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STRATEGIC CONTROL ALGORITHM DEVELOPMENT
Volume I: Summary

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16. Abstract

Strategic control is an air traffic management concept wherein a central control authority determines, and assigns to each participating airplane, a conflict-free, four-dimensional route-time profile. The route-time profile assignments are long term as compared with the short-term, immediate nature of tactical control instructions. The route-time profiles are determined in a manner that provides for predictable and efficient use of both airspace and available runway operation times. This concept results in terminal area capacity increases, delay reductions, safety improvement, and controller workload reductions. Maximum benefits are expected to occur at the busy terminal areas where demand is high and airspace is at a premium.

This volume summarizes the results of a study to develop the basic algorithm for strategic control of arrivals. The strategic control concept is described as to operational concept, ATC system, airplane system, and application to U.S. airspace. The requirements placed on the algorithm by airplane performance and runway operation are discussed. The logic of the developed algorithm is presented. The algorithm performance was evaluated with a fast-time terminal area simulation; the simulation and algorithm performance are described. The benefits of strategic control in terms of increased airfield capacity, reduced airspace requirements, improved airplane flight economics, and reduced workload and communications are analyzed. Included is a research, development, test, and evaluation (RDT&E) plan for development of strategic control into an operational capability.

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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

This section presents a brief background of the study, as well as the conclusions and recommendations that were reached.

1.1 BACKGROUND

Strategic control is generally defined as control based on long-term planning. However, as used in this study it is a specific method wherein: the air traffic control (ATC) system defines tracks for all flights in four dimensions (crosstrack, along-track, altitude, and time) to resolve traffic conflicts; and the airplanes use precision four-dimensional navigation/guidance equipment to fly these assigned tracks. It is an extension of the traffic control system presently used in the North Atlantic organized system.

Strategic control has often been proposed for use in the future ATC system (e.g., refs. 1, 2, and 3). The need now is to extend this concept to control traffic in high-density domestic airspace. This study was designed to expand the knowledge of what is involved in mechanizing strategic control, how well it would perform, and its impact on the use of airspace. Specifically, the object was to develop the basic algorithm for strategic control, including the detailed design of the basic terminal area algorithm, the functional design of the complete algorithm, and an estimate of the data processing requirements for strategic control. The basic algorithm describes the logic process, including the mathematical formulation of the fundamental operation (thus providing for, but excluding, the details for handling such actions as runway reversals, weather avoidance, etc.). The integration of strategic control into the airspace system and its interface with other airspaces and airplanes not equipped for strategic control were to be defined.

This volume summarizes the results of the Strategic Control Algorithm Development (contract DOT-TSC-538). Details of the study are not included in this volume in order to make the document more readable. The serious investigator is referred to other volumes for detailed descriptions of the analyses and study results. The detailed analyses are presented in volume II, the strategic algorithm is described in volume III, and the evaluation model and computer program are documented in volume IV.

1.2 CONCLUSIONS AND RECOMMENDATIONS

As a result of this study, the following conclusions were reached:

1) The potential benefits of strategic control to increase airspace capacity, reduce control/communication workload, and reduce flight time (operating cost and fuel savings) make it an attractive solution for these current ATC problems.

2) In the future, when the wake-turbulence spacing constraint is reduced so that the runway operations rate is constrained only by runway occupancy time, strategic control will support operating airfields at double today's capacity.

3) Successful strategic control algorithm design requires the application of detailed data on the performance capabilities of specific airplane types and models.

4) Successful strategic control algorithm design necessitates a detailed knowledge of the airborne avionics guidance/control laws.

5) The present effort could be the basis for developing the capability to satisfy the area navigation (RNAV) plan requirement for four-dimensional RNAV in high-density terminal areas by 1982.

The recommendations relative to strategic control development are:

1) Maintain continuity of research and development toward the capability to implement strategic control.

2) In the near term:

   - Refine the basic arrival algorithm and evaluation model.
   - Develop and experiment with a real-time program.
   - Integrate the algorithm and airborne guidance equipment in a real-time simulation.

2.0 STRATEGIC CONTROL CONCEPT

Strategic control may be generally described as a control concept wherein ATC advance planning defines four-dimensional paths for participating flights to resolve the traffic situation, and the airplanes are flown to conform to these four-dimensional paths. A four-dimensional path has the horizontal position and altitude continuously defined as a function of time. The four-dimensional path is referred to in this study as the route-time profile (RTP).

Strategic control may be envisioned as a system in which the entire flight is scheduled from assigned takeoff time to assigned landing time. However, the discussion in this section concentrates on terminal area control since this is the most likely place for initial application of the concept due to the greater need and benefits.

Figure 2-1 shows arrivals to a high-density runway. The flights have routes and time schedules that bring them sequentially onto the runway while maintaining the desired longitudinal, lateral, and vertical spacing between airplanes. Traffic not in the strategic control system is shown using a separate runway, but the system can be operated to accept both equipped and unequipped traffic on the same runway. Equipped traffic in this context refers to airplanes having the avionics necessary to operate in a strategic control environment.

2.1 OPERATIONAL CONCEPT

In a terminal area, ATC would compute four-dimensional flightpaths for all strategically controlled traffic (both arrivals and departures) by considering the present position of the flights and runway use scheduling. These four-dimensional flightpath assignments would allow for geometry, environmental, and airplane performance considerations. The general requirements for these strategic flightpaths are that they:

- Define the desired airplane flightpath location in terms of horizontal position, altitude, and time.
- Provide paths that are nonconflicting, with safe separation between airplanes.
- Sequence and space airplanes for operation onto and off of the runway(s).
- Make efficient use of available airspace.
- Minimize flight penalties by using paths and profiles that match the desired route and airplane performance envelope as closely as practical.

To study the operational use of the concept, a strategic arrival control geometry structure was selected that can be varied to represent different arrival patterns. This geometry structure allows the waypoints to be placed to accommodate terrain features,

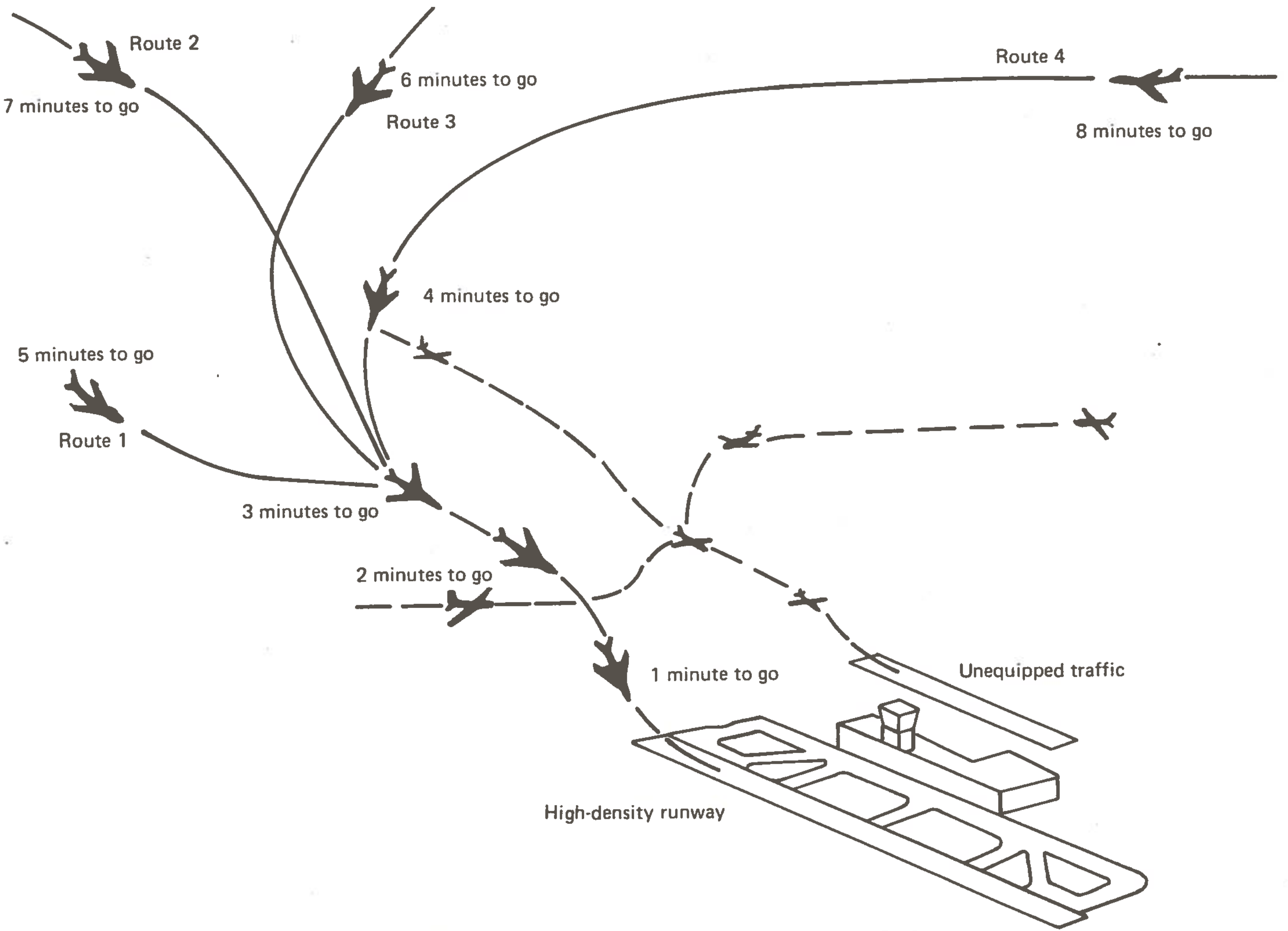


FIGURE 2-1.—STRATEGIC ARRIVAL CONTROL

available airspace, noise abatement, and other path-influencing factors. The resulting paths may be either direct to the runway, as shown in figure 2-2a, or complex, as shown in figure 2-2b.

Airplanes enter strategic control 150 to 175 nautical miles from the airport at one of several entry fixes. For entry to the terminal area (approximately 35 nautical miles from the airport), initial approach fixes are defined to integrate traffic from the corresponding entry fixes. At least one turn fix is used inside the initial approach fix to position the track within the terminal area, and merge fixes are used where arrival routes merge.

The airplane speed profile is varied between the entry fix and initial approach fix to achieve the desired spacing control. Parallel tracks are used between the entry fix and initial approach fix to resolve conflicts. From an initial approach fix to the outer marker, all flights use a common speed and altitude profile. Inside the outer marker, each airplane is flown at its appropriate final approach speed.

Figure 2-3 shows how the path for an arrival can be characterized. The complete path can be defined by waypoints with X, Y, and Z coordinates (most likely latitude, longitude, and altitude for passing over the waypoint), time for passing each waypoint, and the use of constant acceleration between waypoints.

The logic used by ATC to develop arrival route-time profiles is as follows:

1) Initial data such as present position, weight, and planned final approach speed are obtained from the flight.

2) Other data needed include winds and temperatures along the arrival routes, airplane performance, and common speed/altitude profiles from each initial approach fix (IAF) to the outer marker.

3) Each flight is scheduled to use the runway by:

   - Computing the earliest possible threshold time

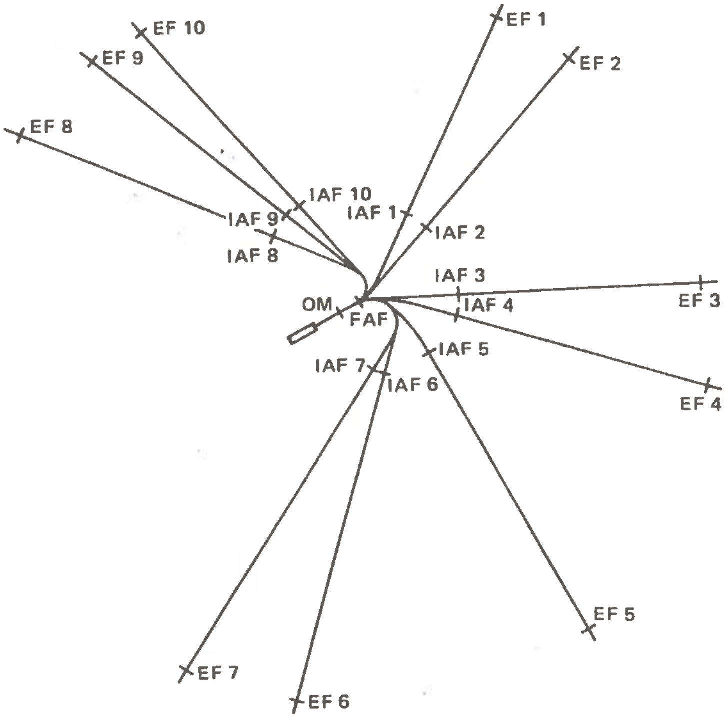
   - Defining a landing sequence (e.g., order of earliest possible arrival)

   - Assigning the earliest available threshold time (that each flight can make)

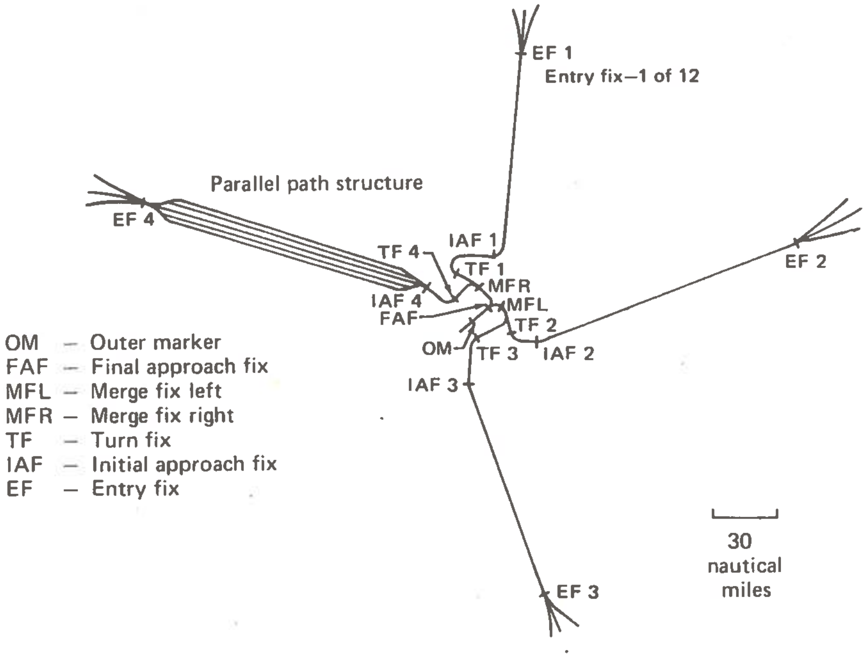
4) The route-time profile is then built for each flight in sequence by:

   - Using the minimum threshold separation requirement and difference in final approach speeds to compute outer marker time

   - Using the common profile from IAF to outer marker to compute the IAF scheduled time



a. DIRECT ROUTING



b. APPLICATION TO COMPLEX TERMINAL AREA

FIGURE 2-2.–STRATEGIC ARRIVAL CONTROL GEOMETRY STRUCTURE

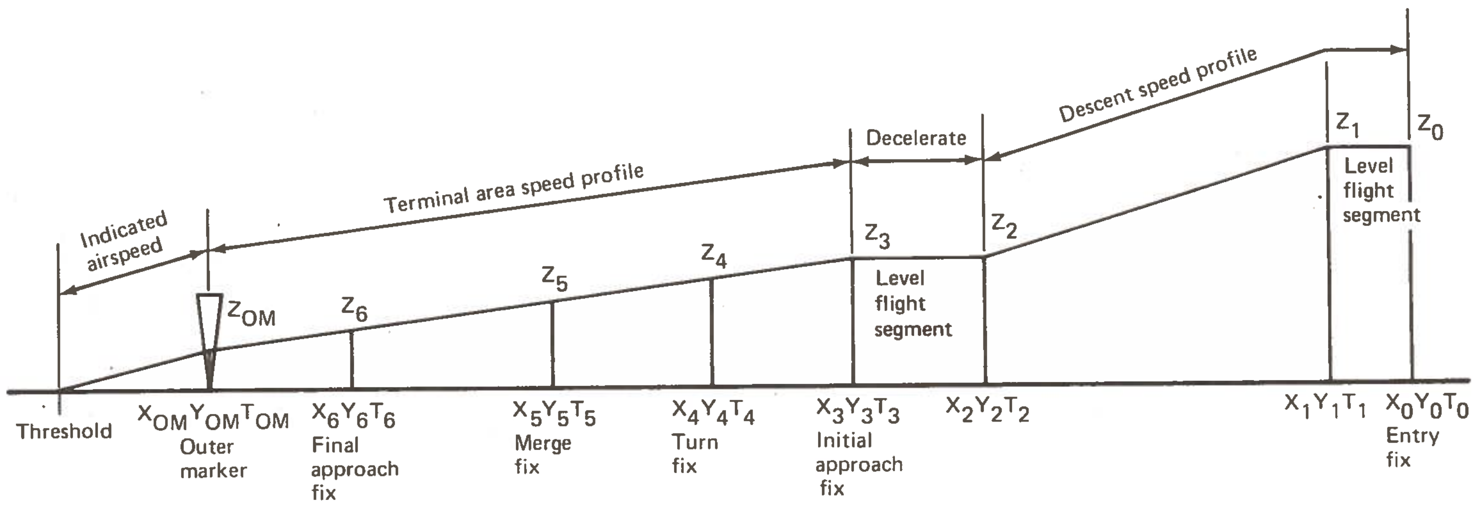


FIGURE 2-3.—STRATEGIC CONTROL ARRIVAL PATH

- Using the initial approach fix scheduled time, the expected entry fix time, and the airplane's performance data to compute a conflict-free route-time profile that satisfies the boundary conditions

The flight requirement is for the airplane to maintain its scheduled position as a function of time, with an error that is small compared with the planned spacing between flights. Thus, if flights are nominally separated longitudinally by 60 seconds, the airplane should maintain its assigned schedule to something like 2 seconds (one sigma).

The responsibility for navigation and airplane flight control is entirely within the airplane. As shown in figure 2-4, the desired position (route-time profile) of the airplane is determined by the ground-based ATC scheduling function. The desired position is then compared to the actual position as measured by the airplane navigation system. Any position errors result in guidance commands, i.e., steering commands to the flight control system and speed commands to the autothrottle. The control mechanization is complete when the flight control system causes the airplane to fly to minimize the position error.

A generalized functional description of ATC operations while using strategic control is shown in figure 2-5. The figure includes the surveillance and potential intermittent position control (IPC) functions.

2.2 ATC SYSTEM

The strategic control concept requires a means of position determination, a navigation system, a digital data link, and a central data processor, but does not depend upon the availability of any particular ATC equipment. It is described here in the context of the FAA Upgraded Third Generation System as it might be adapted for strategic control. Figure 2-6 shows the functional elements of such a system. The VOR/DME would provide the navigation environment with potential use of the Microwave Landing System (MLS) in the terminal area.

