the airplane on the velocity-time schedule, deviations in arrival time occur at each waypoint. The control algorithm used in the model is based on the concept of groundspeed correction to match the arrival time at each of the waypoints with the scheduled arrival times of the waypoints. The groundspeed correction scheme for any two successive waypoints is described below.

Let V_a, T_a and V_b, T_b represent the assigned velocity and time of arrival at the waypoints i and i + 1, respectively, and τ_a represent the arrival time error due to control. The actual time T_{ra} of arrival at the ith waypoint is

$$T_{ra} = T_a + \tau_a$$

Assuming constant acceleration flight between any two successive waypoints, the assigned average velocity is given by

$$V_{avg} = \frac{V_a + V_b}{2}$$

The required average velocity is

$$V_{avg_R} = \frac{V_{avg}\,(T_b - T_a)}{T_b - T_{ra}}$$

The required velocity at the (i + 1) waypoint to make good the assigned time is

$$V_{b_R} = 2\,V_{avg_R} - V_{ra}$$

where V_{ra} is the actual velocity at waypoint i.

The required flight acceleration between the waypoints is

$$A_R = \frac{V_{b_R} - V_{ra}}{T_b - T_{ra}}$$

If this computed velocity V_{b_R} is within the speed constraints of the airplane at the assigned altitude of the (i + 1) waypoint, the airplane is assigned V_{b_R} (the revised velocity V_{rb} at the waypoint i + 1). If, however, V_{b_R} is outside the speed constraints, the airplane is assigned one of the boundary values as expressed mathematically

1) $V_{mnb} \leqslant V_{b_R} \leqslant V_{mxb}$, $\quad V_{rb} = V_{b_R}$

2) $V_{b_R} > V_{mxb}$, $\quad V_{rb} = V_{mxb}$

3) $V_{b_R} < V_{mnb}$, $\quad V_{rb} = V_{mnb}$

If V_{b_R} satisfies either of the inequalities 2 or 3 above, the revised arrival time and acceleration are calculated from the time required to fly the segment length between i and (i + 1) waypoints as

$$V_{avg_R} = \frac{V_{ra} + V_{rb}}{2}$$

$$\Delta T = \frac{d_{ab}}{V_{avg_R}}$$

$$T_{rb} = T_{ra} + \Delta T$$

$$A = \frac{V_{rb} - V_{ra}}{\Delta T}$$

Where d_{ab} is the segment length between the waypoints i and i + 1.

5.3.4 Revised Arrival Times at Control Fixes

Revised arrival times at the control fixes are computed based on the along-track error at each fix point.

Consider a waypoint that is also a control fix point. Denote the waypoint number as j and fix number it represents as k.

Let the along-track error at the k^{th} fix be ξ_k and the revised velocity at the j^{th} waypoint (or fix K) be V_{rj}. The arrival time error ΔT_k at k^{th} fix is the time taken to fly the distance ξ_k. If ξ_k is negative the arrival time at the fix will be later than the revised arrival time T_{rj} at the j^{th} waypoint and if ξ_k is positive the arrival time will be earlier than T_{rj}.

For $\xi_k > 0$, ΔT_k is obtained by solving the quadratic equation

$$V_{rj}(\Delta T_k) - \frac{1}{2}A_{j-1}(\Delta T_k{}^2) = \xi_k$$

where A_{j-1} is the acceleration between the waypoints j - 1 and j and is assumed to be constant. Thus,

$$\Delta T_k = \frac{-V_{rj} \pm \sqrt{V_{rj}{}^2 + 2\,\xi_k\,A_{j-1}}}{A_{j-1}}$$

Only the solution with a positive sign behind the radical is valid.

If $A_{j-1} = 0$, ΔT_k is computed as

$$\Delta T_k = \frac{\xi_k}{V_{rj}}$$

The revised arrival time at fix k, thus, is

$$T_{frk} = T_{rk} - \Delta T_k$$

Similarly, if ξ_k is negative ΔT_k is obtained as

$$T_k = \frac{-V_{rj} + \sqrt{V_{rj}{}^2 + 2|\xi_k|A_j}}{A_j}$$

where A_j is the acceleration between the waypoints j and j + 1.

If $A_j = 0$, ΔT_k is computed as

$$\Delta T_k = \frac{|\xi_k|}{V_{rj}}$$

The revised T_{frk} in this case is given by

$$T_{frk} = T_{rk} + \Delta T_k$$

For the last fix, if ξ_i is negative ΔT_{rk} is computed assuming constant revised velocity at the last fix.

5.4 EVALUATION MODEL DATA GENERATION

The generation of the geometry, aeroperformance, and traffic data input to the model is discussed in the following paragraphs.

5.4.1 Geometry Data

The geometry data for the approach tracks into Los Angeles International are constrained in the x-y horizontal plane by the ground terrain in the area of the airport and by the availability of nonrestricted airspace surrounding the terminal area. The z-coordinates or the altitude of the approach tracks are limited by safe ground obstacle clearance and adherence to the descent track slopes. Minimum altitude boundaries are also set for avoidance of smaller community airport traffic. The outermost radius of the strategic control points or entry fixes is specified by the aeroperformance capabilities of today's commercial transports in meeting the requirements of a 2° or 3° glide slope path. Section 6.3 contains a specific discussion on how the intermediate control fixes such as the initial approach fix, turn fix, etc., are positioned along the descent track and how other detailed constraints on the approach paths as set down by Federal Aviation Administration rulings affect the geometry layout. The coordinates take the form of (x, y, z) with the x and y values measured in nautical miles and the z value measured in thousands of feet.

5.4.2 Aeroperformance Data

The aeroperformance data are based on an analysis of the velocity profiles described in section 3.1.5 for each of the airplane types used as traffic in the Los Angeles International study case. The data used for this section consist of the minimum and maximum landing gross weights of each airplane type and data points, consisting of speeds and altitudes, to define the velocity envelopes for each of those particular weights.

More points are taken from areas of high nonlinearity than from the linear portions of the velocity plots. The data consist of a number of altitudes with velocity values corresponding to the minimum and maximum speeds possible at that altitude for both the minimum and maximum landing weights allowable for the airplanes. For each altitude there are four velocity values. Also supplied by the aeroperformance data are the maximum cabin pressure differentials allowed for each airplane as required by the airframe structure.

The airplanes used to simulate the current traffic flow through Los Angeles International are the 707, 727, 737, 747, DC-10, and 720B. This selection assumes that the CV-880 and DC-8 have capabilities similar to the 707, the DC-9 has similar performance to the 737, and the L-1011 to the DC-10.

The velocity profile graphs used to generate the aeroperformance data are shown in figures 5-40 through 5-45.

5.4.3 Discrete Traffic Data

The discrete traffic data generated for the Los Angeles model consist of specific airplane-by-airplane arrival and departure data. The arrival data contain the time of arrival at the entry fix, the entry fix number, the type of airplane, the speed and altitude of the airplane upon entering the entry fix, and the arrival gross weight. The departure data contain the runway departure time and the airplane type and departure gross weight.

