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STRATEGIC CONTROL ALGORITHM DEVELOPMENT
Volume IIB: Technical Report (Concluded)

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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 the 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.

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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 equiped 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 report.

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6.0 STRATEGIC CONTROL APPLICATION AND AIRSPACE STRUCTURE

The primary objective of the air traffic control system is to enable safe and efficient movement of traffic. As airspace becomes more congested the safety objectives must be met but loss of efficiency will necessarily occur in the form of delays, schedule restrictions, route deviations, and increases in controller manpower requirements. With sufficient traffic growth some type of improvement will have to be made in many areas of terminal and en route airspace to prevent excessive loss of efficiency. The purpose of this section is to identify these areas and the time periods to which strategic control should be applied to provide the needed improvement. Also, plans for structuring airspace for strategic control in an example area (Los Angeles) are proposed. The approach taken and the basic assumptions used are of the type useful for an introductory look at a new concept rather than for making a final decision between two or more well-developed systems.

The report is ordered with a discussion of the terminal area work first, then the en route work, followed by the strategic airspace plans. The final section contains supporting data, curves, etc., used in the three tasks.

6.1 STRATEGIC CONTROL TERMINAL AREAS

Determination of the terminal areas that are candidates for strategic control has been based on a set of basic assumptions from which criteria were developed. The criteria involve airfield capacity and projections of airport air-carrier traffic. These items are discussed and the results illustrated in the following sections.

6.1.1 Criteria for Application to Terminal Areas

This section presents the rationale used to establish requirements for terminal area strategic control and summarizes the results.

6.1.1.1 Assumptions

The criteria for strategic control at specific airports are based on the following assumptions:

1) It is considered that strategic control will be the standard FAA control program: it has been developed to the production state, and therefore the criteria are for deciding where it will be used (versus justifying development on a cost/benefit basis).

2) Strategic control will be used primarily for control of air carrier airplanes and some more expensive general aviation airplanes. Basically, it will control those airplanes equipped with precision four-dimensional navigation/guidance systems. A small percentage of lesser equipped airplanes can be handled, but when they become a significant portion of the traffic (e.g., 10%) the benefits of strategic control will be minimal and an automated tactical system such as metering and spacing would be a better choice.

3) Strategic control will be used on-line when the traffic demand, on a runway-by-runway basis, contains a high percentage of adequately equipped airplanes and when an appropriate form of tactical control is employed. Example situations are:

   a) Arrivals are being conducted to two runways with mostly air carrier operation on runway number one, and a significant percentage of general aviation on runway number two. Strategic control will be used for runway number one.

   b) The majority of operations to an airport are air carriers. Strategic control will be used for all runways with the occasional unequipped airplanes tactically hand carried in a designated slot in the strategic stream. The controller, with his instructions and the pilot/airplane response, are effectively a four-dimensional navigational guidance system of reduced accuracy requiring only a larger spacing to operate in the strategic stream.

   c) Traffic is light but many are air carrier airplanes. Air carrier airplanes will operate strategically (fly assigned four-dimensional tracks) with other airplanes fit in using tractical control.

   d) During certain hours most operations are air carriers while general aviation operations predominate during the remainder of the day. Strategic control will be used during the busy air carrier hours.

4) Air carrier airplanes will comprise the majority of equipped users and forecasted air carrier operations represents the expected number of equipped users.

6.1.1.2 Criteria Determination

To justify installation of the strategic control capability, the level of operations must be of sufficient magnitude and a high percentage of the operations must be by airplanes equipped with precision four-dimensional navigation/guidance systems. Thus, the strategic control application criteria are: level of operations and percent equipped airplanes.

1) Level of Operations. Under IFR conditions today, the controllers are working near their capacity. If a system of control were available that could significantly reduce the control/communications workload under these conditions it would be used.

   Eventually, a criterion based on annual IFR air carrier operations (or some similar statistic) may be used to identify when a facility is eligible for strategic control. However, at this stage, the year in which the busy-hour demand reaches the airport IFR capacity appears to be indicative of when a method of easing workload (and therefore expanding capacity) is really needed.