The surveillance system would supply airplane horizontal position and altitude data to be used both as initial conditions for route-time profile generation and for conformance monitoring as the flight progresses. The Discrete Address Beacon System (DABS) would provide this capability.

A digital data communications link would connect the airplane navigation/guidance computer and the ATC central data processor for transmission of airplane-related data (e.g., landing weight and speed) and assigned route-time profiles. Appropriate monitoring displays and approval action switches would be provided to the pilot and controller.

The central data processor will store the program and data, generate the route-time profiles, and compare surveillance-measured position to assigned position as a basis for conformance monitoring.

The controller would function primarily in an air traffic management role. His main tasks would be adjusting the computer program configuration to match conditions and

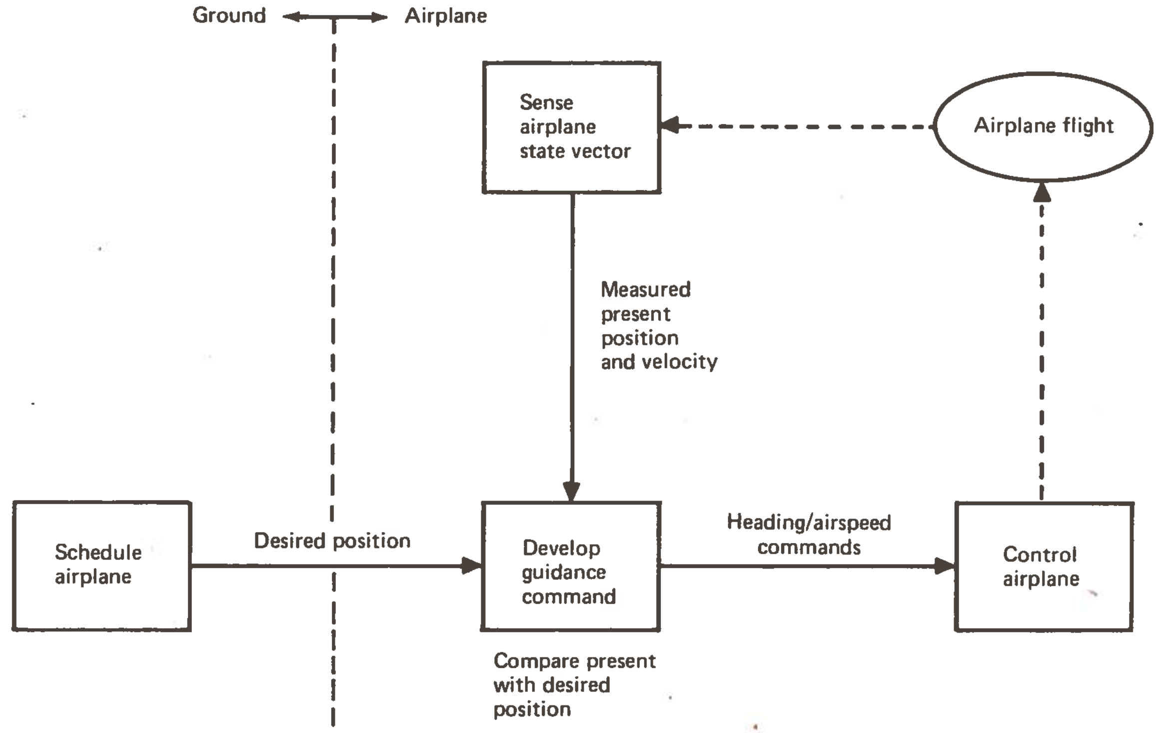


FIGURE 2-4.—AIRPLANE FLIGHTPATH CONTROL FUNCTIONS

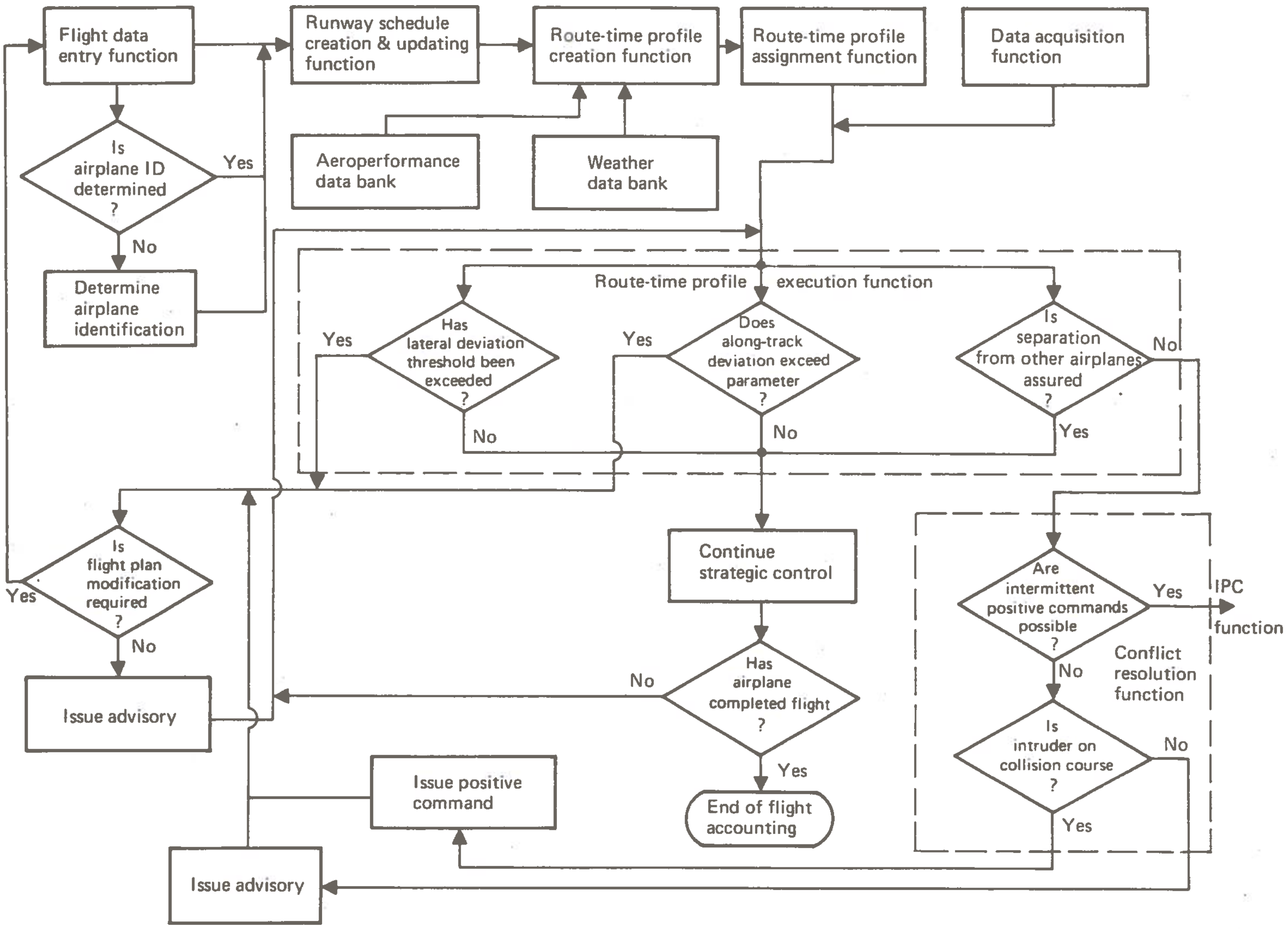


FIGURE 2-5.—ATC FUNCTIONAL OPERATION USING STRATEGIC CONTROL

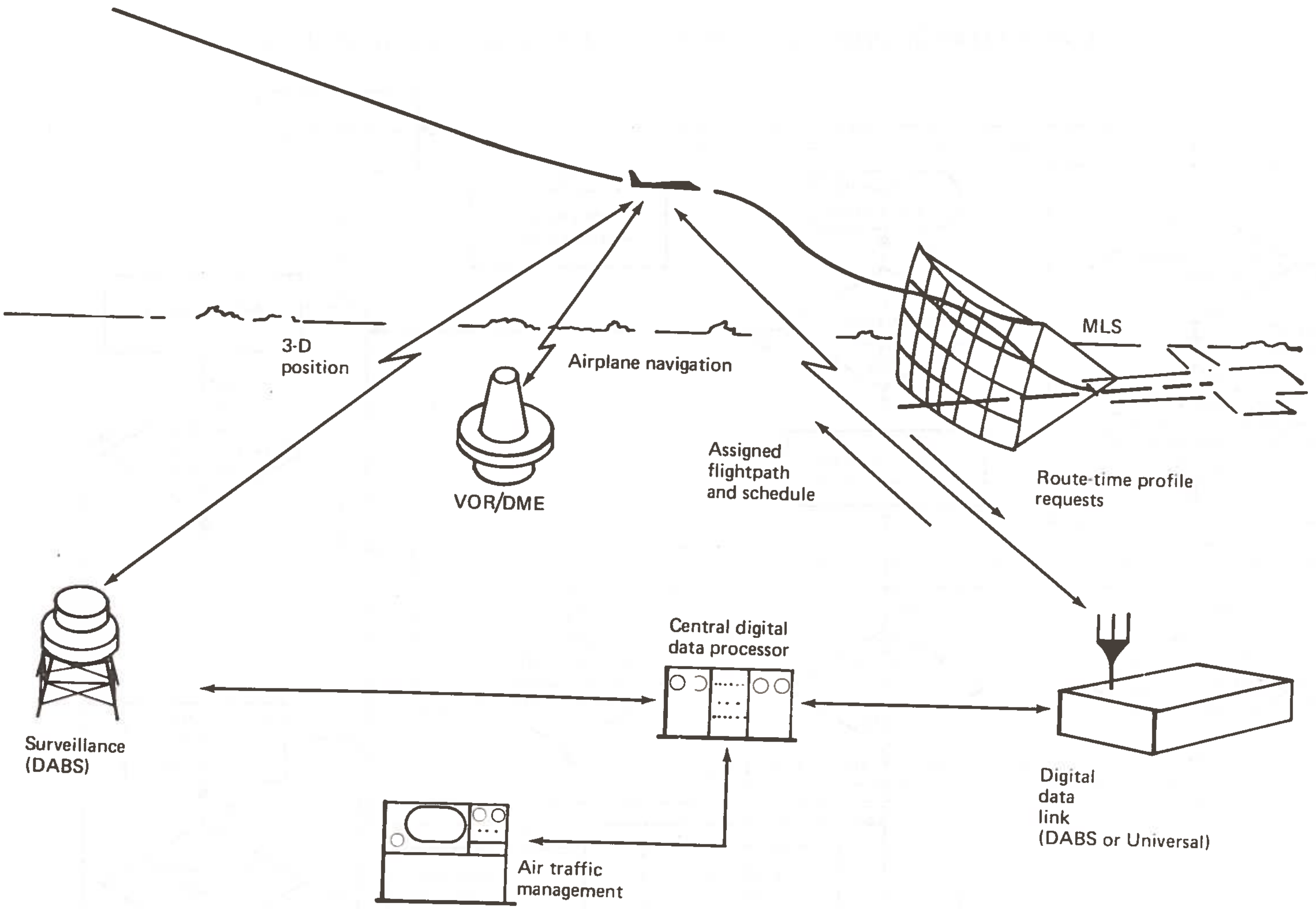


FIGURE 2-6.—ATC SYSTEM FOR STRATEGIC CONTROL

monitoring system status. In the initial operating period, controllers may be required to provide backup for system failure; however, as experience (confidence) is gained, active intervention by the controller would be superseded by appropriately selected and monitored machine actions.

2.3 AIRPLANE SYSTEM

Each airplane operating under strategic control needs to be equipped with a surveillance transponder, a data link modem and display, a four-dimensional navigation capability, and a guidance computer. The principal elements of the airplane system required for strategic control are shown in figure 2-7. The navigation computer program uses VOR/DME inputs to compute present position and groundspeed. An inertial measurement unit can be used to augment the radio navigation.

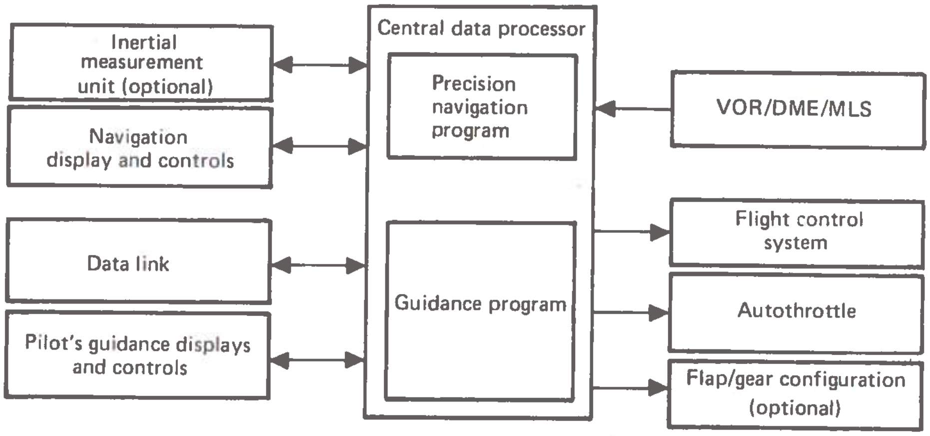


FIGURE 2-7.—AIRPLANE SYSTEM

The route-time profile is received via the data link and is input to the guidance computer, where it is checked against airplane performance. The guidance computer uses the navigation system outputs and the stored route-time profile to generate commands for the flight control and autothrottle systems. The more sophisticated systems may control the flap and landing gear configuration.

The pilot is provided a guidance display that could present such information as the route-time profile, present position, time to go, and time/position errors.

2.4 APPLICATION IN U.S. AIRSPACE

Strategic control would be the most stringent level of control in the ATC system. As such, it would be used at those times and places where increased ATC system capacity was needed to handle the traffic demand. This would be during peak periods (when traffic approaches or exceeds capacity) for those runways and air routes that consistently operate at capacity with air carriers and the more sophisticated, high-performance general-aviation airplanes. These classes of airplanes are expected to comprise the majority of users since they are able to purchase the required avionics, benefit the most by operating during peak hours, and need to use large runways during periods of heavy traffic.

2.4.1 Application To Terminal Areas

If strategic control were an off-the-shelf operational capability, it is assumed its advantage of reduced control/communication workload would be used (along with other system improvements) to increase the airfield IFR capacity above today's values. The criteria that were used to estimate when strategic control would be applied to a terminal area were:

- The traffic demand for those runways used primarily by air carrier aircraft exceeds the IFR practical hourly capacity, defined in reference 4 as that level of traffic for which the average departure delay will be 4 minutes.
- Ninety percent or more of the traffic on these runways is air carrier and well-equipped, general-aviation airplanes (those most likely to be equipped for strategic control) on IFR flight plans.

Estimates of the year that air carrier demand would exceed capacity were made for all U.S. airports likely to become saturated by the year 2005 (refer to vol. 2, sec. 6.1.3). The IFR practical hourly capacity was determined for the air carrier runway configuration used for the majority of IFR operations at each airport. Known runway improvement plans were considered. This capacity was compared with the forecast busy-hour operations corresponding to the low, nominal, and high traffic growth forecasts discussed in section 6.1.3, volume 2. The results are shown in figure 2-8. With nominal traffic growth to 28 million arrival operations, 24 airports will be candidates for strategic control by 1995.

There is no forecast for the percentage of air carrier operations by runway; even data for today's operations by runway is sketchy. Table 2-1 shows some sample busy-hour data for five airports. Considering that the scheduled air taxis as well as the air carriers will operate in a strategic mode, it is easy to assume that during busy hours on selected runways the majority of operations will be by airplanes equipped for strategic control.

2.4.2 En Route Application

The greatest benefit of en route strategic control occurs for busy routes between strategic controlled terminal areas. For overlapping strategic control terminal areas, direct handoffs preclude the need for en route control. A busy route can be equated to the criteria for a long-thin sector, as used in the *National Aviation System Ten-Year Plan*, of about 25 flights during the busy hour. Thus the criteria that were used to estimate when strategic control would be applied to en route segments were:

- Only those segments connecting nonoverlapping strategic control terminal areas are candidates.
- Busy-hour flights must equal or exceed 25 air carrier operations.

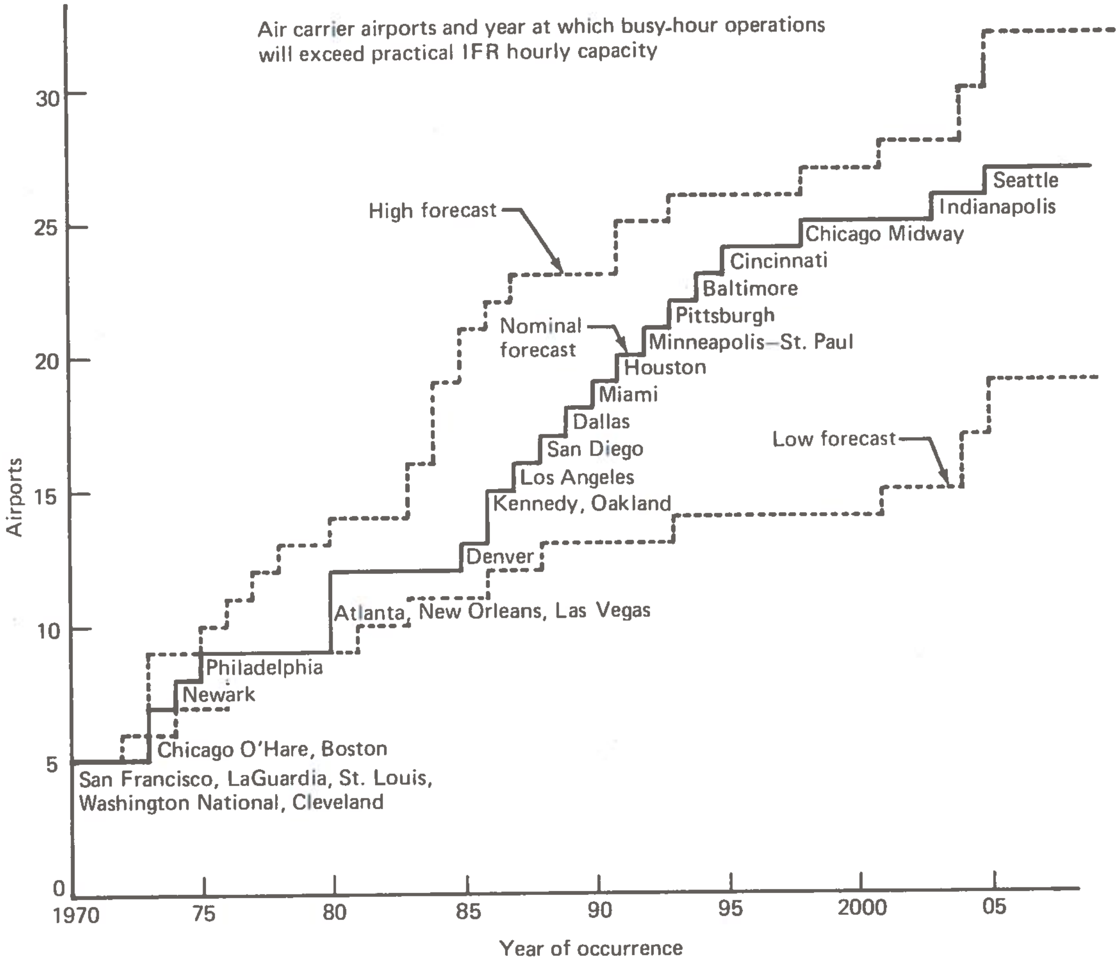


FIGURE 2-8.—STRATEGIC CONTROL AIRPORTS

TABLE 2-1.—BUSY-HOUR RUNWAY USE BY USER CATEGORIES

Airport	Busy hour	Runway	Air carrier	Scheduled air taxi	General aviation	Military	Percent air carrier + scheduled air taxi
J. F. Kennedy May '73	2000-2100	31L	39	0	0	0	100
		31R	28	1	1	0	97
		32	0	5	4	0	56
Newark May '73	1700-1800	22R	16	0	6	0	67
		29	16	5	5	0	81
La Guardia May '73	1800-1900	4	0	2	2	0	50
		22	0	0	2	0	0
		31	60	2	5	0	93
		32	0	0	1	0	0
Los Angeles International Jan '73	1000-1100	24R	0	1	1	0	50
		24L	14	3	1	0	94
		25R	28	0	2	0	93
		25L	17	0	4	1	77
Chicago O'Hare Nov '72	FY 1973 peak day busy hour	All	150	12	12	0	93

Busy-day scheduled airline flights between qualified city pairs, as taken from the *Official Airline Guide* for a Friday in May 1972, were multiplied by the fleet growth factors, as discussed in section 6.2.2 of volume 2. The resulting busy-hour flights by route were plotted against years. Figure 2-9 shows the en route segments that are candidates for strategic control and the year they become candidates for the low, nominal, and high traffic forecasts.