The entry fix arrival times were obtained by computing, from an analysis of a computed descent history (table 5-5), the time each airplane required to make the descent from the entry fix to the runway threshold. These values were then subtracted from the runway threshold time of arrival obtained from a schedule list for Los Angeles International Airport (LAX). The earliest arrival at the entry fix is given the arrival time of zero and all subsequent arrivals are based on this zero point. The arrival times are in seconds. The data base used was 1700 to 1859 hours for LAX 1972 scheduled traffic.

TABLE 5-5.—COMPUTED DESCENT HISTORY

Distance	Time	Altitude	Speed
		37,000 feet	0.80 Mach (460 knots true airspeed)
13 nautical miles	0.0273 hour		
		33,800 feet	0.80 Mach (490 knots true airspeed) (280 knots calibrated airspeed)
95 nautical miles	0.2328 hour		
		10,000 feet	280 KCAS (325 knots true airspeed)
15 nautical miles	0.0487 hour		
		10,000 feet	250 KCAS (290 (knots true airspeed)
17 nautical miles	0.0607 hour		
		5,000 feet	250 KCAS (269 knots true airspeed)
12 nautical miles	0.0533 hour		
		1,500 feet	175 KCAS (179 knots true airspeed)
5 nautical miles	0.0300 hour		
		0	160 KCAS (160 knots true airspeed)