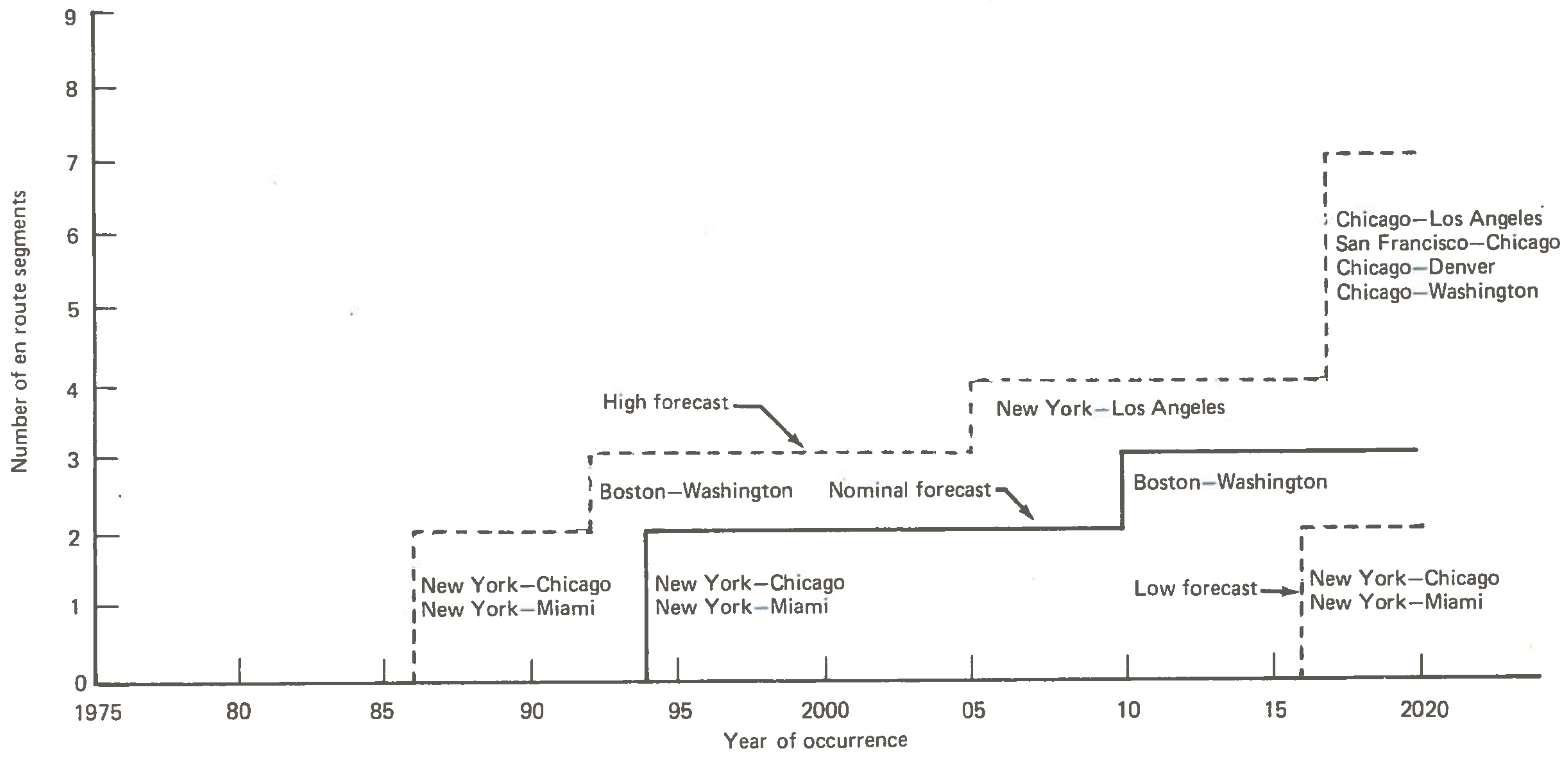


FIGURE 2-9.–STRATEGIC CONTROL EN ROUTE SEGMENTS

3.0 STUDY

The study had as a principal objective the development of the basic algorithm for strategic control of arrivals* into a terminal area. Several complementary objectives were built around this principal objective:

- A functional design of an algorithm for strategic control in all airspace
- An estimate of the data processing required for strategic control
- An analysis of how strategic control would be integrated into the airspace
- An estimate of the benefits of strategic control
- A research, development, test, and evaluation (RDT&E) plan for bringing strategic control to the stage where it could be committed to implementation

Figure 3-1 shows the individual study tasks and their interrelationships. Tasks 1 and 2 established the basic requirements for the algorithm design in task 3. In task 4, a fast-time terminal area simulation model was developed and integrated with the algorithm for algorithm development and performance evaluation. Tasks 5 through 8 were complementary analyses to support overall evaluation of the strategic control concept.

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*Departures were considered in building the arrival schedule, but strategic departure routing was not the subject of this contract.

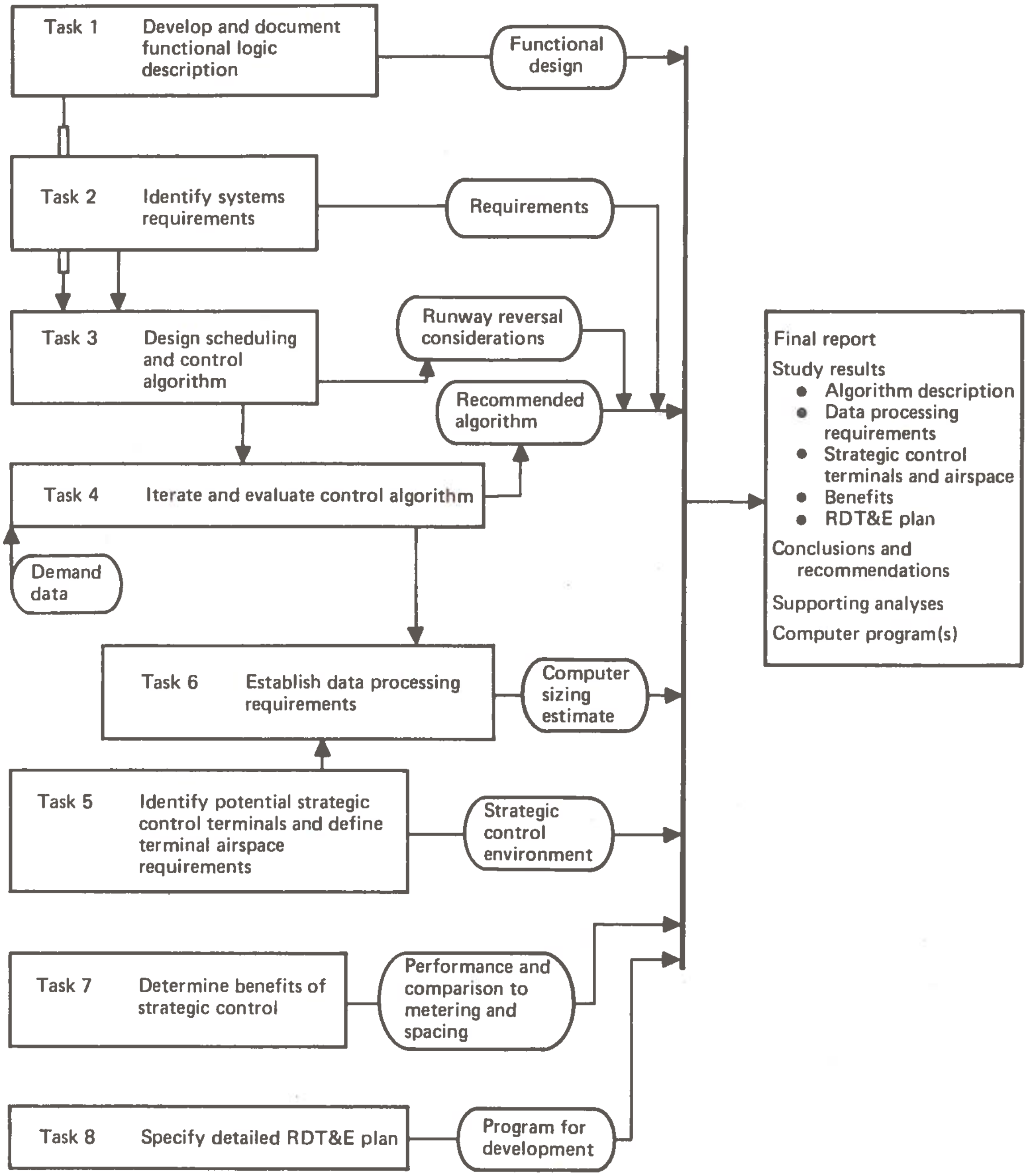


FIGURE 3-1.—STUDY PLAN OVERVIEW

4.0 STRATEGIC CONTROL REQUIREMENTS

Requirements placed on the algorithm design by airplane performance and runway operation, and requirements on the communications and data processing subsystems resulting from the use of strategic control, were studied.

4.1 AIRPLANE PERFORMANCE

The algorithm must define route-time profiles that are within the performance envelope of each airplane type to be controlled. Table 4-1 lists the air carrier airplane types that are expected to be used in the majority of operations during 1975-1985. Airplane performance for the post-1985 fleet is assumed similar to that of today's airplane fleet. This assumption is consistent with anticipated airplane design considerations.

TABLE 4-1.—AIRPLANE TYPES (1975-1985)

737-200	727-100	L1011-1
737-200 Adv	727-200	L1011-2
	707-120B	
DC 9-30	720B	DC-10-10
DC 9-40	707-320B	DC-10-30
DC 9-50		
	DC-8-61	747-100
F-28	DC-8-63	747-200
Mercure II		7X7
	A300B	
	A300B-7	

For each type, the route-time profile must consider the airplane's gross weight, Mach/speed limits, cabin repressurization rate, anti-icing power requirements, and the effects of wind and temperature on performance. Figure 4-1 is an example of the speed performance capability data that are required for each airplane type as a basis for calculating the descent transition portion of the route-time profile.

4.2 RUNWAY OPERATION

The algorithm must schedule runway operations by considering the required spacing between operations (arrival-arrival, arrival-departure, departure-departure, and departure-arrival). The spacing may be a fixed-distance (as in today's operations), fixed-time, or runway occupancy.

Scheduling must be for a single runway and for parallel runways considering the spacing dependencies corresponding to dual-lane, dependent parallel, and independent parallel operation. The capability to operate according to different arrival-departure priority schemes and to accommodate pop-up traffic must be available.

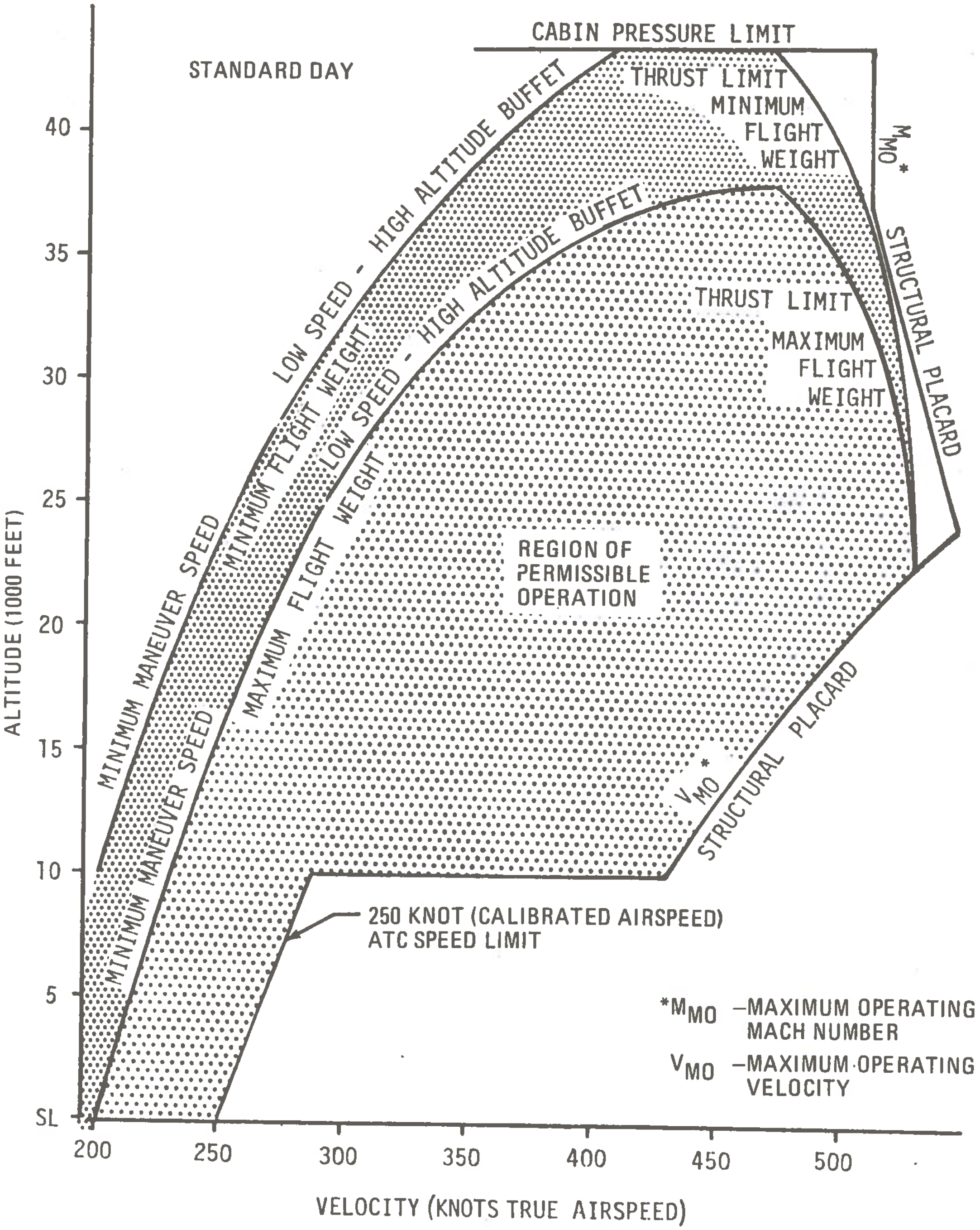


FIGURE 4-1.–TYPICAL SPEED/ALTITUDE AEROPERFORMANCE LIMITS

4.3 COMMUNICATIONS

The digital message types, format, and bit count for normal strategic arrival control are shown in table 4-2. Normally, each message would be transmitted once per airplane landing. Since route-time profiles are lists of extensive and exact data, an automated computer-to-computer (data-link) communication system was assumed. Voice communication was found to be inadequate due to the slow speed, extensive workload, and proneness to error.

TABLE 4-2.—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

4.4 DATA PROCESSING

An estimate was made of the data processing sizing requirements for strategic control terminal area operations. Sizing was for the 24 airports (shown in fig. 2-8) that were chosen as candidates for strategic control based on the 1995 nominal traffic estimate. These airports represent 17 terminal areas.

The peak data processing load will occur when all traffic in the terminal area must be rescheduled due to a shift in active runways.

A sizing estimate was made for each terminal area based on: (1) rescheduling within 5 minutes, (2) forecast 1995 busy-hour operations (refer to sec. 6.1.3, vol. 2), (3) the number of strategic control points in that terminal area, and (4) the data processing estimates for each individual strategic control function. The latter were verified by comparison with the CDC 6600 computer implementation of the algorithm developed in this study.

The results ranged from 0.0124 mips (millions of instructions per second) and 13.29×10^6 bits of core storage for San Diego to 0.079 mips and 15.86×10^6 bits of core storage for New York. The total for 17 terminal areas was 0.5516 mips and 236×10^6 bits of core.

The computing capability required is available in off-the-shelf equipment that is well within the state of the art. In addition, this concept might be able to be added directly to ARTS III or NAS Stage A computers.

5.0 ALGORITHM DESCRIPTION

An algorithm was developed that generates nonconflicting route-time profiles for strategic arrivals to a terminal area.

5.1 SYSTEM GEOMETRY

The terminal area control geometry (fig. 2-2) involves the area within a radius of 150 to 175 nautical miles of the runway. This control area encompasses the flights from en route cruise to the runway.

The airplanes cross an entry fix at en route altitude. They then descend to the initial approach fix according to the assigned route-time profiles. It is along this segment that sequencing and spacing control is achieved by controlling the descent speed. Parallel tracks between the entry fix and initial approach fix are provided to resolve conflicts.

From an initial approach fix to the outer marker, each airplane flies the same route-speed altitude profile. From the outer marker to threshold, each airplane flies its unique planned final approach velocity.

The terminal area is divided into quadrants with multiple entry fixes in each quadrant (three per quadrant were used in this study). This allows relatively direct flight from en route air routes to the initial approach fix. Inside the initial approach fix, one turn fix (there could be more) is used to adjust the initial approach track as required by terrain clearance, noise, etc. Merge fixes are used first to join the traffic in each pair of quadrants; then, in the single runway case, a final approach fix joins the two streams into one, which is aligned with the runway.

A specific profile was chosen for descent from entry fix to initial approach fix (fig. 5-1). A straight line was used with a 250 feet per nautical mile gradient. Airplanes fly past the entry fix, intercept the descent path, and fly down it. A 10-nautical-mile level flight segment allows deceleration to a calibrated airspeed of 250 knots at the initial approach fix.

When merging from three entry fixes at one initial approach fix using parallel tracks, the tracks would cross and thus produce conflicts. Therefore, the descent profile for each entry fix intercepts the initial approach fix at a different altitude. For example, initial approach fix altitudes of 10,000, 11,000, and 12,000 feet are each fed from a respective entry fix. Final altitude merging is accomplished just inside the initial approach fix.

5.2 ALGORITHM OPERATION

The three main functional operations of the algorithm are sequencing, scheduling, and route-time profile generation. In this context, sequencing is the determination of the threshold priority, and scheduling is the assignment of threshold arrival time. Figure 5-2 shows these operations as used in connection with the evaluation model (model operations

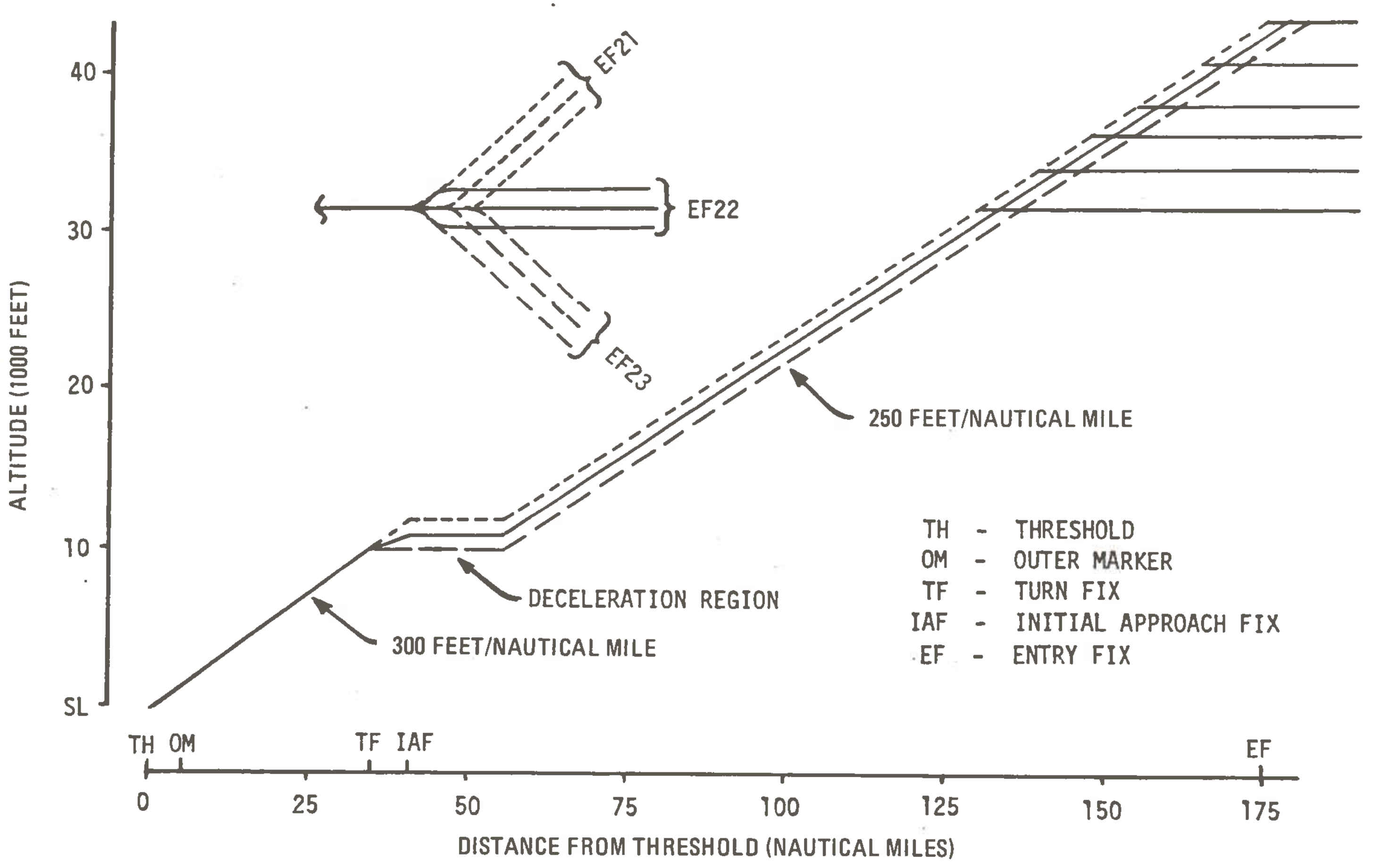


FIGURE 5-1.—DESCENT TRACKS

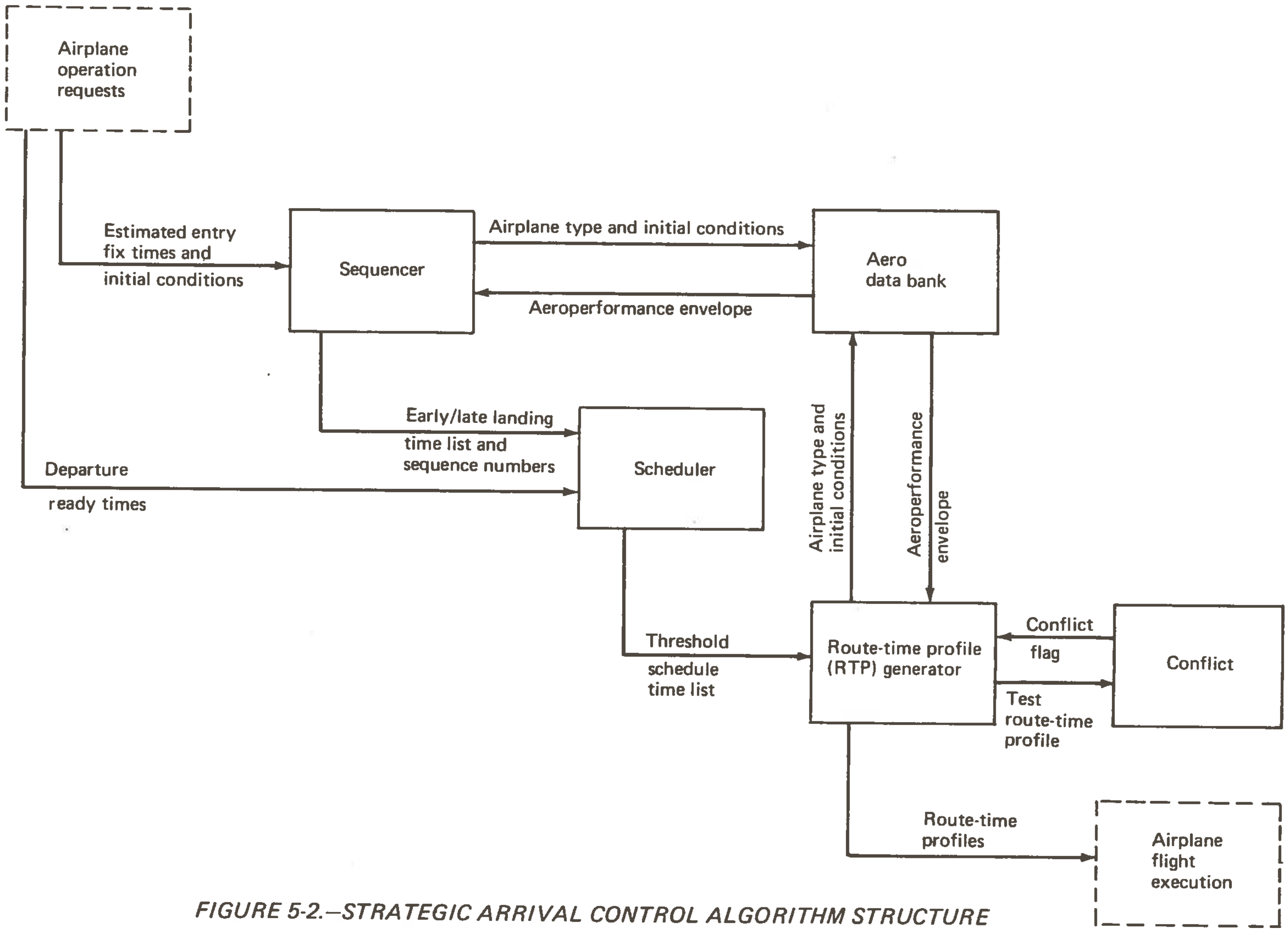


FIGURE 5-2.—STRATEGIC ARRIVAL CONTROL ALGORITHM STRUCTURE

in dashed boxes). The other two principal elements are the aeroperformance data bank and the conflict detection routine. The latter is an integral part of route-time profile generation.

5.2.1 Sequencing

A modified "first-come, first-served" strategy was employed to order the airplanes at the threshold. Figure 5-3 shows the sequencing logic. Based on the estimated entry fix arrival time, a route-time profile was created via the longest parallel, and the estimated earliest landing time was computed. The minimum cabin repressurization time was calculated and if it limited the minimum descent time, the estimated earliest landing time was modified to reflect this limitation. These values were then ordered to establish the threshold sequence.

The estimated latest landing time for each arrival was then calculated using the shortest parallel path. The difference between the estimated earliest and latest landing times represents the "scheduling window" (i.e., times that may be scheduled without holding outside the entry fix). Determining the estimated earliest landing time on the longest path and the estimated latest landing time on the shortest path ensures that the scheduling window is independent of the particular path that may be used in assigning the route-time profile.

5.2.2. Scheduling

The scheduling function allocates the available threshold operation times between the arrivals and departures in a manner that satisfies the demand, ATC constraints, and airplane performance constraints. The possible arrival scheduling windows result from the sequencing function, as does the order in which arrivals are scheduled. If an airplane cannot be scheduled in this scheduling window, an entry fix hold is created (i.e., slowed prior to entry fix or put in a holding pattern) and the airplane is then scheduled at the earliest available threshold time. The functional form of the scheduling logic for arrivals is shown in figure 5-4.

The scheduling function builds a table of scheduled landing times by considering that each succeeding airplane must be given adequate separation from the airplane ahead. The separation may be either runway occupancy time of the airplane ahead or in-air separation times or distances.

When the preceding airplane has a faster final approach speed, in-air separation will be minimum at the outer marker. In this case, the threshold separation (schedule) is increased to provide satisfactory separation at the outer marker. Since the airplanes fly the common speed/path profiles from the initial approach fix to the outer marker, separation then exists in the entire near-terminal area.

Three separate schedulers were developed to evaluate different arrival-departure strategies. Scheduler 1 is used when arrivals have absolute scheduling priority. The arrivals are scheduled without regard to departure demand. The opportunity departures are then scheduled into any time space, occurring between arrivals, large enough to accommodate the departure.