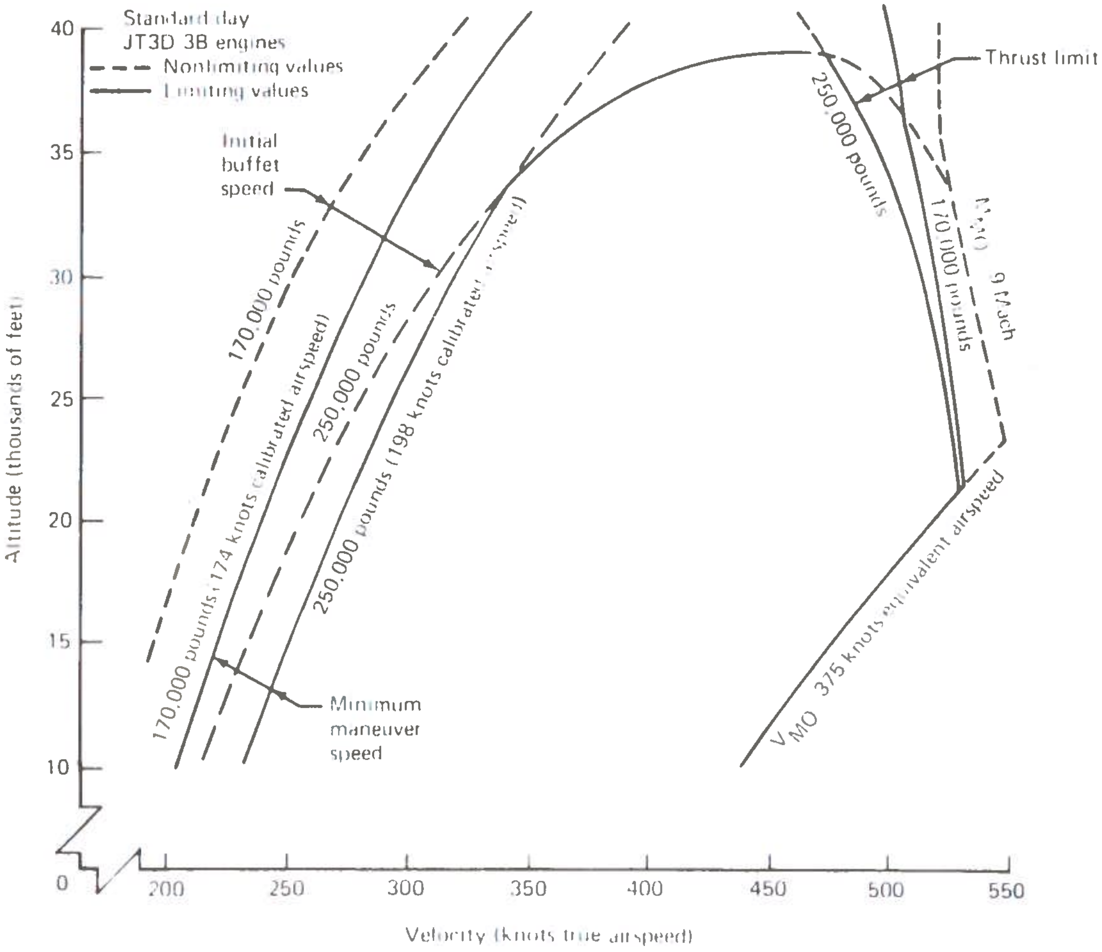


FIGURE 5-40.—707-320B ADV., 320C, VELOCITY PROFILE

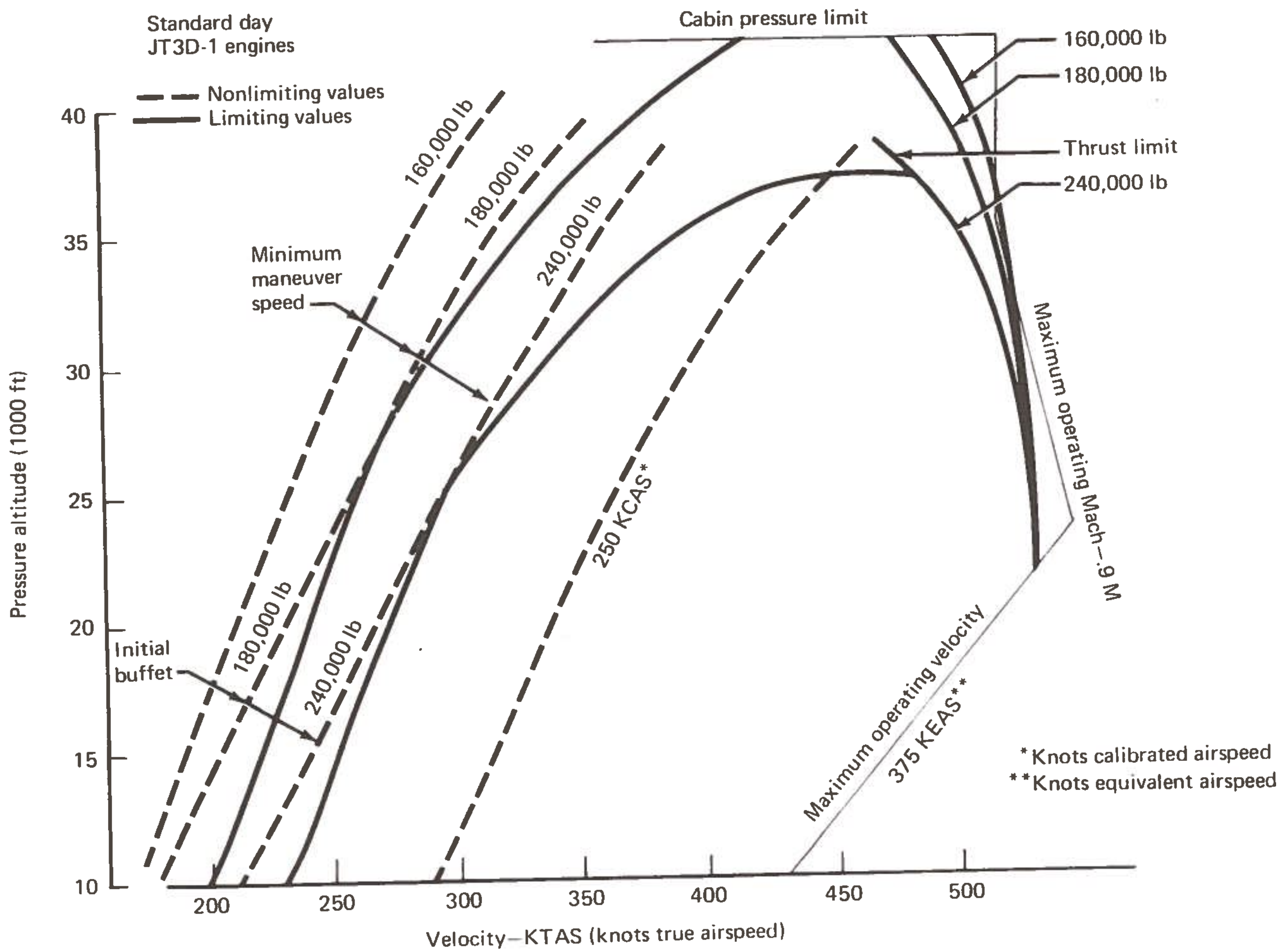


FIGURE 5-41.—720B VELOCITY PROFILE

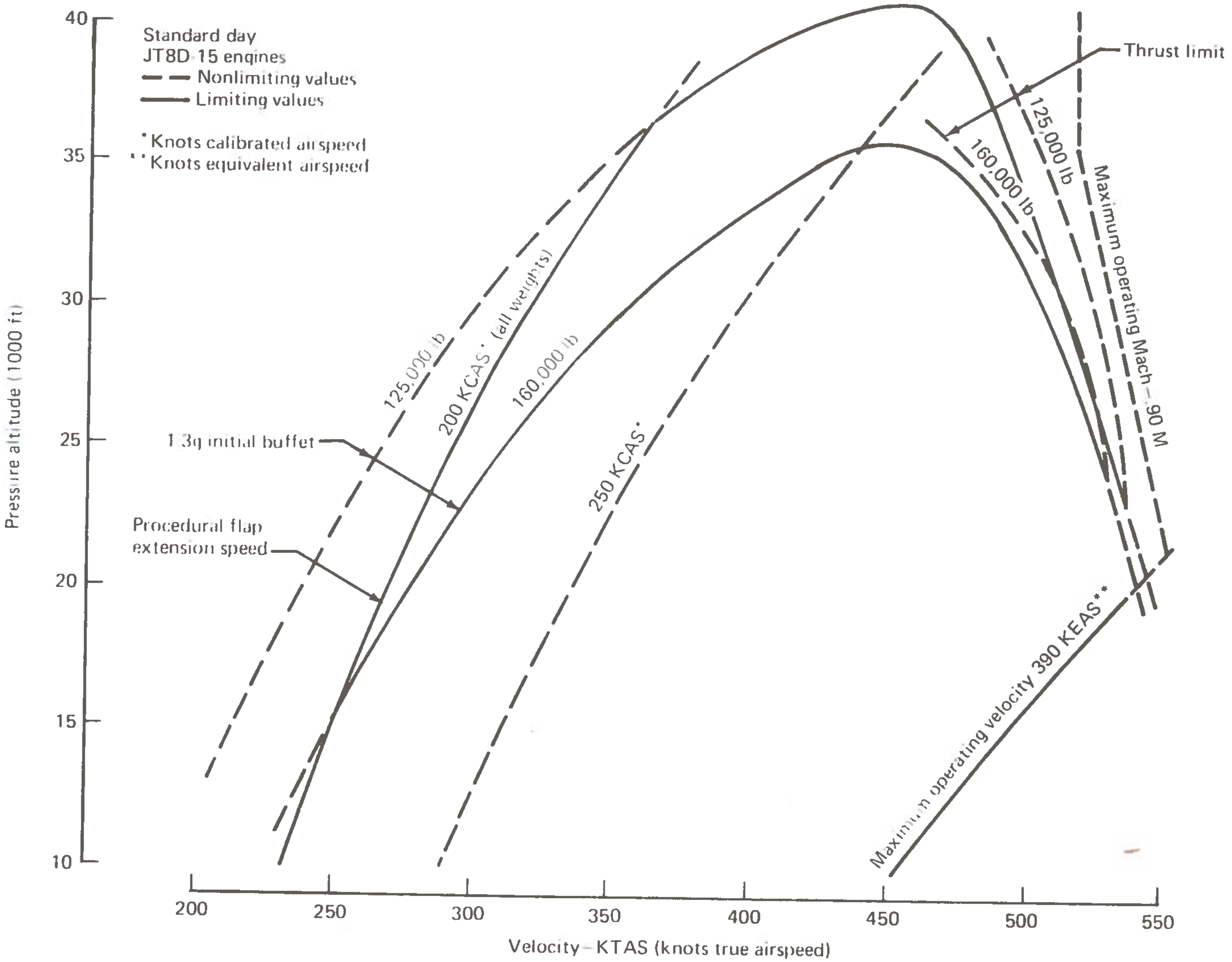


FIGURE 5-42.—727-200 VELOCITY PROFILE

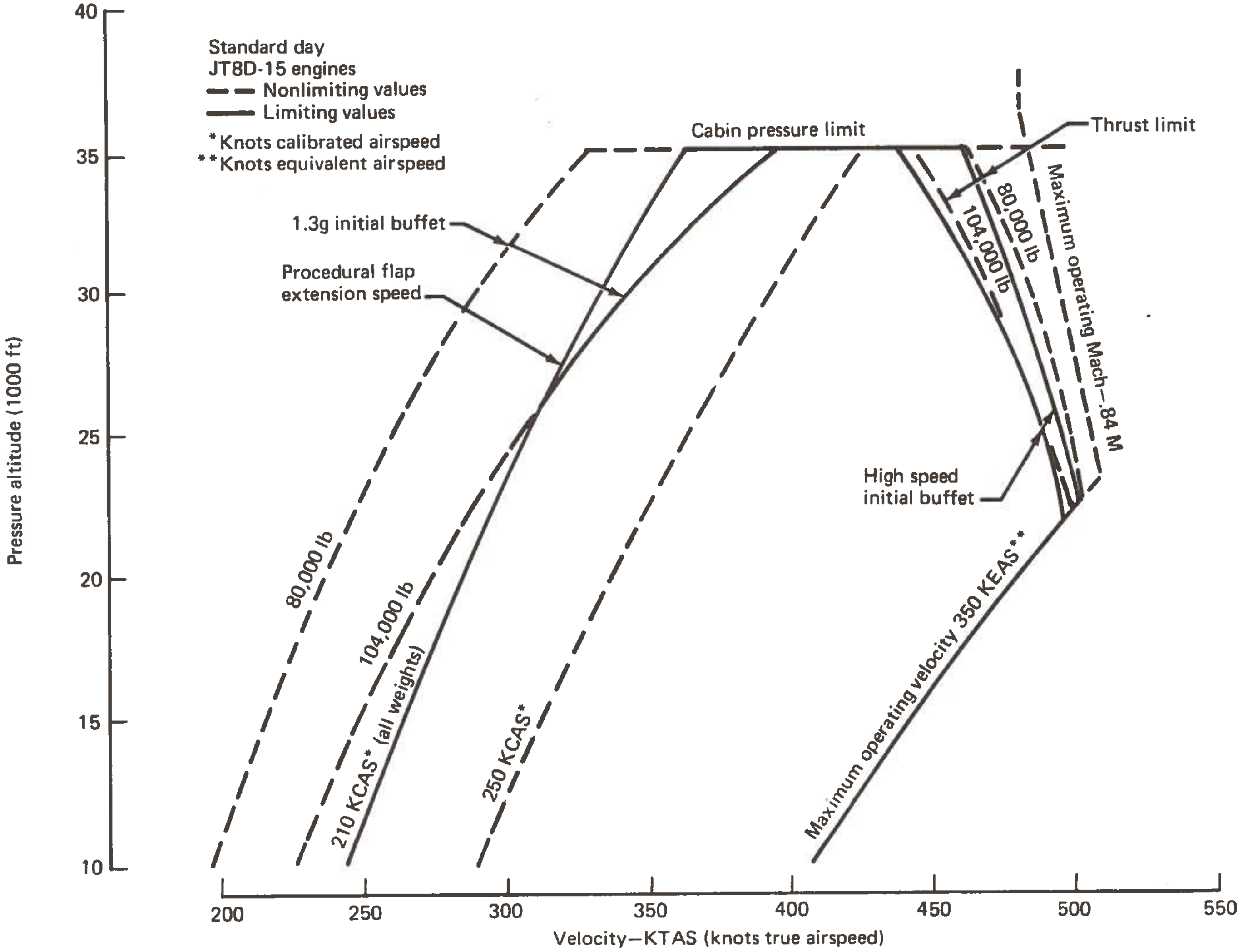


FIGURE 5-43.—737-200 VELOCITY PROFILE

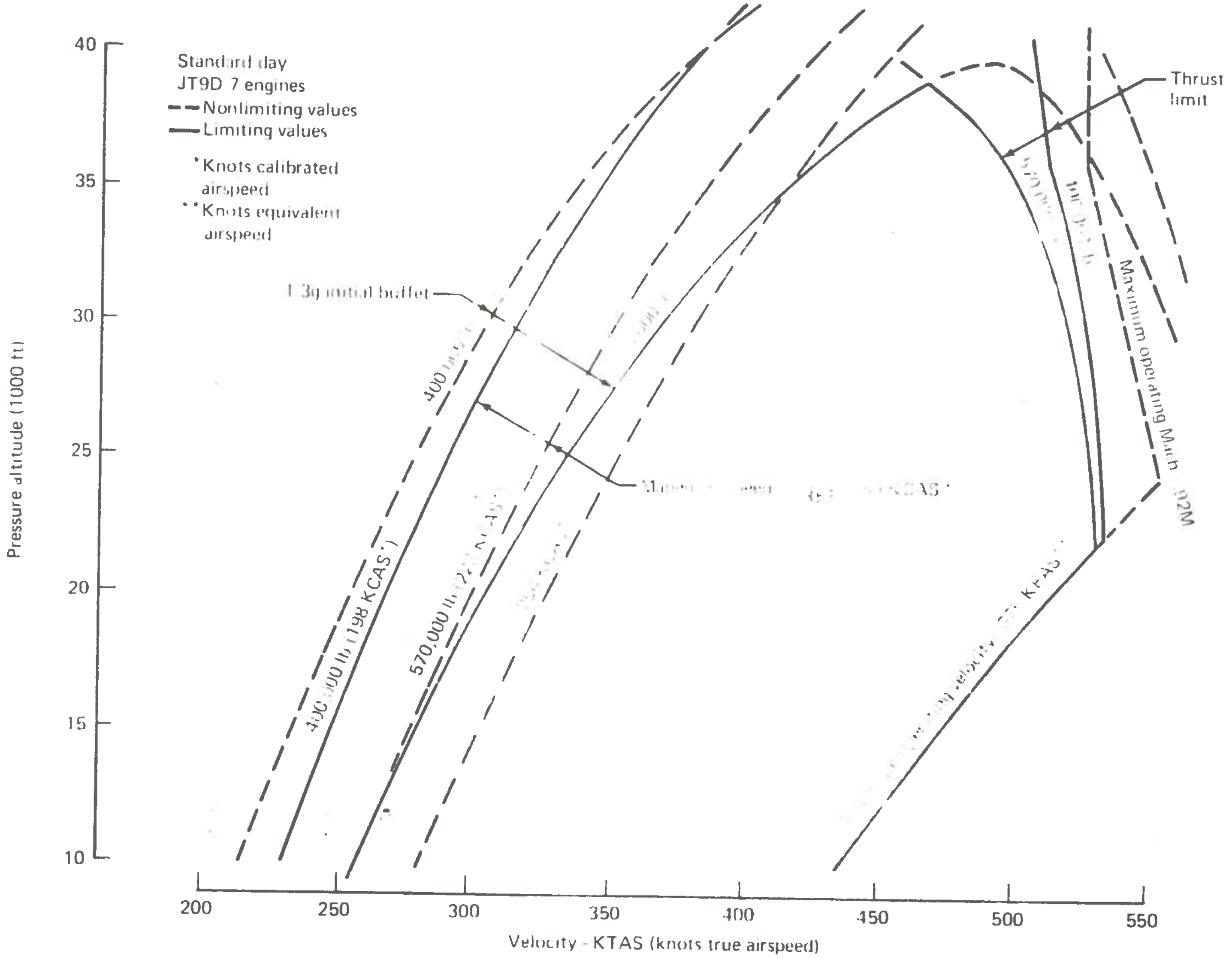


FIGURE 5-44.—747-100, -200B VELOCITY PROFILE

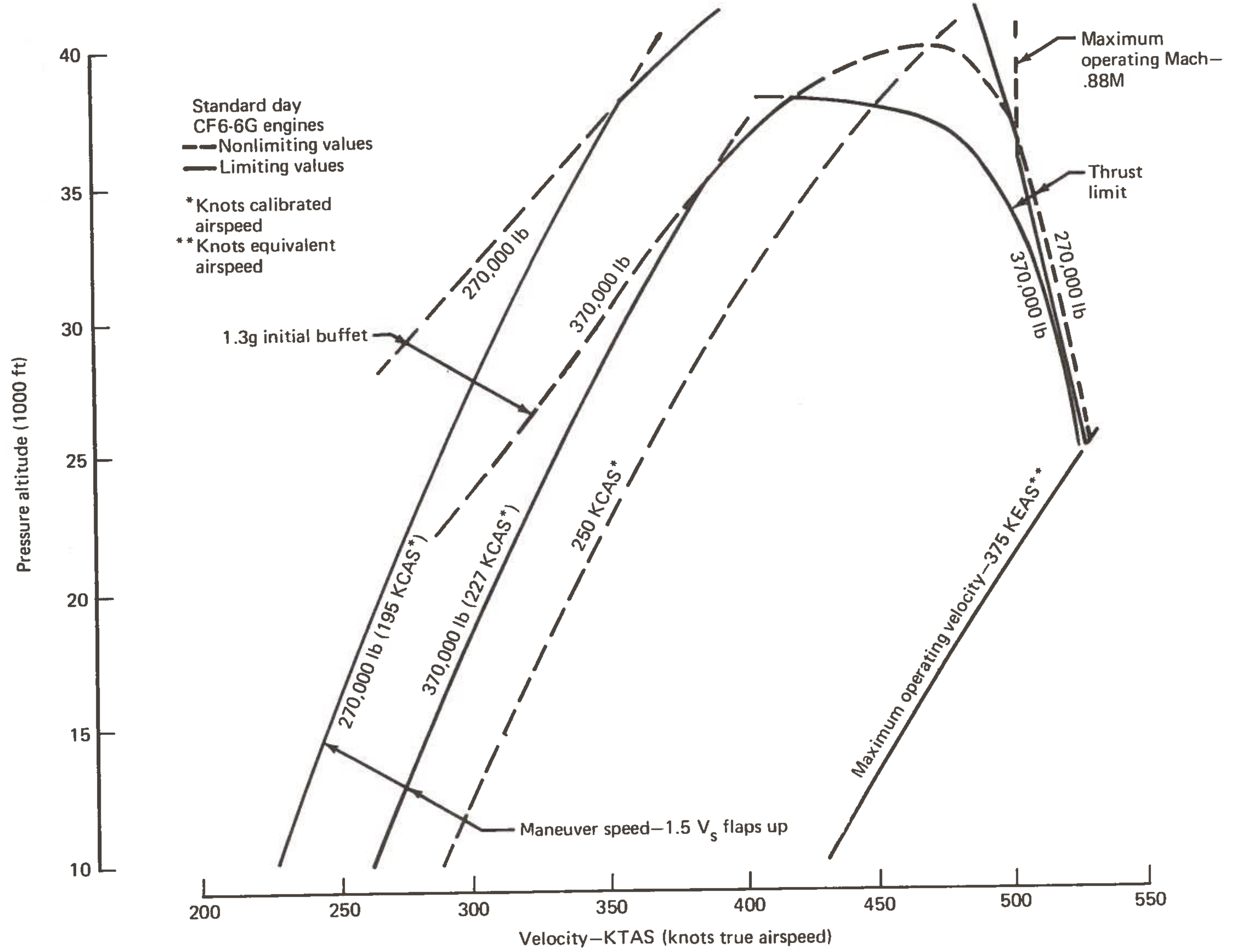


FIGURE 5-45.—DC-10-10 VELOCITY PROFILE

The airplane speed data are obtained from the airplane velocity profiles. Using these profiles to suggest a range for the airspeeds, the final values are defined by picking the speed that would prove to be the optimum in terms of both flying time and fuel consumption for the altitude being flown by the airplane.

The altitudes are determined by air traffic control restrictions on east-west and north-south flight level designations and by the length of the trip being flown by the airplanes. The altitudes are constrained by the altitude capability of each airplane.

The airplane gross weight at arrival is calculated using a 50% load factor on top of the operating empty weight of the airplane with fuel weight allotment for flying the descent track with the capability of a missed approach and flight to a 200-nautical mile alternate.

The entry fix designation for each flight is a correlation between the flights point of origin and the entry fix geometry layout for LAX.