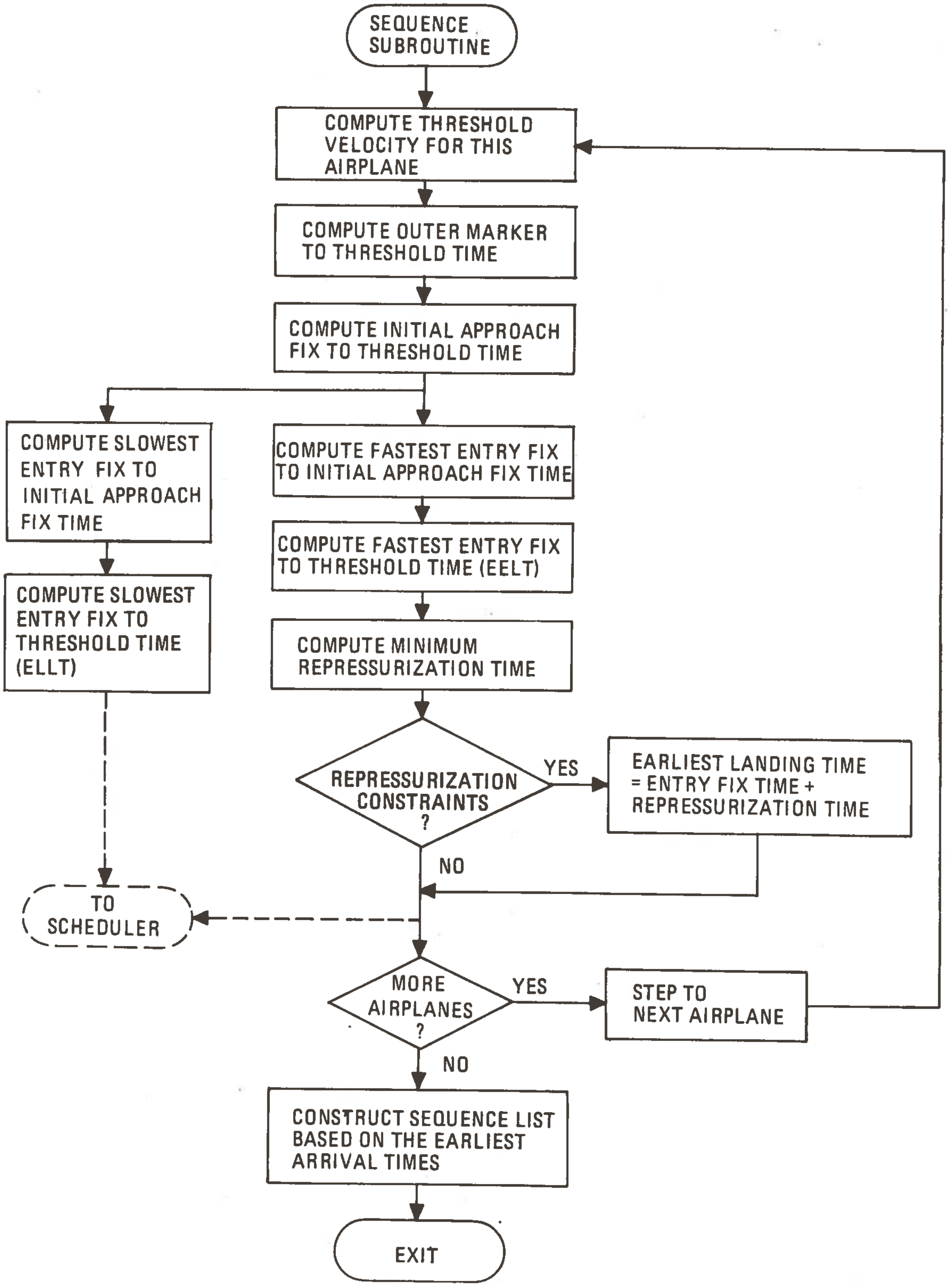


FIGURE 5-3.–SEQUENCING LOGIC

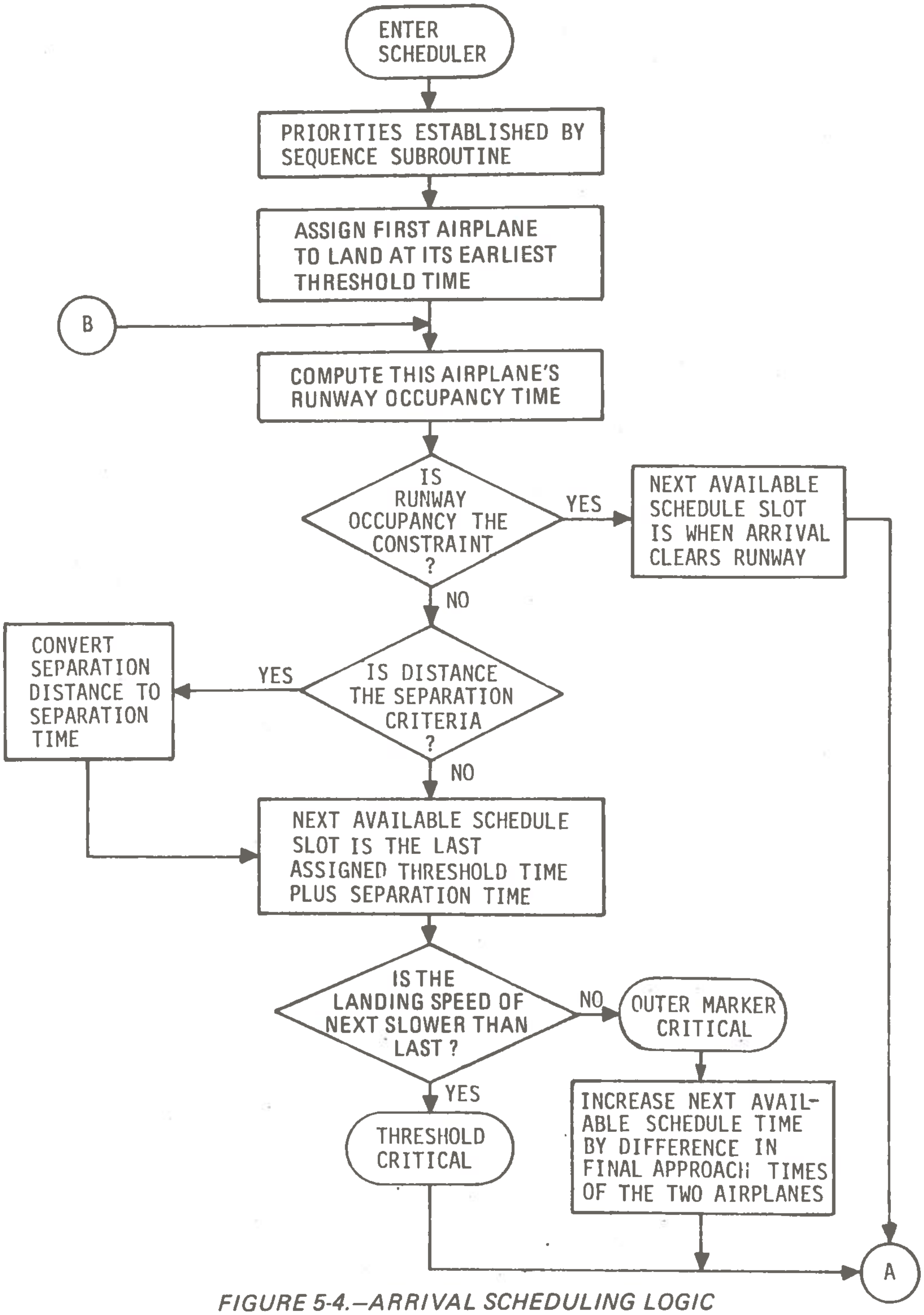


FIGURE 5-4.—ARRIVAL SCHEDULING LOGIC

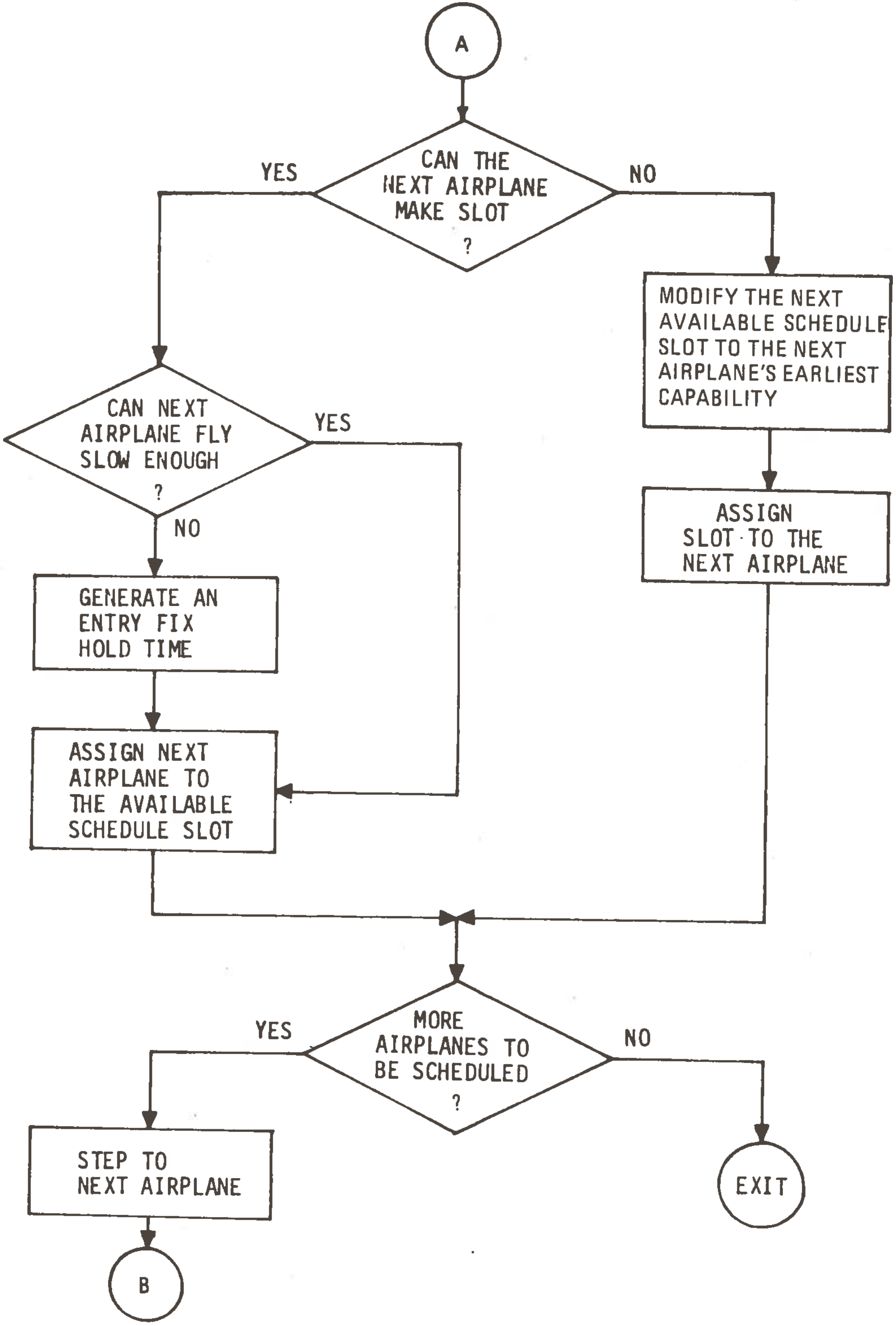


FIGURE 5-4.—CONCLUDED

Scheduler 2 is similar to scheduler 1 in that opportunity departures are interspersed in the arrival stream. The principal difference is that during arrival scheduling, arrival-arrival spacing is increased to provide departure time slots. These departure slots are large enough to accommodate any of the waiting departures.

Scheduler 3 schedules arrivals subject to predicted arrival and departure times. This scheduler balances the priority between the arrivals and departures, assuming both are available at the scheduling time.

5.2.3 Route-Time Profile Generation

The route-time profile (RTP) generation function determines the waypoints and times through which the airplane must sequence to achieve the scheduled landing time. This function ensures that the route-time profile is conflict free during execution. Figure 5-5 shows the logic for this function.

In generating the route-time profile, the wind, temperature, aeroperformance limits, and geometry are all considered. The process involves the following steps:

1) Determine the time required for the airplane to make a transition from the outer marker to the threshold by considering the outer marker distance and the planned final approach speed.

2) Determine the initial approach fix to outer marker time by considering the path geometry and the common speed profile.

3) Establish a target initial approach fix time by subtracting the above times from the scheduled landing time.

4) Determine a target time to transit the outer terminal area by differencing the estimated entry fix time and the target initial approach fix time.

5) Choose a velocity schedule consistent with the airplane's performance limits.

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

7) Compare the target and trial initial approach fix times. If they are not equal, adjust the velocity profile and repeat steps 5, 6, and 7 until the times agree. When agreement is reached, a route-time profile has been generated.

8) Test the route-time profile from step 7 against the airplane ahead on the trial path to determine if a conflict exists.

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

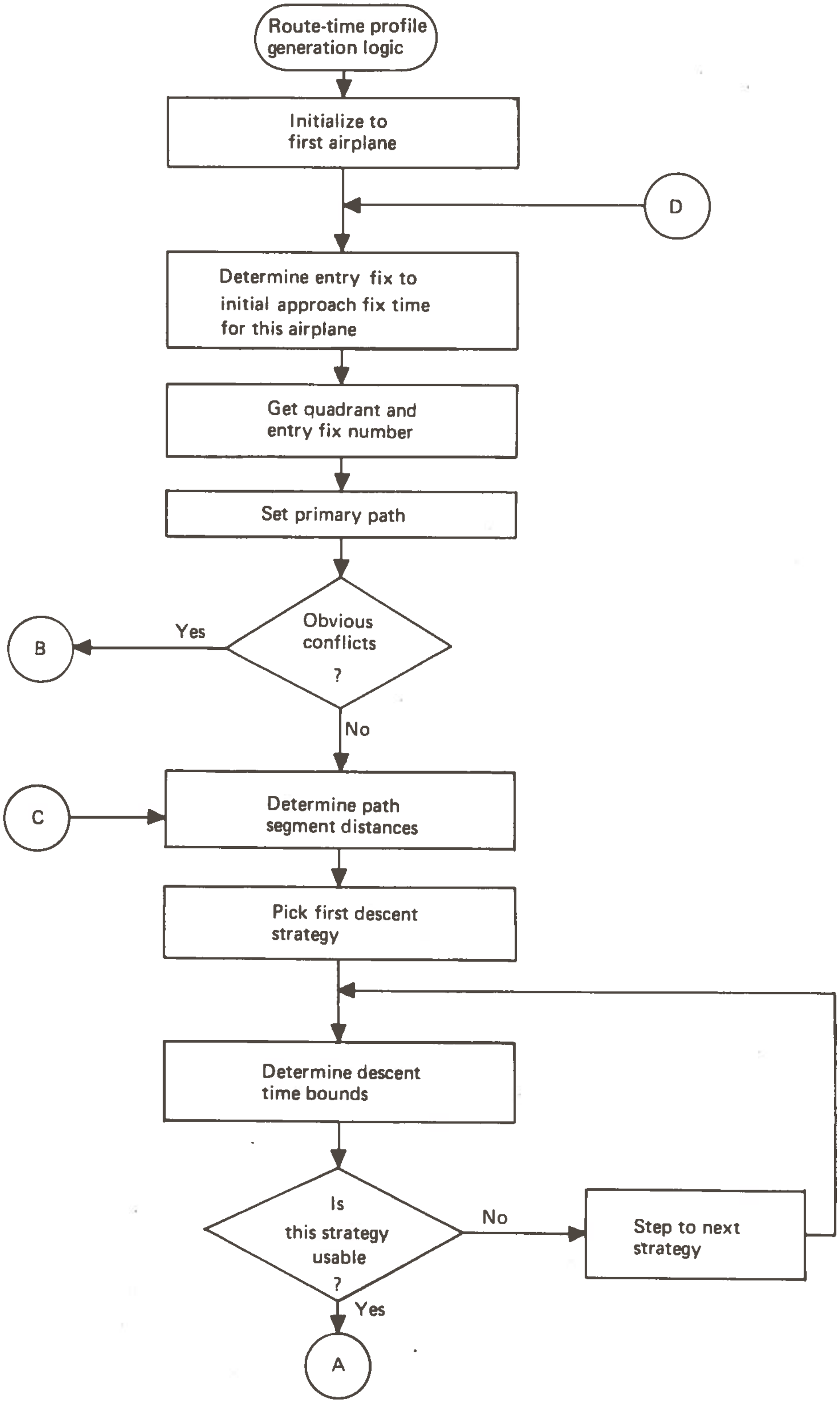


FIGURE 5-5.—ROUTE-TIME PROFILE GENERATION LOGIC

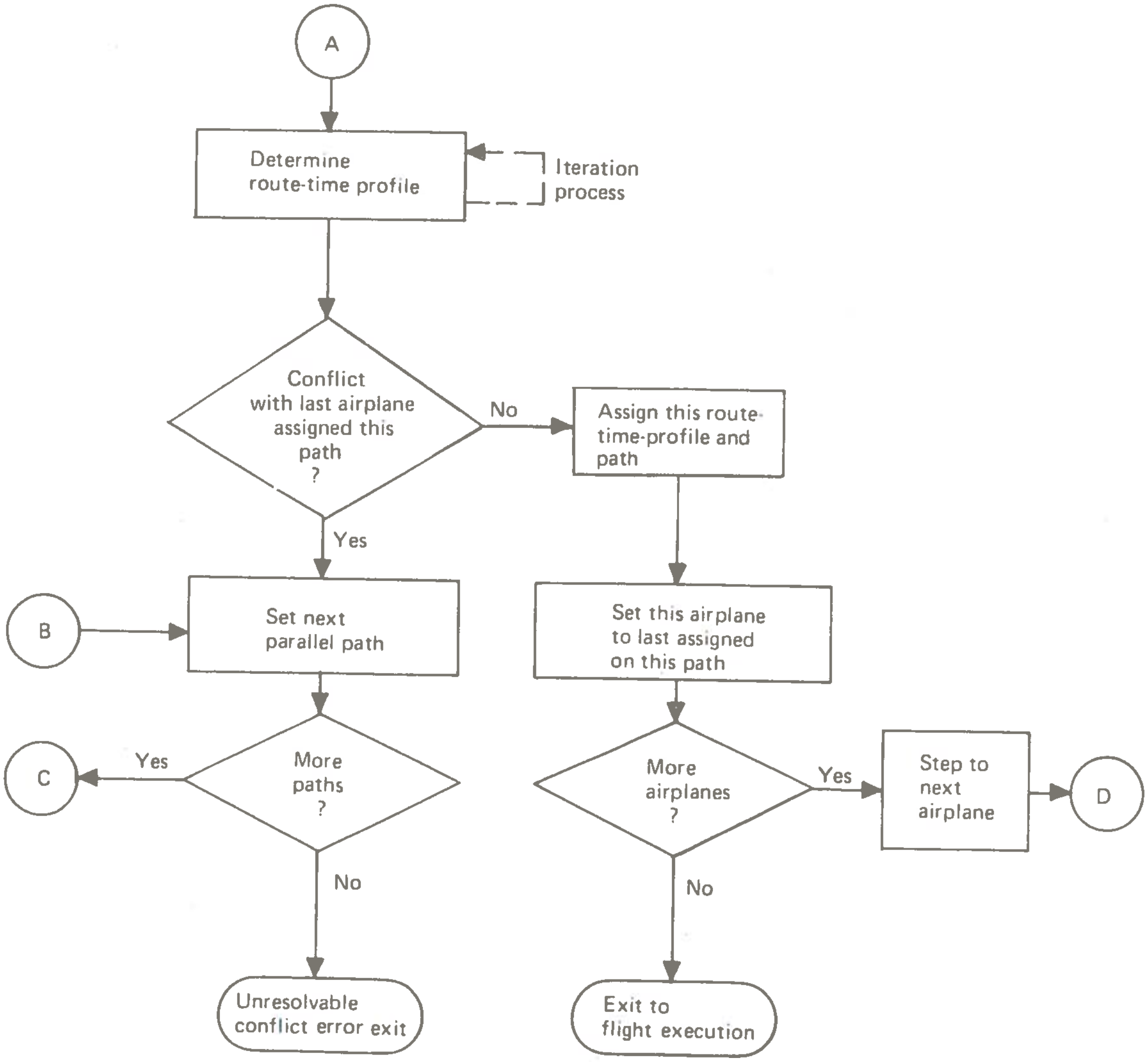
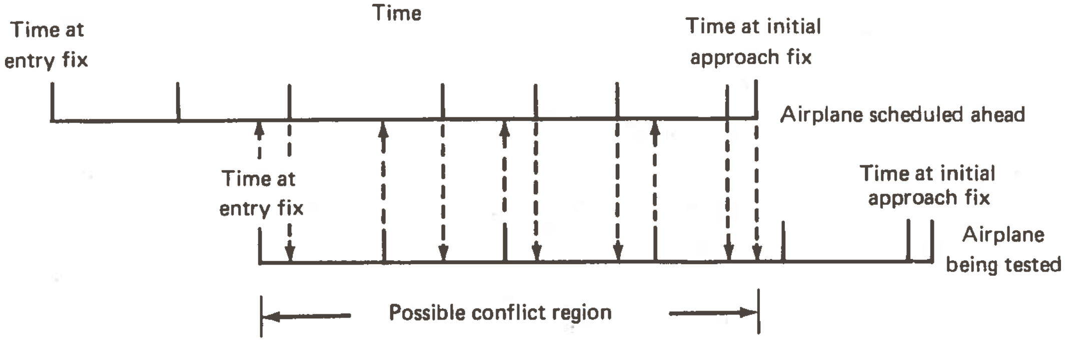


FIGURE 5-5.—CONCLUDED

Specific details for accomplishing this function are given in volumes II, III, and IV. Some general comments on the technique are provided below.

Figure 5-6 graphically shows the process and steps required for conflict detection. Basically, this process overlays the route-time profiles for two successive airplanes on a path and does a point-by-point comparison to ensure that separations are not violated.

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.

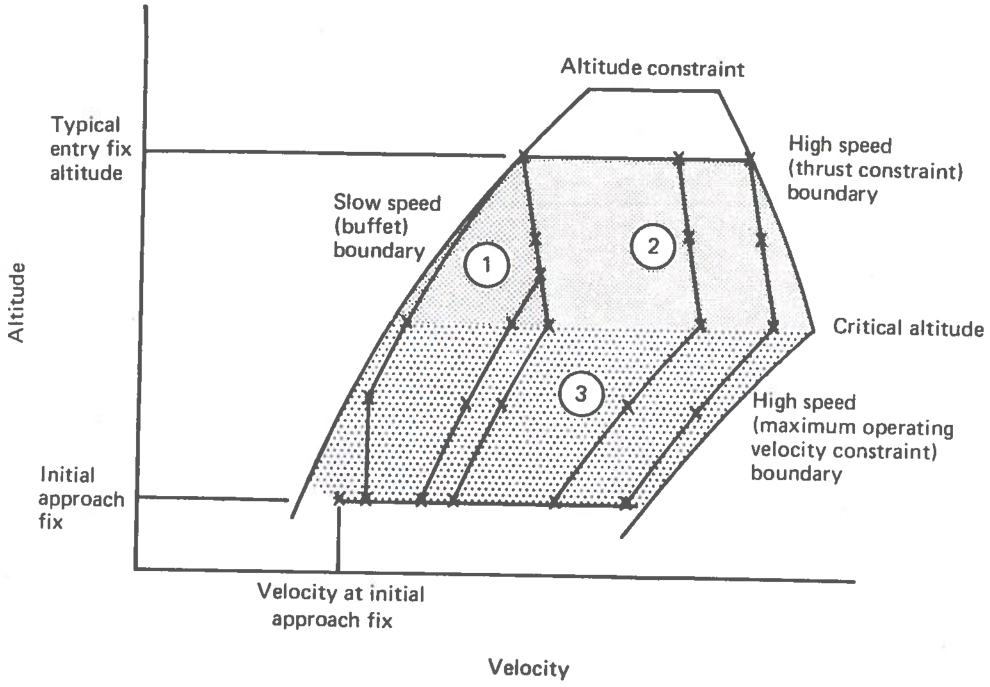
④ If constraints are violated, a conflict exists and a new trial path must be selected for the airplane being tested.

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

FIGURE 5-6.—CONFLICT DETERMINATION PROCESS

The process for determining route-time profile generation strategies is shown in figure 5-7. This figure indicates the relationships between the aeroperformance boundaries and the letdown trial velocity profiles. Table 5-1 shows the form of data generated for a single route-time profile. Interpretation of this table requires an understanding of the following aeroperformance considerations:

1) The airplane is required to fly faster than the low-speed boundary to keep from approaching a stall condition.



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 5-7.—ROUTE-TIME PROFILE GENERATION STRATEGIES

TABLE 5-1.– 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)

2) The airplane is required to fly slower than the high-speed boundary either because of structural limitations, typically placarded as V_{MO} (maximum operating velocity) or M_{MO} (maximum operating Mach), or because of a lack of engine power to exceed the thrust constraint.

3) Airplanes typically descend along constant Mach (M), constant calibrated airspeed (CAS), or a combination of the two lines. It should be noted that constant calibrated airspeed or Mach numbers represent different true airspeeds at different altitudes.

4) The altitude constraint shown may result from either insufficient power to climb higher or a structural limitation on cabin pressure differential.

6.0 ALGORITHM PERFORMANCE

To test and evaluate the algorithm, a fast-time simulation model of the terminal area was constructed. The algorithm was integrated into the model, and a set of experiments was conducted to assess algorithm performance and sensitivity to demand and subsystem capabilities.

6.1 EVALUATION MODEL

The model simulates strategic terminal area operations. A macro flow of the model is shown in figure 6-1. For this study, the terminal area geometry was set to represent strategic arrivals at Los Angeles International Airport (fig. 6-2).

The input traffic list is built by associating each flight from the traffic generator with an entry fix.

The strategic algorithm schedules the flights and generates a route-time profile for each flight using the path description for the associated entry fix and the stored aeroperformance and forecast wind/temperature data.

For flight execution, each flight is flown from entry fix to threshold. Airplane position is a function of the flight control system, including the effects of errors in the forecast winds and temperatures, the navigation system, and the guidance/control system.

The data for all flights are assembled in the output. The output provides:

- Summaries of
    - Runway operations per hour
    - Flow through each fix and along each path
    - Time and distance separation violations at the threshold and at each fix point
    - Scheduled and operational delay
- Operational statistics on separations, time in terminal area, and delay time
- Detailed schedules showing time, velocity, and altitude for each flight at each fix point

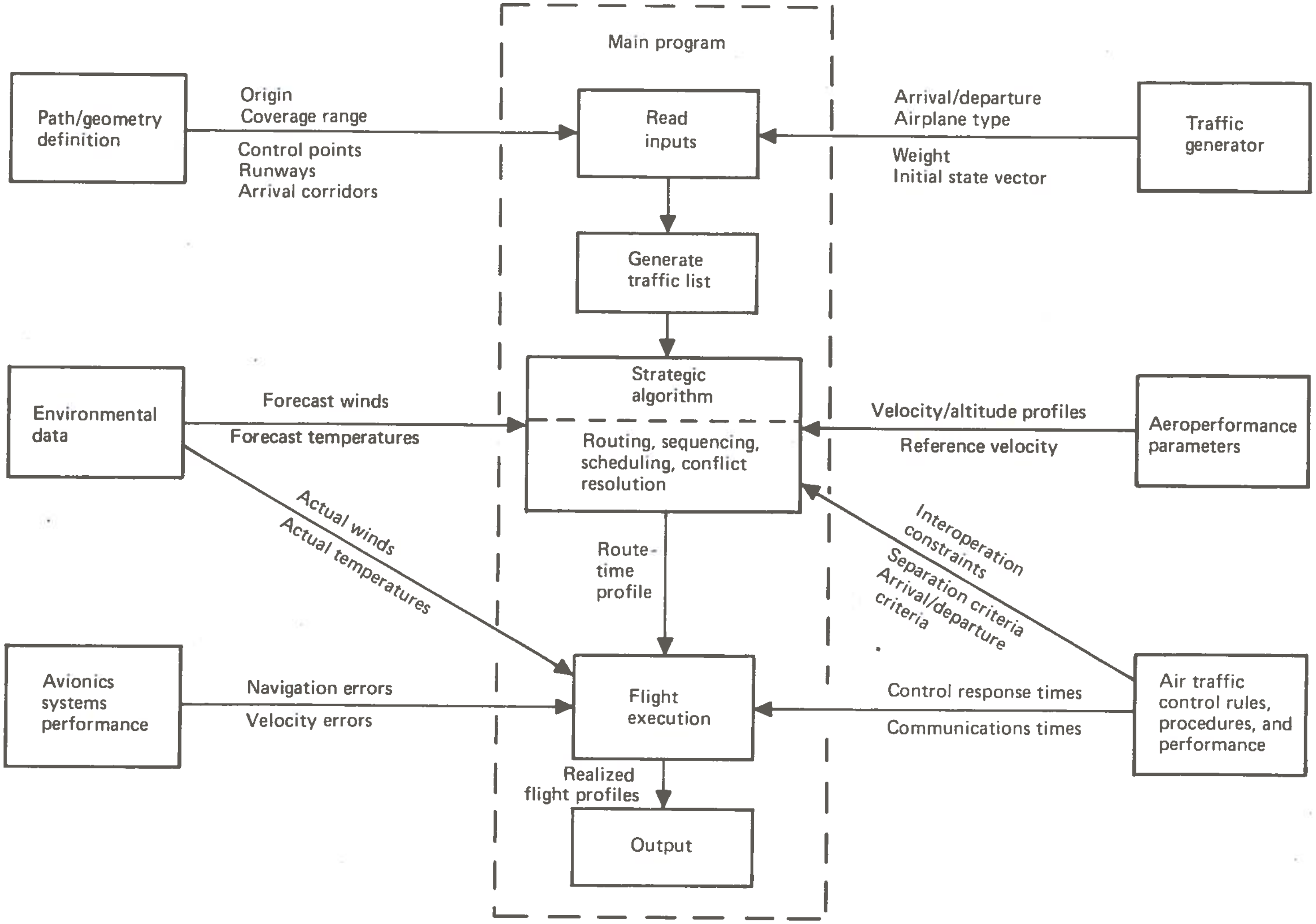


FIGURE 6-1.—STRATEGIC ALGORITHM EVALUATION MODEL MACRO FLOW

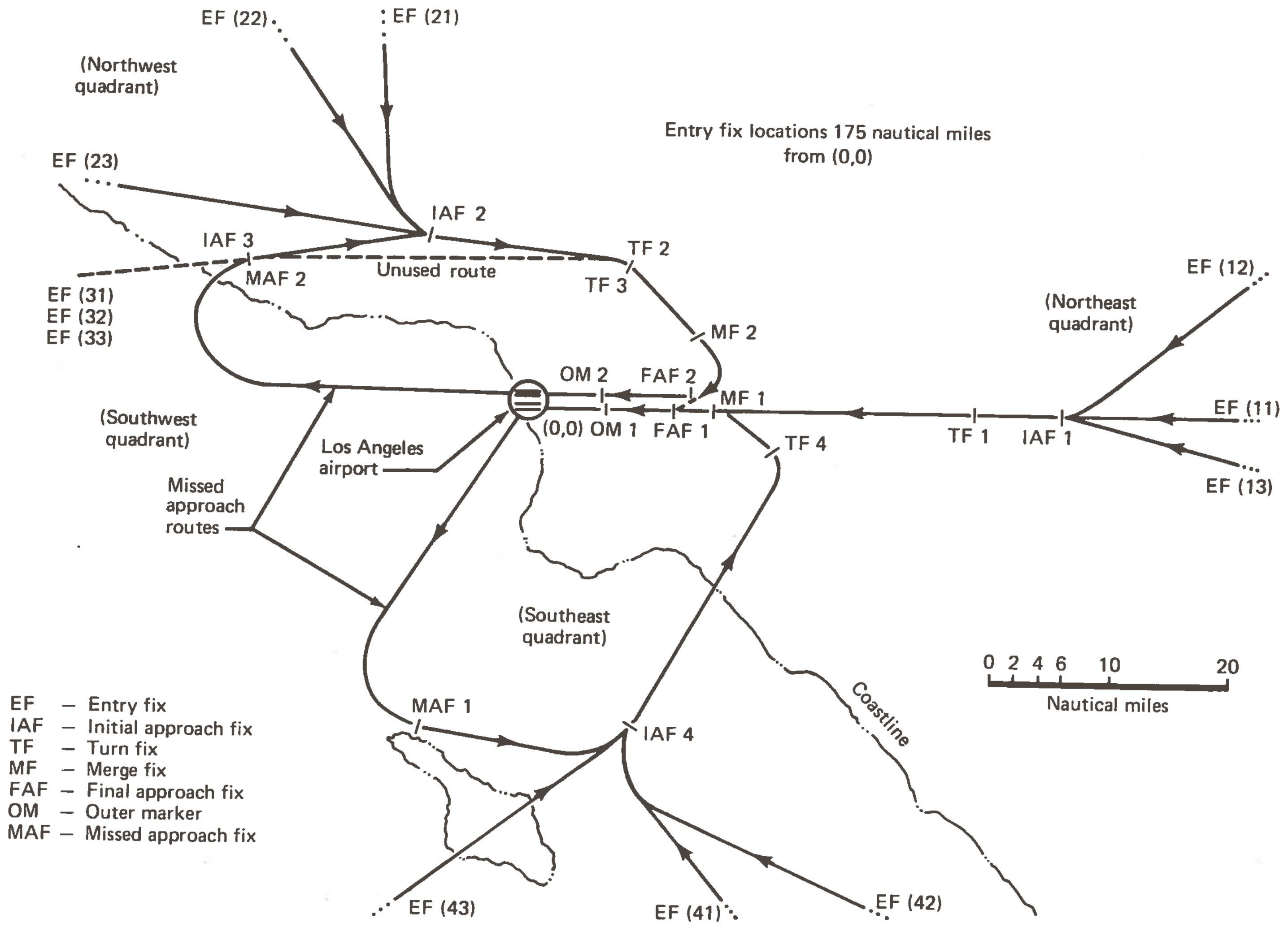


FIGURE 6-2.—LOS ANGELES STRATEGIC ARRIVAL GEOMETRY

6.2 EXPERIMENT PLAN

The basic set of experiments was designed to test the logic of the algorithm for arrivals to a single runway, as well as to assess the sensitivity to navigation/guidance accuracy, schedule-keeping accuracy, control radius, and throughput (number of arrivals and/or departures processed per hour). In addition, the experiments tested the algorithm for scheduling of departures, operation to dual parallel runways, handling of future Los Angeles International Airport type operations, and the impact of unequipped and unanticipated arrivals.

Table 6-1 shows the experiment/data set matrix. Vertical lines on the matrix represent data sets. One evaluation model run was made per data set. A collection of one or more data sets constitutes an experiment. A zero value on a vertical line (data set) indicates that the corresponding parameter value on the horizontal line was used. Other values are explained in the key at the bottom of the page.

6.3 PERFORMANCE

The basic algorithm for arrivals to a single runway was tested with system errors set to zero. It was free from conflicts, verifying the basic logic. Tables 6-2 and 6-3 show the path usage for the 1972 and 1995 Los Angeles traffic. These data indicate that parallel paths between entry fix and initial approach fix are required, but since only three were used, the airspace needed is small.

The arrival-only algorithm was run with three different levels of navigation and control performance. Navigation errors are measured as the difference between the true and the intended position. Control errors are the difference between the intended and the perceived position. Values selected were:

Performance level	Navigation error (nautical miles)	Control error (seconds)
Low	0.50	10
Medium	0.10	5
High	0.05	2

Figure 6-3 summarizes the effect of avionics (navigation and controls) performance by plotting probability of conflict on final approach against a parameter combining the navigation and control errors. Using a criterion of 1% conflicts, the avionics performance requirements are:

	1972 Los Angeles traffic	1995 Los Angeles traffic
Navigation error	0.2 nautical mile (one sigma)	0.1 nautical mile (one sigma)
Control error	6 seconds (one sigma)	3 seconds (one sigma)

These are the performance levels that an equipped user would be required to meet in order to fly in the strategic control system.

TABLE 6-1.—EXPERIMENT/DATA SET MATRIX

EXPERIMENTS

ALTERNATIVE PARAMETER VALUES	1. Debug Algorithm		2. Navigation/ Guidance Accuracy Requirements					3. Schedule Keeping Accuracy					4. Control Radius 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 Impact
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
125 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 ariplanes input.

TABLE 6-2.—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 6-3.—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									

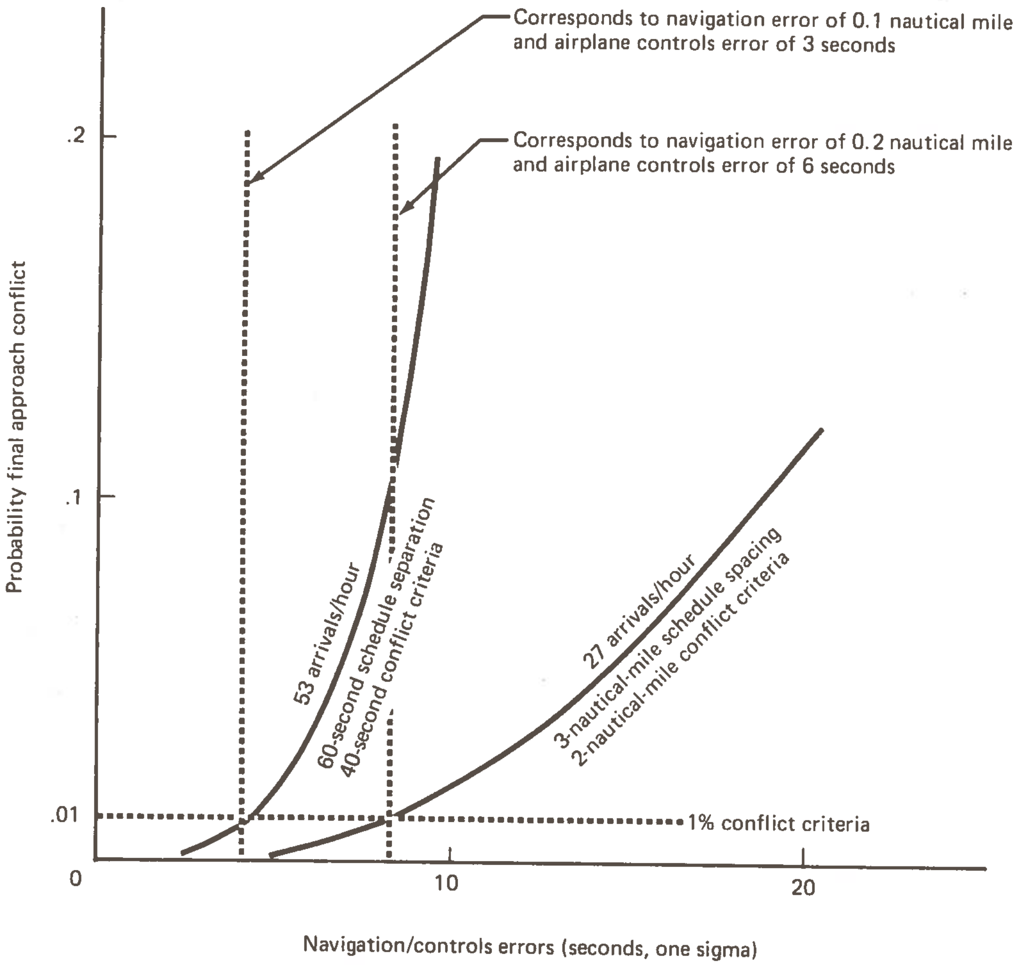


FIGURE 6-3.—NAVIGATION/CONTROLS REQUIREMENTS

6.3.1 Schedule-Keeping Accuracy

The sensitivity of strategic control to entry fix arrival accuracy (relative to the scheduled entry fix time) was investigated. Arrivals were uniformly distributed within the hour, since variation about today's essentially random within-hour schedule would not be productive. The most important criterion is for the system to accept arrivals without holding at the entry fix.

Figure 6-4 shows the results for the 1972 and 1995 demand levels (27 and 53 arrivals per hour, respectively). Since en route holding will occur when delay reaches 6 to 8 minutes (depending on entry fix location and airplane type), it appears that a schedule-keeping accuracy of 300 seconds (one sigma) would suffice for 1972 but this should be tightened to about 60 seconds (one sigma) for 1995—assuming a basically uniform schedule.

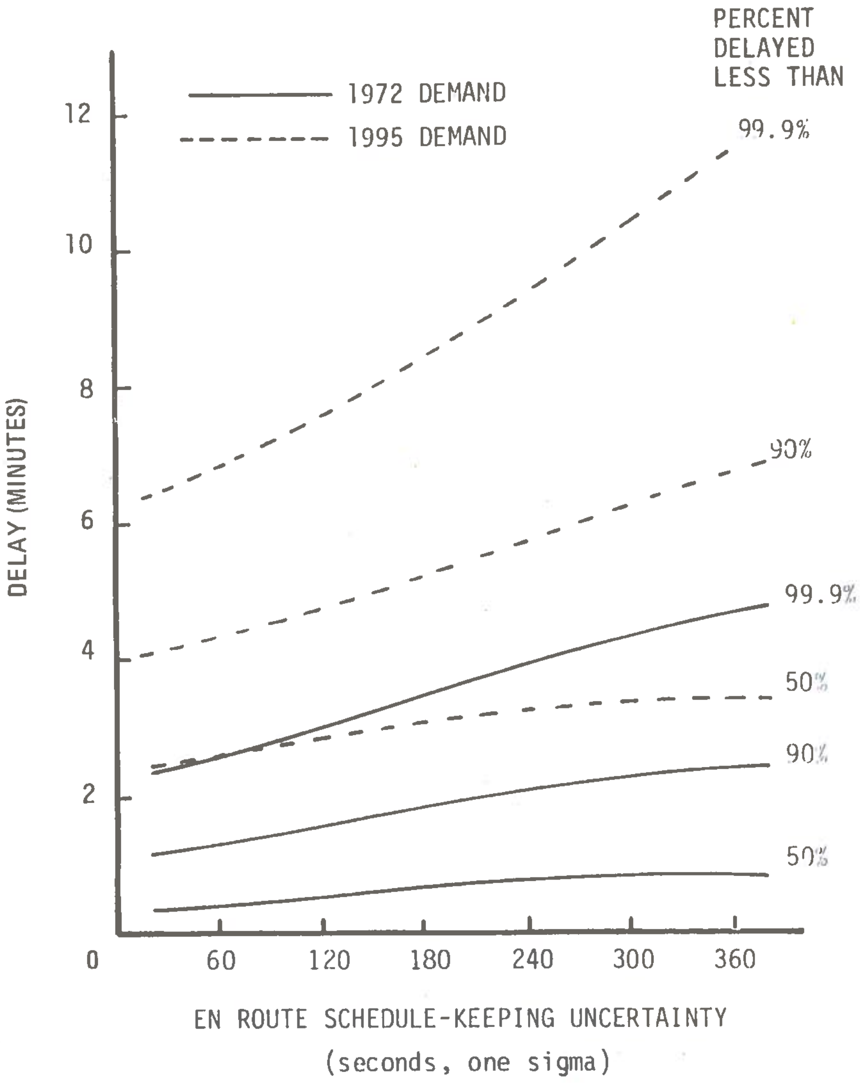


FIGURE 6-4.—DELAY SENSITIVITY TO EN ROUTE DELIVERY ACCURACY

Analysis using an airline type schedule indicated that the 1972 traffic would have essentially no entry fix holds; when grown to 1995 levels, however, there could be up to 30% entry fix holds for one runway or up to 10% holds for two runways. Thus, a uniform within-hour schedule with 60-second (one sigma) en route schedule-keeping accuracy appears to be the 1995 requirements.

6.3.2 Control Radius Sensitivity

The control radius was varied between 150 and 200 nautical miles. As the distance increased, more airplanes could use the primary path and some delay reduction accrued. Evaluation model results indicate the control concept is relatively insensitive to changes in control radius over the 150- to 200-nautical-mile range.

6.3.3 Arrival Throughput Sensitivity

Arrival throughput (the number of arrivals processed per hour) to a single runway was varied for interoperation times from 60 to 132 seconds (60 to 27 operations per hour). A uniform within-hour arrival schedule was assumed. The higher throughput increased the use of offset paths and the total delay, but without the need for more paths or for entry fix holding.

6.3.4 Departure Scheduling Strategies

Three departure scheduling strategies were tested for the 1972 Los Angeles traffic to a single runway. The first scheduler provides absolute priority for arrivals, with departures scheduled as the opportunity arises. The second scheduler increases the arrival-arrival spacing to allow for a departure if it is available. The third scheduler assigns arrival and departure time slots on an equal priority, assuming advance notice of departure operations.