The departure times are the runway departure times as shown by the 1972 LAX schedule for 1700-1850. The departures leaving at 1700 are referenced zero and subsequent departures are listed on this time line, the units being seconds.

Also created for the simulation model is a data set representing traffic flow at LAX in 1995. The traffic level was obtained by scaling up the present day LAX schedule by a factor of 1.86 and spreading the added traffic throughout the same 2-hour time period used earlier. Though the traffic was spread through the 2-hour period, the same maxima and minima found in the 1972 schedule were kept for these data as well. The breakdown of airplane type used (categorized as short range, medium range, and long range) for both the 1972 schedule and the 1995 schedule is shown in table 5-6. The fleet used in the 1995 traffic set included the 727, 737, 747, and the DC-10.

TABLE 5-6.—AIRPLANE RANGE MIX

Airplane type	Range (nautical miles)	Percentages of total traffic Los Angeles International	
		1972	1995
Long range	1800	35.2	14.2
Medium range	400 – 1800	41.8	57.2
Short range	400	23.0	28.6

5.4.4 Distributed Traffic Data

There are two types of distribution data used for the simulation model. One assumes a normal distribution for airplane arrivals and departures at the entry fix with a mean interoperation time of 132 seconds for arrivals and 147 seconds for departures and a standard deviation of 113 seconds; the other distribution data assume an Erlang distribution for arrivals and departures with an order parameter of one and interoperation time for arrivals of 132 seconds, departures 147 seconds. Both data sets assume uniform distributions for takeoff weights, arrival altitude, and speed. The Erlang data set assumes a normal arrival weight distribution, while the normal data set assumes a uniform distribution for arrival weight.

Figure 5-46 indicates how well the Erlang distribution approximates the discrete airplane arrival data. The family of Erlang distributions has the form:

$$P_n(t) = C_n t^n e^{-\alpha t}, \quad n = 1, 2, \ldots. ; \alpha > 0$$

The normalizing constant C_n has the value

$$C_n = \frac{\alpha^{n+1}}{n!}$$

and the exponential parameter α is related to the mean, $\bar{t}$, of the distribution by

$$\bar{t} = \frac{n+1}{\alpha}$$

This class of distributions has the free order parameter in addition to the exponential parameter (whose specification is equivalent to choosing the mean, $\bar{t}$).

5.4.5 Detailed Data File

This section lists in detail the data used for the geometry, aeroperformance, discrete traffic, and distribution traffic data sets. The data are contained in tables 5-7 (geometry), 5-8 (aeroperformance), 5-9 (discrete traffic, 1972), 5-10 (discrete traffic, 1995), and 5-11 (distribution traffic). Figure 5-47 shows the near-runway geometry input for LAX strategic control.