Figures 6-5 and 6-6 show the cumulative probability of delay for arrivals and departures, respectively, for each scheduler. It can be seen that the departure delays for scheduler 1 are excessive. Scheduler 2 and 3 delays are similar and within acceptable bounds. Thus, at the 1972 traffic level, operations would be acceptable without the burden of advance notice of departures (scheduler 2).

6.3.5 Future Operations

Los Angeles International operations were simulated as two dual-lane runway pairs: one for northeast and southeast traffic (runways 24 R/L) and one for northwest and southwest traffic (runways 25 R/L). For each runway pair, arrivals were assumed on one surface and departures on the other. Scheduler 2 was used, giving priority to arrivals with interspersed departures.

The 1995 traffic demand was slightly over 100 operations per hour. A 60-second arrival-arrival spacing was used. Figure 6-7 shows the cumulative probability of delay curves for arrivals and departures.

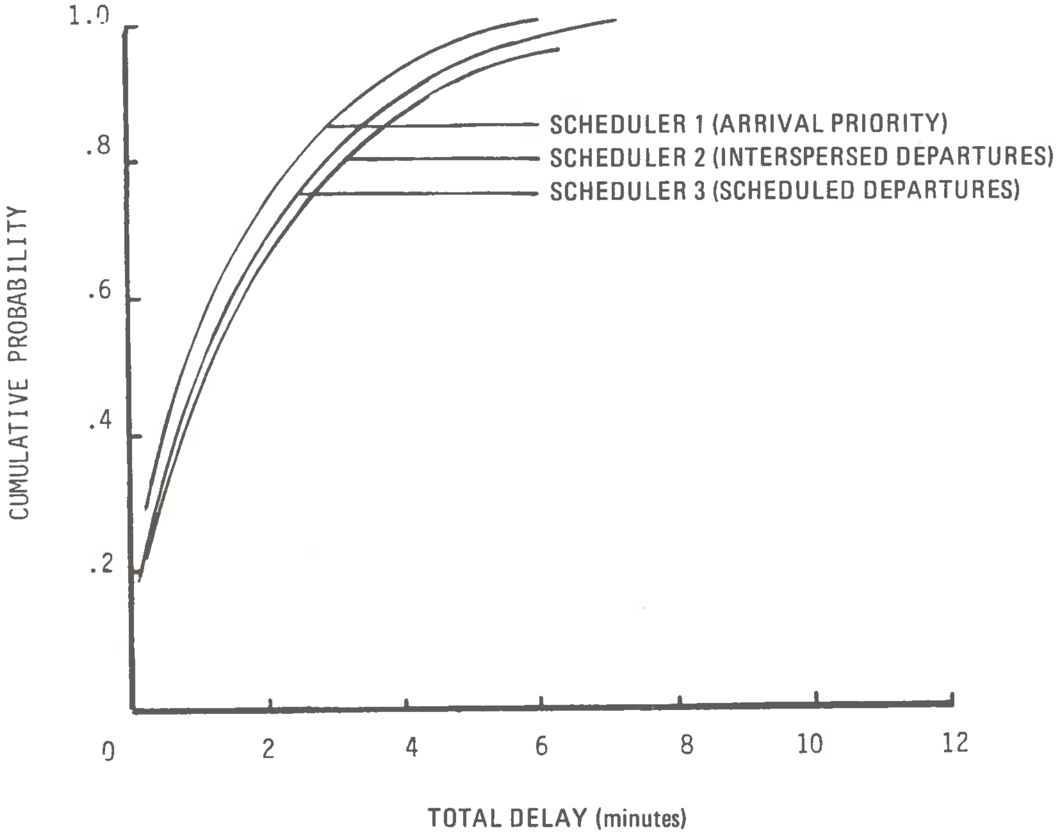


FIGURE 6-5.—ARRIVAL DELAY DISTRIBUTIONS

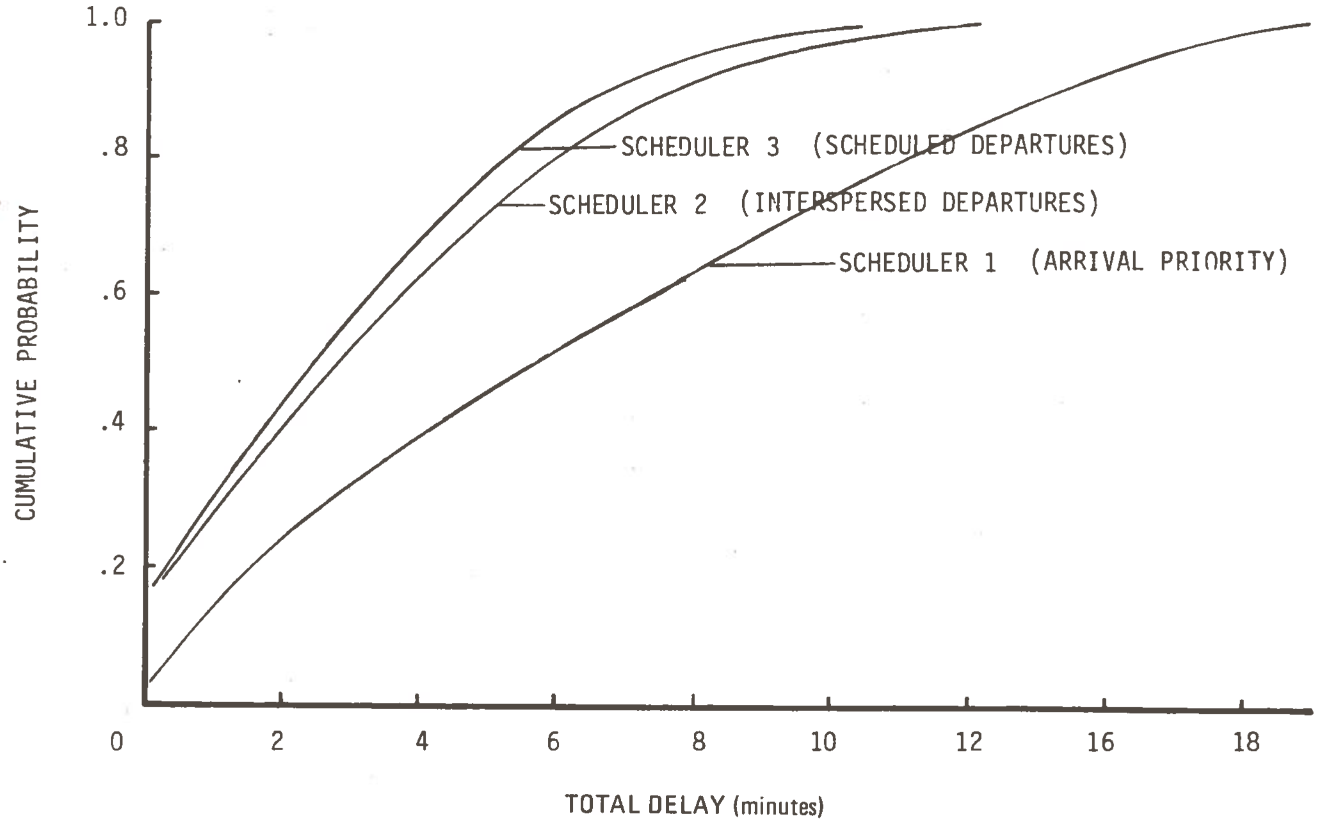


FIGURE 6-6.—DEPARTURE DELAY DISTRIBUTIONS

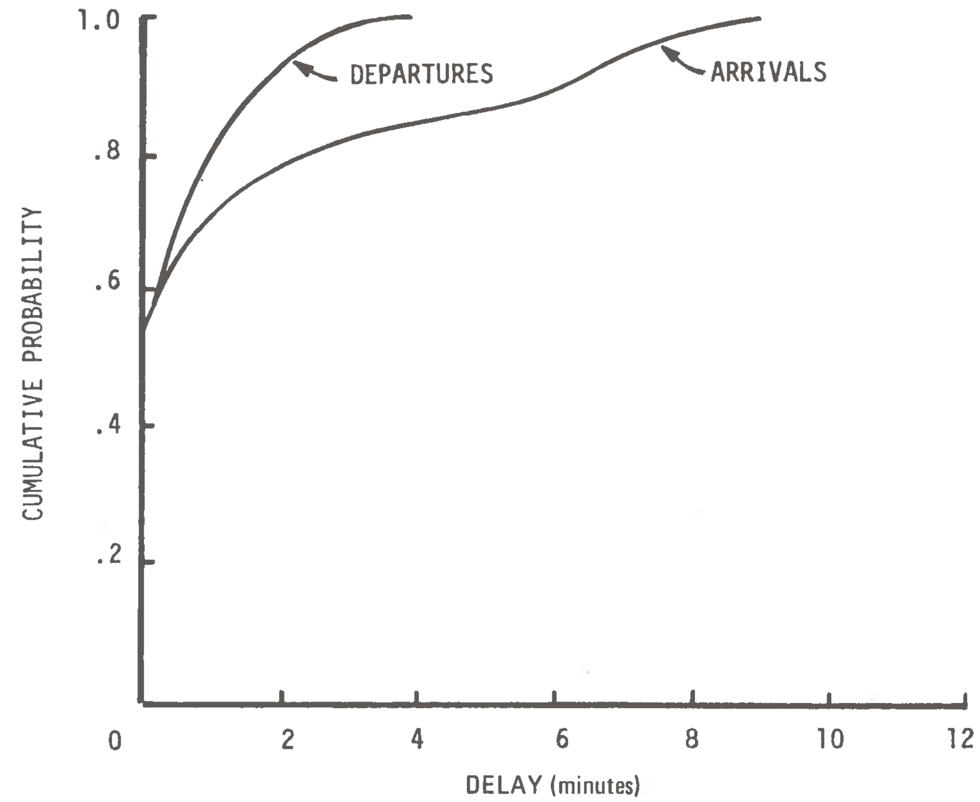


FIGURE 6-7.—LOS ANGELES OPERATIONS DELAY DISTRIBUTIONS

6.3.6 General Aviation Impact

The arrivals-only case for a single runway was run using the 1972 Los Angeles International traffic set. Five unequipped airplanes per hour were inserted near the runway into special nonstrategic user time slots to demonstrate the capability of the algorithm to handle general aviation. This general aviation load (five out of 32 operations per hour) only slightly increased (from 1% to 1.3%) the probability of exceeding the 2-nautical-mile in-air safety constraint.

7.0 BENEFITS

The Federal Aviation Administration (FAA) presently controls traffic in high-density terminal areas using manual radar vectoring. An automated control system called metering and spacing is being developed wherein a computer calculates the required vectoring instructions. Strategic control is potentially the successor to either of these control systems. Therefore, the benefits analysis was based on comparing performance using strategic control to that achievable with manual vectoring or metering and spacing. ("Basic" metering and spacing was assumed: ARTS III computes and displays speed, heading, and altitude commands to the control, who in turn relays these commands by voice communication to the pilot [ref. 5]).

The potential benefits of strategic control are increased ATC system capacity (or reduced delay for a given level of operations), reduced airplane operating costs, reduced ATC system operating costs, and increased safety. The particular advantages of strategic control that provide the basis for these benefits are given below.

- *Minimum Airspace Requirements*—Since spacing control is exercised along track, only the safety buffer around the track needs to be protected and additional airspace is *not* required for path stretching. This maximizes airspace capacity, increasing the freedom of flight and reducing the number of situations where lack of available airspace constrains airfield operations.

- *More Flexibility in Use of Available Airspace*—Since the terminal area track shape is adaptable and easily varied, the number and location of tracks can be changed to fit the existing traffic situation.

- *Reduced Flight Time*—With all control exercised along track, the arrival flightpath does not require that the nominal track be longer to allow for path stretching and shortening; thus, the nominal flight time is reduced.

- *Reduced Controller Workload*—Strategic control automatically provides safe separation between airplanes, with the controller normally monitoring only the traffic flow. Thus, the controller workload of generating and issuing control instructions is removed as a constraint on the flow rate, and the workload per operation should be substantially reduced.

- *Reduced Communications*—Since the path control function is contained entirely within the airplane and does not require ground-based guidance, the only control communciation involved in the direct control of airplanes is path assignment. Thus, communication load is removed as a constraint on flow rate.

- *More Precise Airplane Control*—The increased precision by the airplane to control along-path position versus time results from having the guidance and control entirely within the airplane, allowing reduced yet safe separation between airplanes.

- *More Optimum Flight Tracks*—System flexibility provides more opportunity for individual flights to fly the most desirable path from the operator's standpoint.
- *Continued Operation During ATC Service Interruption*—When the strategic ATC system is interrupted, each airplane already has an assigned conflict-free flightpath, and can continue toward its destination in relative safety compared with an ATC system that relies on continuous ground surveillance for safe separation.
- *Independent Navigation and Surveillance*—In an ATC system such as today's, the surveillance and navigation environments are separate systems. Strategic control, by using the surveillance system for separation monitoring and the navigation system for airplane path control, provides separately redundant protection against either ground or airborne blunders. This protection is not available in manual vectoring or basic metering and spacing since both path control and separation monitoring are provided by the ground surveillance system.

Table 7-1 summarizes the benefits analysis, in terms of percentage improvement for selected criteria, relative to today's manual vectoring at the Los Angeles International traffic level. Details of each of these benefits with derivation of the numbers is contained in volume II, section 8. Some highlights of these results follow.

TABLE 7-1.—BENEFITS SUMMARY

EVALUATION CRITERIA	PERCENT IMPROVEMENT OVER MANUAL VECTORING*	
	BASIC METERING AND SPACING	STRATEGIC
RUNWAY OPERATIONS RATE	28.7	48.8
TOTAL DELAY (Daily Avg)	64.3	96.4
TERMINAL AREA FLOW RATES	50.0	100.0
NOMINAL TRACK LENGTH	-13.4	-1.8
NUMBER OF CONFLICTS	34.2	60.0
CONTROL WORKLOAD	33.3	66.7
COMMUNICATION LOADING	23.2	53.9

*1972 TRAFFIC LEVEL

7.1 INCREASED CAPACITY

With controller workload and communications removed as constraints and increased precision in delivery of airplanes to the final approach fix, airfield capacity can be increased. Figure 7-1 shows the relative capabilities of manual vectoring, basic metering and spacing, and strategic control to handle Los Angeles International traffic.

The key assumptions to this analysis were:

- IFR operations using Los Angeles International Airport traffic schedule and mix were assumed.
- An independent pair of closely spaced parallel runways was used.
- Control and communications workload would constrain the arrival spacing to 3 nautical miles for manual vectoring and 2.5 nautical miles for basic metering and spacing.
- Wake turbulence was removed as a constraint.
- The relative delivery accuracies for manual vectoring, metering and spacing, and strategic control were 18, 8, and 2 seconds (one sigma), as detailed in volume II, section 8, at the final approach fix.
- Strategic control could define diverging paths immediately upon takeoff, so departure-departure spacing was constrained only by potential collision on the runway (first aircraft 6,000 feet and airborne).

Figure 7-1 indicates that under today's (1972) actual IFR conditions:

- Los Angeles International Airport could experience significant delays during the busy hour (Friday, May 1972).
- Basic metering and spacing could reduce the average busy-hour delays below the desired Department of Transportation criterion of 6 minutes (ref. 6).
- Strategic control provides for growth to twice today's traffic level.

7.2 AIRSPACE USE

Airspace requirements for manual radar vectoring generally include a volume of airspace inside each initial approach fix for path stretching and airspace to allow stretching of the downwind leg. Figure 7-2a shows the current nominal arrival and departure routes (west flow) for Los Angeles International. The terminal control area (shaded) indicates some of the airspace requirements. That additional airspace most frequently used for vectoring is also shown.