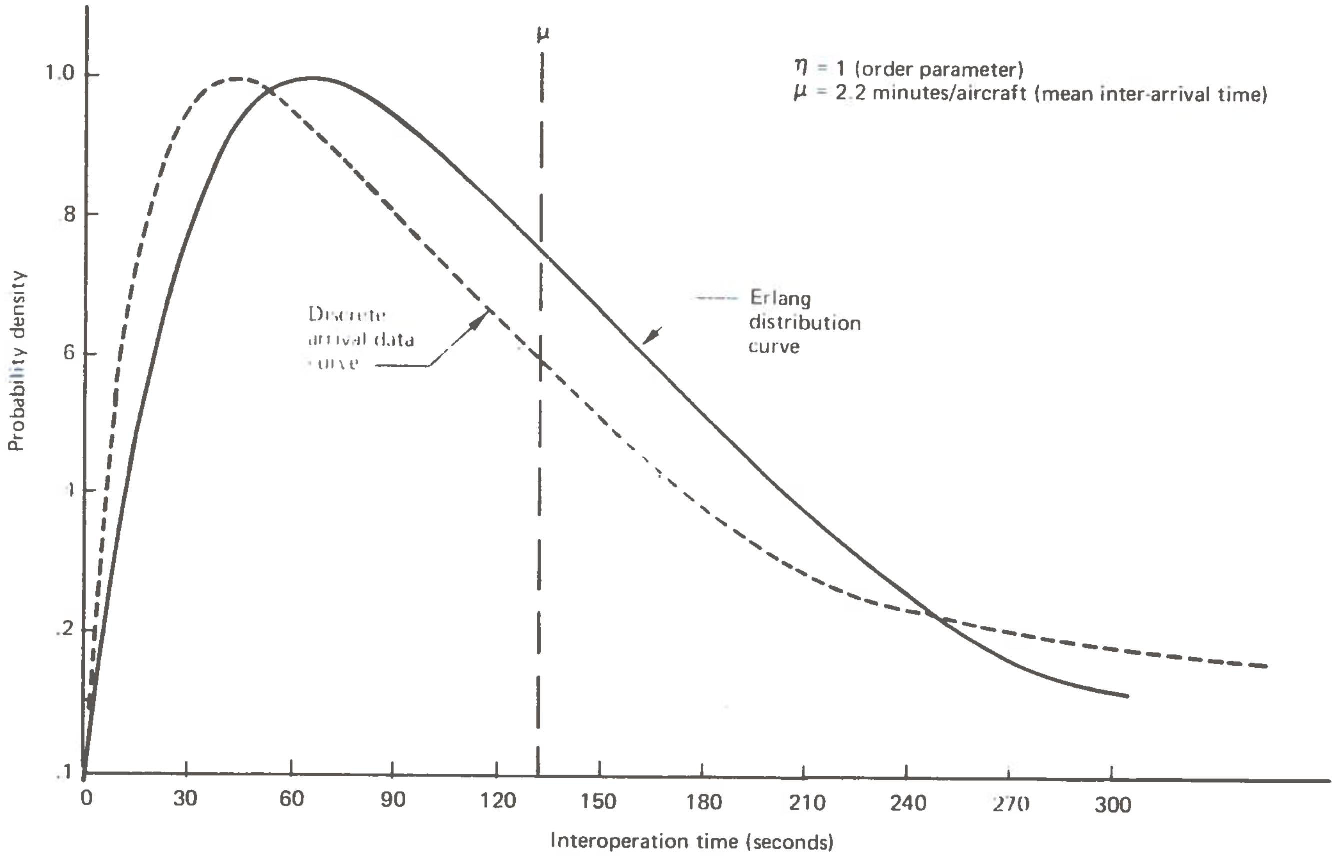


FIGURE 5-46.—ERLANG DISTRIBUTION MODEL

TABLE 5-7—GEOMETRY DATA SET

Los Angeles International approach control fix geometry coordinates	
Quadrant 1	Entry fix (1, 1)-(0, 175, 13.5) (1, 2)-(-83, 154, 10.5) (1, 3)-(33, 172, 13.) Initial approach fix (1)-(0, 43, 10.) Turn fix (1)-(0, 36, 10.)
Quadrant 2	Entry fix (2, 1)-(-173, -21, 11) (2, 2)-(-142, -101, 11) (2, 3)-(-39, -171, 10) Initial approach fix (2)-(-14, -9, 10) Turn fix (2)-(-10, 5, 7)
Quadrant 3	Entry fix (3, 1)-(0, -175, 10) (3, 2)-(0, -175, 10) (3, 3)-(0, -175, 10) Initial approach fix (3)-(-12, -22, 10) Turn fix (3)-(-10, 7, 6)
Quadrant 4	Entry fix (4, 1)-(142, 102, 10) (4, 2)-(94, 148, 10) (4, 3)-(122, -126, 10) Initial approach fix (4)-(26, 8, 10) Turn fix (4)-(3, 19, 5)
Merge fix (runway 1)	(0, 14, 3.3)
(runway 2)	(-3, 16, 5.0)
Final approach fix (runway 1)	(0, 11, 3.3)
Outer marker (runway 1)	(0, 5, 1.5)
Threshold (runway 1)	(0, 0, 0)
Missed approach (runway 1)	(26, -10, 10)
Final approach fix (runway 2)	(-1, 12.5, 3.7)
Outer marker (runway 2)	(-1, 5, 1.5)
Threshold (runway 2)	(-1, 0, 0)
Missed approach (runway 2)	(-12, -24, 10)

TABLE 5-8.—AEROPERFORMANCE DATA SET

Altitudes (feet)	Minimum speed at minimum weight (knots true airspeed)	Maximum speed at minimum weight (knots true airspeed)	Minimum speed at maximum weight (knots true airspeed)	Maximum speed at maximum weight (knots true airspeed)
Airplane 707	Minimum landing weight – 170,000 pounds Maximum landing weight – 247,000 pounds Maximum cabin pressure differential – 8.6 pounds per square inch			
10,000	202	435	229	435
21,600	243	530	275	527
32,000	288	515	325	505
34,000	300	510	340	498
36,000	310	503	360	488
38,000	323	500	390	478
39,000	330	498	415	470
Airplane 727	Minimum landing weight—125,000 pounds Maximum landing weight—160,000 pounds Maximum cabin pressure differential—8.6 pounds per square inch			
10,000	231	452	231	452
15,000	250	492	250	492
20,000	270	535	277	530
24,000	288	523	304	530
31,000	325	510	365	500
34,000	345	498	405	482
36,000	360	490	447	447
Airplane 737	Minimum landing weight—80,000 pounds Maximum landing weight—104,000 pounds Maximum cabin pressure differential—7.5 pounds per square inch			
10,000	243	407	243	407
22,500	295	500	295	495
26,000	312	495	312	485
31,000	340	480	353	465
35,000	364	465	395	445
Airplane—747	Minimum landing weight—400,000 pounds Maximum landing weight—565,000 pounds Maximum cabin pressure differential—8.9 pounds per square inch			
10,000	230	436	255	436
22,000	276	534	315	532
32,000	328	523	385	515
36,000	352	513	425	497
39,000	375	510	468	468

TABLE 5-8.—CONCLUDED

Altitudes (feet)	Minimum speed at minimum weight (knots true airspeed)	Maximum speed at minimum weight (knots true airspeed)	Minimum speed at maximum weight (knots true airspeed)	Maximum speed at maximum weight (knots true airspeed)
Airplane—DC-10	Minimum landing weight—270,000 pounds Maximum landing weight—370,000 pounds Maximum cabin pressure differential—8.6 pounds per square inch			
10,000	226	430	262	430
25,000	290	528	330	526
35,000	338	506	388	497
37,000	350	503	405	480
38,000	355	501	417	448
Airplane—720B	Minimum landing weight—145,000 pounds Maximum landing weight—175,000 pounds Maximum cabin pressure differential—8.6 pounds per square inch			
10,000	160	420	200	420
22,000	205	530	240	530
35,000	265	525	305	514
40,000	320	505	365	480
43,000	330	495	380	475

TABLE 5-9.–DISCRETE TRAFFIC DATA–1972

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
0	747	37	.84	(1, 1)	480	0	727	150
400	707	37	.82	(2, 3)	200	0	707	250
460	727	29	.82	(1, 3)	130	0	DC8	220
740	720	33	.80	(4, 2)	160	0	727	180
860	727	26	.82	(2, 2)	130	0	727	138
1060	737	32	.75	(2, 1)	95	0	737	98
1460	727	26	.82	(2, 2)	130	0	747	545
1500	DC9	31	.75	(1, 1)	95	600	727	163
1560	747	37	.84	(2, 3)	480	600	707	210
1700	727	28	.81	(2, 2)	130	900	727	138
1860	747	37	.84	(1, 2)	480	1200	707	230
1860	727	34	.80	(1, 2)	130	1500	720	205
2260	727	35	.80	(1, 1)	130	1800	727	161
2360	727	24	.82	(2, 2)	130	1800	727	138
2440	720	33	.80	(1, 3)	160	1800	707	210
2460	DC8	37	.82	(1, 2)	200	1800	727	138
2740	727	35	.80	(1, 1)	130	1800	DC8	230
3060	747	37	.84	(1, 2)	480	1800	707	210
3100	DC8	37	.82	(1, 3)	200	1800	727	155
3360	747	37	.84	(1, 2)	480	1800	727	133
3400	DC9	30	.75	(4, 2)	95	1800	707	220
3560	727	26	.82	(2, 2)	130	2100	707	210
3560	727	28	.82	(2, 2)	130	2100	DC9	96
3660	747	37	.84	(2, 3)	480	2400	720	170
4120	727	32	.80	(1, 2)	130	2400	727	150
4160	DC8	36	.82	(2, 1)	200	2700	727	140

TABLE 5-9.—CONTINUED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
4440	DC9	32	.75	(1, 1)	95	2700	720	180
4440	737	22	.72	(1, 2)	95	2700	DC8	250
4860	DC8	37	.82	(2, 3)	200	2700	727	138
4940	737	26	.74	(2, 2)	95	3000	720	180
5060	727	26	.82	(2, 2)	130	3300	727	134
5080	727	30	.82	(1, 3)	130	3600	720	200
5120	720	34	.80	(4, 2)	160	3600	737	98
5400	DC9	22	.72	(1, 2)	95	3600	727	138
5600	727	34	.80	(4, 2)	130	3600	720	230
5940	707	37	.82	(1, 2)	200	3600	DC8	280
6080	DC8	34	.80	(4, 2)	200	4200	720	190
6100	727	35	.80	(1, 1)	130	4200	727	138
6100	720	34	.80	(1, 2)	160	4500	727	138
6120	CV880	37	.82	(1, 2)	200	4500	727	133
6200	727	24	.82	(2, 2)	130	4500	727	140
6200	720	37	.82	(4, 1)	160	4500	DC9	105
6300	707	37	.82	(1, 2)	200	4800	727	135
6360	DC10	36	.84	(1, 2)	300	5400	727	138
6500	727	26	.82	(2, 2)	130	5400	727	133
6600	707	37	.82	(1, 2)	200	5400	747	560
6840	747	35	.84	(1, 2)	480	6000	DC9	100
6930	727	34	.80	(1, 2)	130	6000	DC8	220
7000	737	32	.75	(2, 1)	95			
7060	727	35	.80	(1, 1)	130			
7120	CV880	34	.82	(1, 2)	200			
7160	747	35	.84	(4, 2)	480			

TABLE 5-9.—CONCLUDED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
7300	727	35	.80	(1, 1)	130			
7300	DC8	34	.80	(1, 2)	200			
7400	727	26	.82	(2, 2)	130			
7480	707	34	.82	(1, 2)	200			
7540	737	22	.72	(2, 2)	95			

TABLE 5-10.–DISCRETE TRAFFIC DATA–1995

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
0	747	37	.84	(1, 1)	480			
125	DC10	35	.82	(1, 1)	300			
225	DC10	33	.82	(4, 2)	300			
305	DC10	35	.82	(1, 2)	300			
465	727	33	.80	(4, 2)	130			
695	727	26	.82	(2, 2)	130			
705	DC10	33	.82	(4, 2)	300			
875	737	32	.75	(2, 1)	95			
975	DC10	35	.82	(1, 2)	300			
1015	727	26	.82	(2, 2)	130			
1045	727	29	.78	(1, 1)	130			
1270	DC10	33	.82	(1, 2)	300			
1440	DC10	35	.82	(1, 1)	300			
1565	747	37	.84	(1, 2)	480			
1655	727	28	.81	(2, 2)	130			
1575	727	34	.80	(1, 2)	130			
1505	727	35	.80	(1, 1)	130			
1710	727	24	.82	(2, 2)	130			
1500	DC10	33	.82	(1, 1)	300			
1665	727	29	.78	(4, 2)	130			
1575	727	33	.80	(1, 3)	130			
1810	737	26	.75	(2, 2)	95			
1865	747	37	.84	(1, 2)	480			
1985	727	35	.80	(1, 1)	130			
2045	DC10	33	.82	(1, 2)	300			
2165	747	37	.84	(1, 2)	480			

TABLE 5-10.—CONTINUED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
2115	747	37	.84	(1, 3)	480			
2165	DC10	33	.82	(1, 2)	300			
2100	DC10	35	.82	(1, 1)	300			
2525	737	30	.75	(4, 2)	95			
2285	DC10	35	.82	(1, 3)	300			
2855	727	26	.82	(2, 2)	130			
2725	737	21	.72	(1, 2)	95			
2930	727	31	.79	(1, 2)	130			
3260	737	22	.72	(2, 2)	95			
3310	727	32	.80	(1, 2)	130			
3265	737	27	.75	(1, 3)	95			
3555	727	32	.82	(2, 1)	130			
3380	737	22	.72	(1, 2)	95			
3565	747	37	.84	(2, 3)	480			
3550	737	26	.75	(2, 2)	95			
3570	727	32	.80	(2, 1)	130			
3735	737	26	.74	(2, 2)	95			
3480	DC10	33	.82	(1, 1)	300			
3815	727	26	.82	(2, 2)	130			
3825	727	34	.82	(4, 2)	130			
3675	727	31	.79	(1, 2)	130			
3600	DC10	33	.82	(1, 1)	300			
3855	737	28	.75	(2, 2)	95			
3740	737	22	.72	(1, 2)	95			
3735	727	31	.79	(1, 2)	130			
4125	727	34	.80	(4, 2)	130			

TABLE 5-10.—CONTINUED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
3925	737	27	.75	(1, 3)	95			
4145	747	37	.84	(1, 2)	480			
4305	727	34	.80	(4, 2)	130			
4335	737	28	.75	(2, 2)	95			
4205	727	35	.80	(1, 1)	130			
4225	737	27	.75	(1, 3)	95			
4565	747	37	.84	(1, 2)	480			
4710	727	24	.82	(2, 2)	130			
4585	737	21	.72	(1, 2)	95			
4725	DC10	33	.82	(4, 2)	300			
4795	747	37	.84	(4, 1)	480			
4745	747	37	.84	(1, 2)	480			
4925	727	29	.78	(4, 2)	130			
5015	727	26	.82	(2, 2)	130			
5050	737	26	.75	(2, 2)	95			
4865	DC10	35	.82	(1, 2)	300			
4925	747	35	.84	(1, 2)	480			
4995	727	34	.80	(1, 2)	130			
4985	DC10	35	.82	(1, 2)	300			
5265	737	32	.75	(2, 1)	95			
4985	727	35	.80	(1, 1)	130			
5105	727	34	.82	(1, 2)	130			
5250	747	35	.84	(4, 2)	480			
5105	727	35	.80	(1, 1)	130			
5175	727	34	.80	(1, 2)	130			
5375	727	26	.82	(2, 2)	130			
5225	727	34	.82	(1, 2)	130			