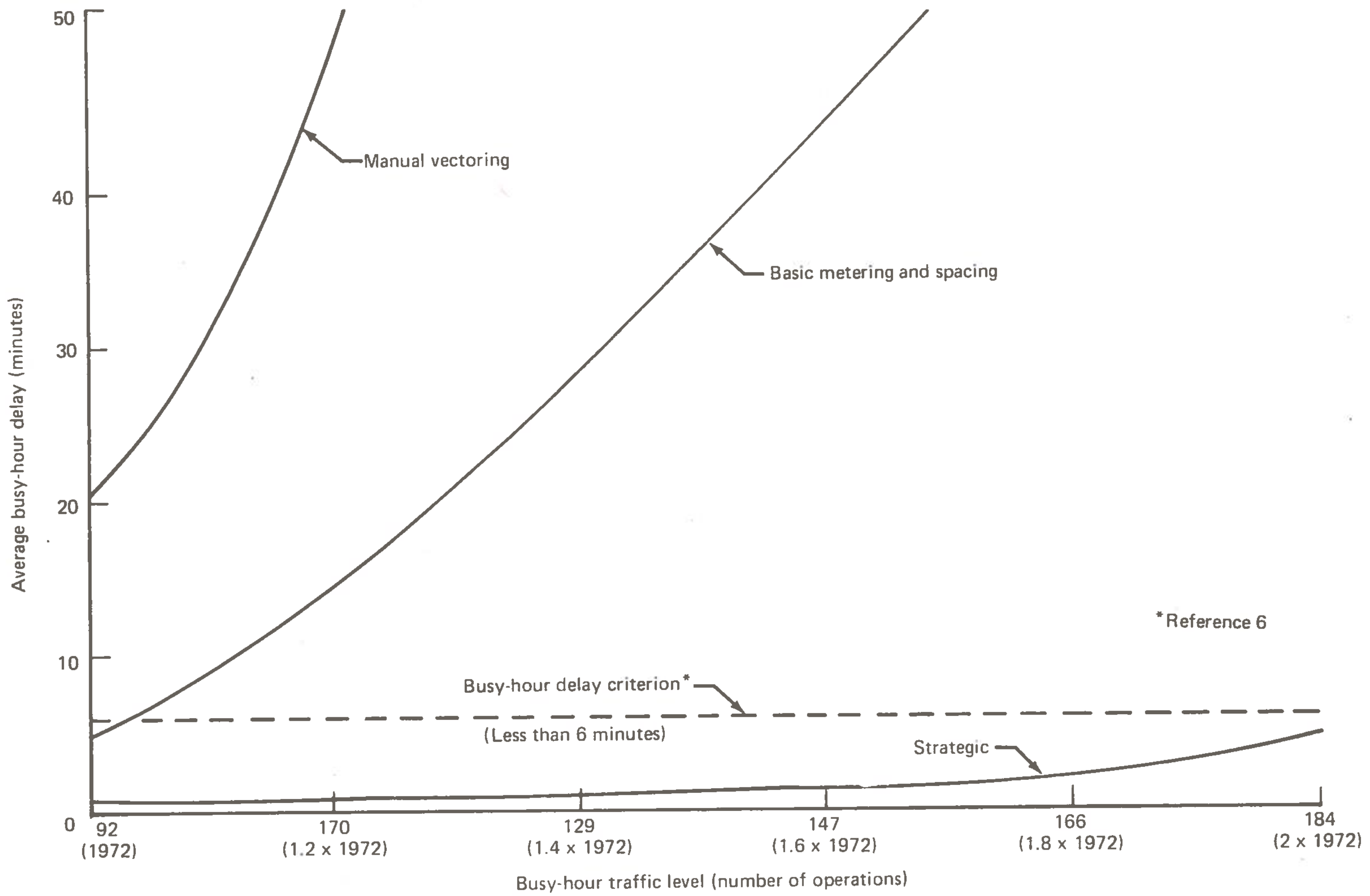
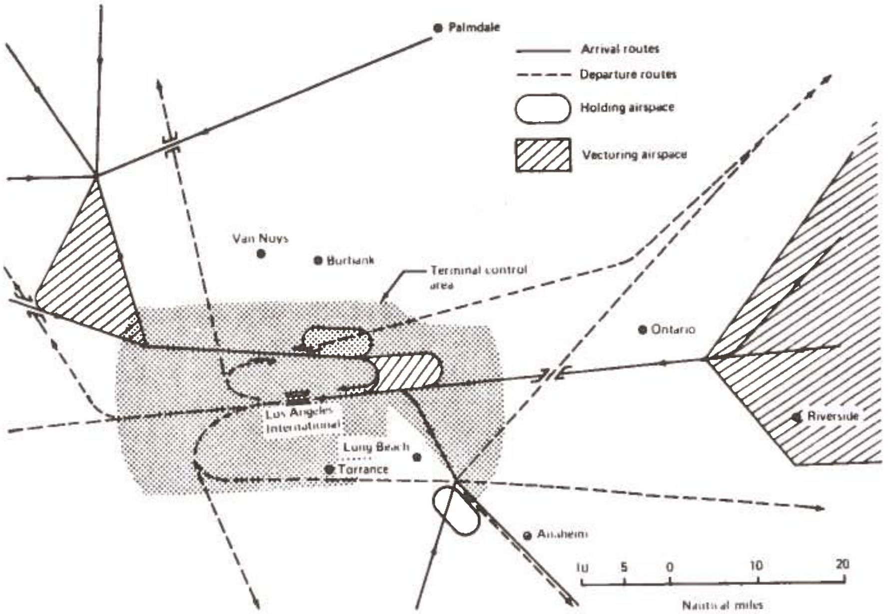
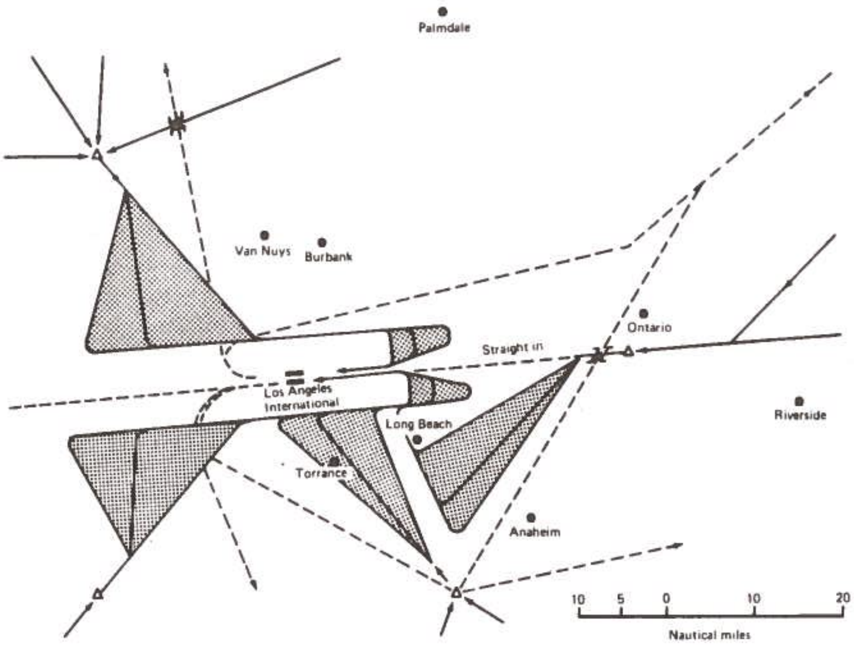


FIGURE 7-1.—BUSY-HOUR DELAY COMPARISON—IFR OPERATIONS



a. WITH PRESENT VECTORING AND HOLDING PROCEDURES



b. WITH METERING AND SPACING

FIGURE 7-2.–LOS ANGELES INTERNATIONAL TERMINAL AREA ROUTING

Figure 7-2b shows the nominal basic metering and spacing airspace requirements for Los Angeles International. Although this may be considered to represent a worse-case application, it was not apparent how else the ±2-minutes adjustment (ref. 7) by path length variation inside the initial approach fix could be accomplished.

Strategic control would use terminal area airspace equivalent to only the basic routes (2 miles or less in width) of figure 7-2a without additional vectoring airspace. This will make valuable low-altitude terminal area airspace available for other uses.

7.3 AIRSPACE ANALYSIS

Structures for the Los Angeles International arrival airspace were developed representing today's operations, a possible application of metering and spacing, and the strategic control concept. These structures were used to configure an airspace simulation model, and traffic was flown through them to develop relative benefit measures for airplane economics, conflicts, and control workload.

The track lengths and their associated flying times were measured as detailed in volume II, section 8. The results show that the nominal track length for a system based on the metering and spacing concept would be 19 nautical miles and 5 minutes longer than the present manual vectoring system or the strategic concept system. This difference would be applied to every approach; by extrapolation to future traffic loads, the average-day economic savings shown in table 7-2 are obtained.

TABLE 7-2.—AIRPLANE ECONOMIC RESULTS (AVERAGE DAY)

Demand year	Average day approaches (air carrier)	Reduction of flying penalties (strategic over basic metering and spacing)	
		Distance (nautical miles)	Time (minutes)
1972	500	9,500	2,500
Low 1995	930	17,700	4,650
Medium 1995, Low 2020	1,290	24,500	6,450
High 1995, Medium 2020	1,760	33,400	8,800
High 2020	2,600	49,400	13,000

The relative number of conflicts and relative workload (in percent of the 1972 manual vectoring case) are combined in table 7-3. Since the model did not resolve the conflicts, they are a measure of the demand on the control system. For manual vectoring and metering and spacing, this would be a real-time load; for strategic control, it would be the load on the data processing system.

TABLE 7-3.—CONTROL WORKLOAD MEASURES

Traffic level	Concept	Relative workload (percent of 1972—manual vectoring)			
		Number of conflicts	Airplanes involved	Duration of conflict	Total
1972	Manual vectoring	100	100	100	100
	Basic metering and spacing	70	80	50	67
	Strategic	40	50	10	33
Twice 1972	Manual vectoring	660	470	460	530
	Basic metering and spacing	250	200	160	203
	Strategic	130	150	40	107
3 times 1972	Manual vectoring	1320	710	950	990
	Basic metering and spacing	500	360	300	390
	Strategic	240	310	80	210
4 times 1972	Manual vectoring	1740	950	1240	1310
	Basic metering and spacing	630	500	420	520
	Strategic	300	420	110	270

7.4 COMMUNICATIONS ANALYSIS

Table 7-4 presents communications links required as a relative measure of the communications loading. To provide a common basis for comparison, the analysis equates all three control concepts to voice communication. Placement of path control within the airplane in the strategic system is responsible for the dramatic reduction in required air-ground communications. Details of this analysis are given in volume II, section 8.

7.5 POTENTIAL COST SAVINGS

A general analysis was made of the potential cost savings that could accrue by using strategic control. The findings as applied to Los Angeles International Airport traffic are summarized in table 7-5. The sources of savings considered are:

- Increased airport revenue due to increased operations
- Decreased airplane direct operating costs due to reduced delay

TABLE 7-4.–COMMUNICATION LINK REQUIREMENTS

Demand year	Number of approach control communication links required*			Number of busy-day approaches
	Manual vectoring	Basic metering and spacing	Strategic	
1972	2	2	1	622
Low 1995	4	4	2	1165
Medium 1995, Low 2020	6	5	3	1610
High 1995, Medium 2020	8	6	4	2200
High 2020	11	9	5	3250

*Assuming 90% loading—links at Los Angeles International Airport approach control.

TABLE 7-5.–STRATEGIC CONTROL COST SAVINGS SUMMARY

Source of savings	Annual savings over basic metering and spacing at Los Angeles International (millions of dollars)	
	1972 (1)	1995
Increased operations	14.0	27.0
Reduced airplane delay	12.1	1147.0 (2)
Reduced passenger delay	4.0	389.0 (2)
Flightpath length reduction	10.0	18.6
Control workload reduction	0.3	0.5
Total	40.4	1582.1

(1) Assuming both systems operating

(2) Based on "unacceptable" delays in the metering and spacing case

- Value of passenger time saved due to reduced delay
- Decreased airplane direct operating costs due to reduced average flightpath length
- Savings by the government due to reduction in the number of controllers needed to handle the traffic

The 1972 traffic level cost savings by using strategic control rather than metering and spacing is considered realistic. The analysis produced an estimated cost savings of about $40 million annually for one airport. Many other U.S. airports could similarly effect substantial cost savings.

On the other hand, the assumption that 1995 Los Angeles International traffic would be handled with metering and spacing with a 60-minute average delay per operation is considered impractical. The numbers (average $1.5 billion annually) only infer relative savings if strategic control were selected as the solution.

8.0 RECOMMENDED RDT&E PLAN

A plan was developed for carrying strategic control from the present conceptual stage to the point where the feasibility, system description, technology, and performance are known in sufficient detail to allow commitment to an implementation program with minimum technical and fiscal risks.

8.1 BASIC PLAN

The plan was arranged along five lines of investigation appropriately integrated to progressively increase the capability in relationship to funds invested. A summary of the plan is given in figure 8-1. The analysis tasks generally precede development, providing maximum knowledge for the least investment. A parallel technical development of the avionics is the key to successful system development. The analysis proceeds through software development and avionics development through flight testing to merge into the mainstream simulation and evaluation effort.

Proof of concept feasibility must rely on an extensive real-time simulation integrated with a "live" airplane since the cost of obtaining and operating a fleet of equipped airplanes would be prohibitive.

The plan is arranged to provide development of the most needed (and most beneficial) capability (arrival control) first and then progress through development of the less urgent capabilities until total strategic control capability is available. Tasks 1 through 4 step from: basic arrivals only; to complete arrival control including nonstandard efforts such as go-arounds and runway reversal; to incorporation of departure control; to extended capabilities including potential en route control applications.

The plan recognizes existing facilities (e.g., the NAFEC simulation and flight test instrumentation), other four-dimensional navigation and guidance development efforts (e.g., NASA's "STOLAND" program and the SST's Advanced Electronic Display System development), and the FAA's ATC system development activity (e.g., metering and spacing).

The plan was scheduled to establish concept feasibility for implementation by 1982 and, through task 5, to develop the subsystem requirements specification. Table 8-1 estimates the cost for this program.

8.2 RECOMMENDED NEAR-TERM RESEARCH

The objectives of near-term research should be to develop the strategic arrival control capability to the point where it can be considered for implementation (e.g., support the RNAV plan by providing four-dimensional navigation in high-density terminal areas by

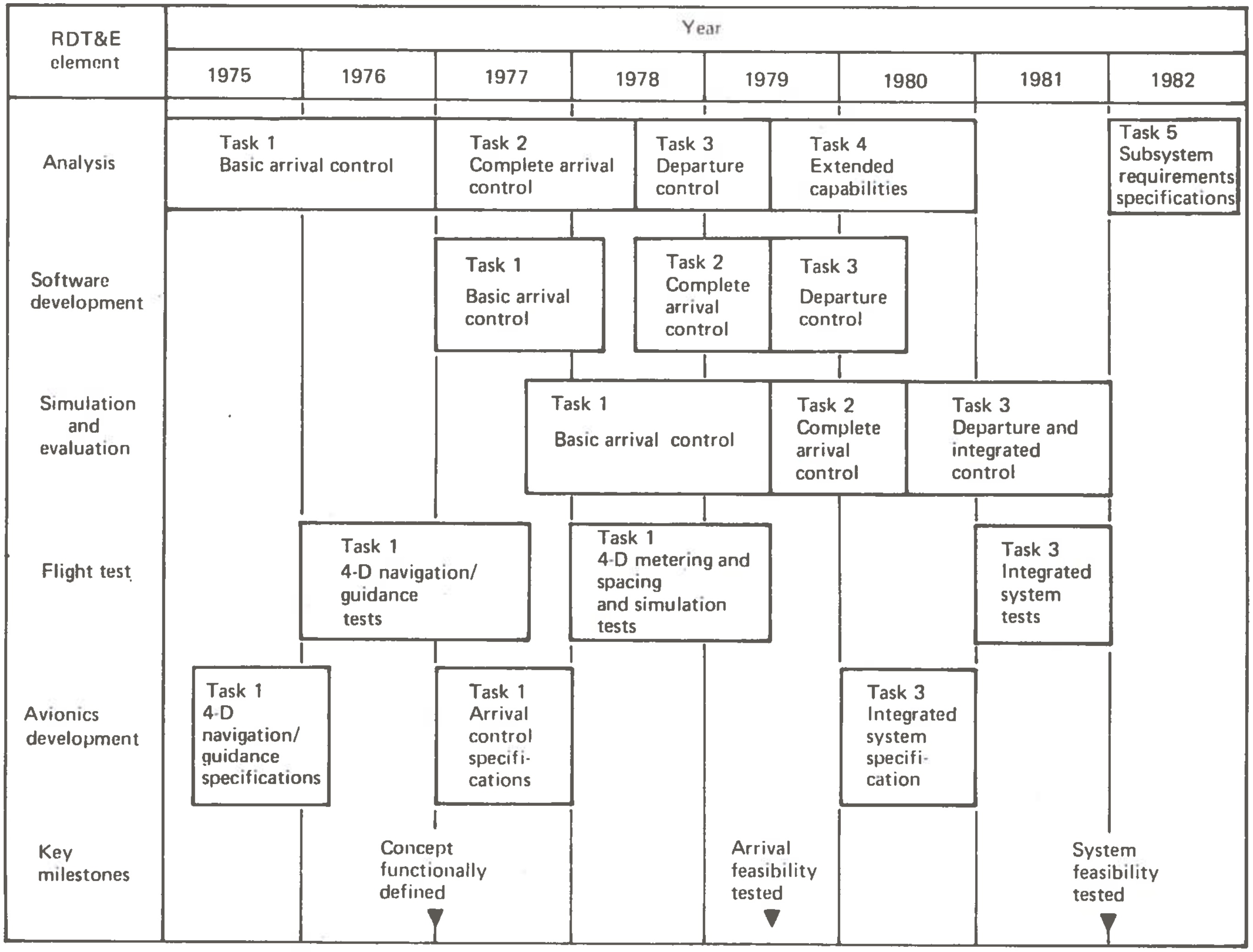


FIGURE 8-1.—GENERAL RDT&E PLAN FOR STRATEGIC CONTROL DEVELOPMENT

TABLE 8-1.—RDT&E PLAN COST ESTIMATE

Strategic control RDT&E fiscal year costs (thousands of dollars)									
Fiscal year	1975	1976	1977	1978	1979	1980	1981	1982	Total
Analysis	300.0	600.0	600.0	600.0	600.0	600.0	300.0	300.0	3,900.0
Software development			319.6	532.3	639.2	639.2			2,130.3
Simulation & evaluation				958.6	1,150.2	1,178.0	1,144.4	572.3	5,003.5
Flight test		150.0	1,300.0	400.0	1,700.0		150.0	1,350.0	5,050.0
Avionics development	183.4	366.6	275.0	275.0		275.0	275.0		1,650.0
Total	483.4	1,116.6	2,494.6	2,765.9	4,089.4	2,692.2	1,869.4	2,222.3	17,733.8

1982), while maintaining continuity of progress toward defining an "ultimate" strategic control capability. Three areas of work are required to support this near-term research objective.

1) Refine the Basic Arrival Algorithm

The present study has made considerable progress in defining the basic arrival algorithm and developing confidence in its feasibility and potential value. However, as in any scientific research endeavor, increased knowledge has presented avenues where further investigation is desired.

The algorithm should be refined by investigating alternatives and seeking better solutions to some of the complicated or relatively inefficient functions. These alternatives to the present algorithm include:

- Improved scheduling
- Transition flightpaths using different profiles such as a "level-off-and-decelerate" step
- Improved conflict testing and resolution
- Approach flightpaths with reduced sensitivity to airplane flight performance

- Spacing adjustment inside the initial approach fix
- Free-form paths not constrained to a fixed geometry for both transition and approach phases

Algorithm performance should be tested further by improving the evaluation model to incorporate:

- Advanced guidance control laws
- Detailed simulation of airplane dynamics

To support the idea that the strategic arrival algorithm might be used operationally in the near future, selected areas of concept refinement should be investigated:

- ATC system interface requirements (surveillance, communication, en route ATC interface)
- Specific procedures for handling operation through weather cells, runway direction changes, and missed approaches

2) Real-Time Programming

To gain insight and experience in programming the algorithm for real-time strategic arrival control, the algorithm should be operated with simulated traffic in real-time ATC simulation (versus the fast-time simulation used in this study).

3) Airborne Four-Dimensional Navigation/Guidance Requirements

The algorithm should be incorporated into a real-time airplane simulation equipped with a four-dimensional navigation/guidance system to develop compatible capabilities, including:

- Path definition
- Flight profile
- Pilot monitoring
- Manual strategic flight

GLOSSARY

The following are the definitions of selected terms whose meaning is vital to a clear understanding of the report.

Route-time profile (RTP)—A flight clearance for strategic control in which the desired three-dimensional flightpath and the time schedule for progress along the path are defined by a series of waypoints with the altitude and time for passing each waypoint.

Scheduling—The assignment of takeoff and landing times before flight departure or entry to the strategic control terminal area by determining that an operation time slot is available on a runway.

Sequencing—The determination of the threshold operation order for the using airplanes.

Strategic control—A centralized management control concept in which nonconflicting flightpaths are determined for all flights on a long-term basis (prior to entering strategically controlled airspace). The clearance for each flight is transmitted to the airplane in terms of a three-dimensional flightpath description, to be flown according to a time schedule. Usually this clearance will consist of a series of waypoints defined in latitude, longitude, and altitude and a time for making each waypoint. Separation is ensured by providing time or distance separation between clearances based on the accuracy with which a flight can achieve its assigned clearance.

Strategic control terminal area—The airspace surrounding strategically controlled runways that is used for the assignment of route-time profiles. This airspace includes paths extending to en route altitudes, and geographically encompasses an area of approximately 150 to 175 nautical miles from the airport.

Terminal area—The area surrounding and including an airport that is presently controlled by the approach and departure control function and the tower.

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REPORT OF INVENTIONS APPENDIX

A diligent review of the work performed under this contract, has revealed no new innovation, discovery, improvement, or invention.