TABLE 5-10.—CONTINUED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS
5415	737	22	.72	(2, 2)	95			
5230	DC10	33	.82	(1, 2)	300			
5290	727	29	.82	(1, 3)	130			
5455	DC10	34	.82	(4, 1)	300			
5405	747	37	.84	(1, 2)	480			
5350	727	30	.82	(1, 3)	130			
5625	DC10	33	.82	(4, 2)	300			
5485	737	21	.72	(1, 2)	95			
5650	737	26	.75	(2, 2)	95			
5465	727	35	.82	(1, 2)	130			
5655	737	24	.73	(2, 2)	95			
5705	727	34	.80	(2, 2)	130			
5525	747	37	.84	(1, 2)	480			
5765	747	37	.84	(1, 2)	480			
5925	727	33	.80	(1, 1)	130			
6310	737	32	.75	(1, 1)	95			
6365	727	29	.78	(1, 1)	130			
6475	747	37	.84	(4, 1)	480			
6565	DC10	33	.82	(1, 1)	300			
6625	727	28	.82	(2, 2)	130			
6665	737	31	.75	(1, 1)	95			
6705	DC10	33	.82	(1, 2)	300			
6785	747	37	.84	(2, 3)	480			
6965	727	34	.80	(1, 2)	130			
7085	747	35	.84	(1, 2)	480			
7160	DC10	35	.82	(1, 2)	300			

TABLE 5-10.—CONCLUDED

ENTRY FIX ARRIVAL TIME	AIRPLANE TYPE	ALTITUDE (000 FT)	SPEED (MACH)	ENTRY FIX NUMBER	ARRIVAL GROSS WEIGHT (000 POUNDS)	DEPARTURE TIME	AIRPLANE TYPE	DEPARTURE GROSS WEIGHT (000 POUNDS)
7220	747	37	.84	(2, 3)	480			
7235	727	30	.78	(2, 1)	130			
7345	747	37	.84	(2, 3)	480			

TABLE 5-11.—DISTRIBUTED TRAFFIC DATA

	Normal arrival data set	Erlang arrival data set
Arrival airplane types	6	6
Departure airplane types	5	5
Airplane types used for arrivals	707, 727, 737, 747, DC-10, 720B	707, 727, 737, 747 DC-10, 720B
Airplane types used for departures	707, 727, 737, 747 720B	707, 727, 737, 747, 720B
Mean arrival interoperation time	132 seconds	132 seconds
Mean departure interoperation time	147 seconds	147 seconds
Standard deviation or order parameter for arrival distribution	113 seconds	1 (order parameter)
Standard deviation or order parameter for departure distribution	113 seconds	1 (order parameter)
Time span of traffic being studied	2 hours	2 hours
Arrival distribution	Normal	Erlang
Departure distribution	Normal	Erlang
Arrival weight distribution	Uniform	Normal
Departure weight distribution	Uniform	Uniform
Arrival altitude distribution	Uniform	Uniform
Arrival speed distribution	Uniform	Uniform

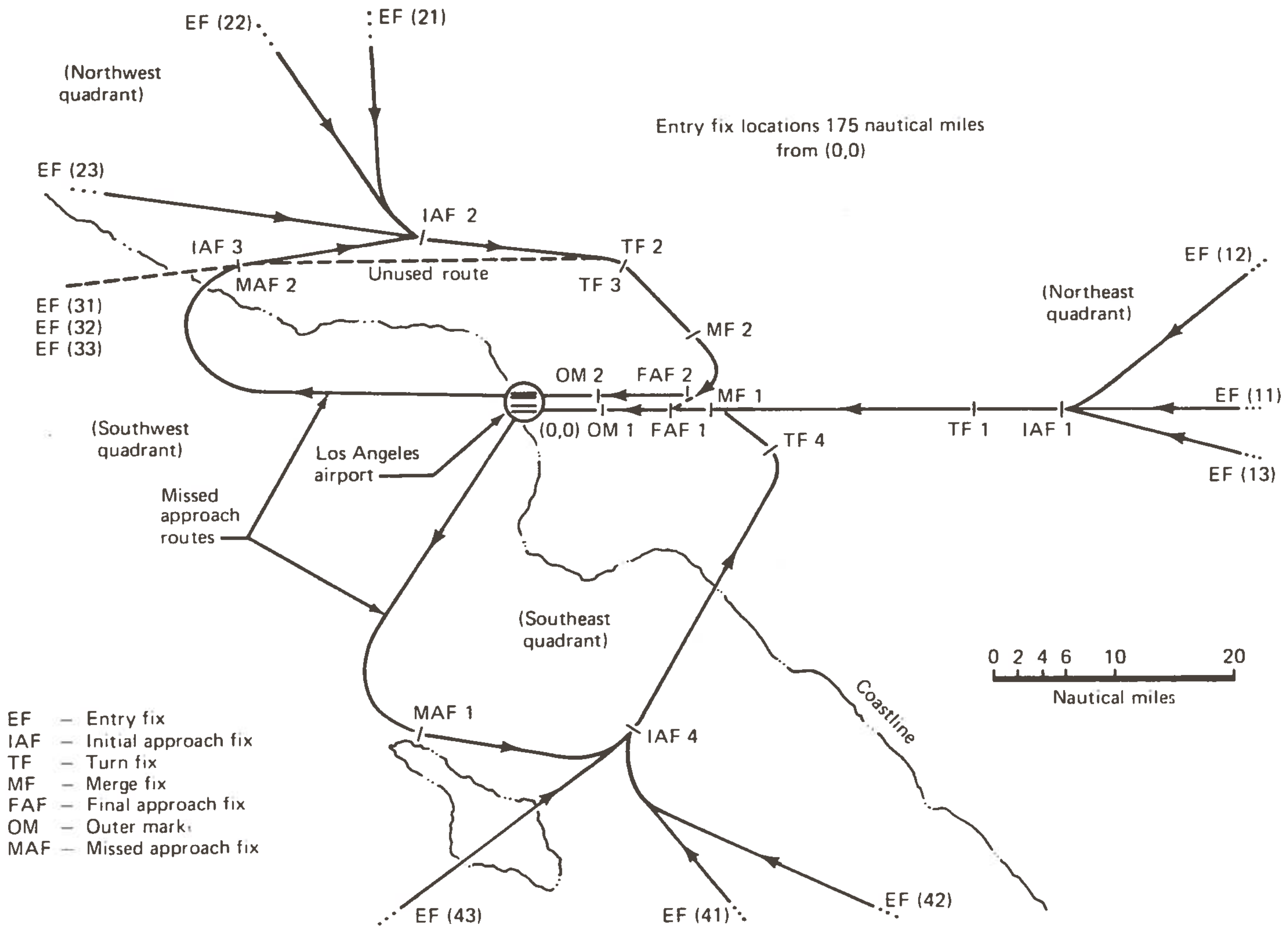


FIGURE 5-47.—LOS ANGELES STRATEGIC ARRIVAL GEOMETRY