   Practical hourly capacity is defined in reference 6-2 as that level of operations during busy hours that will result in a 4-minute average flight delay (under present control procedures) for the two adjacent busiest hours of a typical daily schedule. It is determined for a specific mix of airplanes by performance class.

The IFR practical hourly capacity for mix 4, as defined in reference 6-2, is judged to be representative of (1) today's IFR hourly capacity for air carrier operations (recognizing the effects of wake turbulence on runway operations rate), and (2) the level of control/communication workload above which an improved method of control should be used.

2) Percent of Equipped Airplanes. For strategic control to provide the benefits of increased capacity and reduced control/communications workload, it is necessary to limit the rate at which the system is tactically interrupted to carry lesser-equipped airplanes. Each time a lesser-equipped airplane is carried in the strategic stream, the controller is involved to determine the necessary control instructions (e.g., speed, heading commands) and to communicate these instructions to the airplane. Also, since the guidance accuracy (controller/pilot/airplane/surveillance loop) is considerably less accurate than that of the equipped airplane, the time slot must be larger, thus reducing the flow rate.

The most likely method of controlling a lesser-equipped airplane is to issue speed commands to keep the airplane centered within a time slot. There is no known data on the accuracy of this control mode. However, it is judged to have a one-sigma accuracy of 20 seconds (compared to 2 seconds for equipped aircraft) due mainly to the response times of the surveillance system measuring airplane position and velocity and the pilot/airplane reaction to speed commands.

Considering the effect on both capacity and workload, the equipped airplane should form 90% or more of the traffic during those hours when strategic control is to be used.

6.1.1.3 Summary

The greatest benefits from strategic control will occur by applying it when air traffic is critically heavy and the majority of traffic is properly equipped. This combination will exist at an airport when the commercial air carrier traffic saturates the capacity of the facilities during the busy hours. The remainder of this study discusses the establishment of that time for the principle air carrier airports of large and medium U.S. air traffic hubs.

6.1.2 Capacity Determination

In this section accepted methods are used to estimate the effective limits of traffic flow for the nation's 100 busiest air carrier airports. Air traffic projections taken from other studies are manipulated to determine the times in the future at which airports will be saturated for high and low as well as nominal growth estimates. Detailed results are presented in section 6.4.

6.1.2.1 Definition of Capacity

FAA Advisory Circular AC 150/5060-3 provides estimates of the IFR practical hourly capacity for various runway configurations using present ATC procedures. IFR practical hourly capacity is the estimated number of movements per hour that will result in average departure delays of 4 minutes. Specific estimates used in the study are contained in section 6.4.

The effective air carrier IFR capacity defined as the IFR practical hourly capacity uses the following assumptions:

1) Only that portion of the airport runway configuration that is used by air carrier airplanes for the majority of IFR operations was considered. This is the effective runway configuration.

2) A mix was used consisting of: 60% four-engine jet; 20% two- and three-engine jet and four-engine prop; and 20% executive jet and transport-type twin-engine piston.

3) The capacity achievable under actual instrument meteorological conditions (IMC), although usually lower than that achievable under visual meteorological conditions (VMC), is the maximum control workload and the value of interest in this analysis.

4) The practical hourly capacity values in AC 150/5060-3 are low compared to some other capacity estimates, (e.g., ref. 6-1), but are consistent with observations of current operations under IFR conditions (IMC) and considering the effect of wake turbulence (other estimates are usually for different purposes such as establishing scheduling limits).

6.1.2.2 Capacity Analysis

The runway configuration and knowledge of air carrier operations on the runways (refs. 6-2 through 6-6) were used to develop the effective air carrier IFR capacity for each airport in the large and medium hubs. Data extracted from these references are contained in the supporting data section. Also contained are comments relative to the capacity of some of the busier airports.

6.1.3 Demand Determination

The annual and busy-hour air carrier operations are projected to the year 2005 for the principle airports of all large and medium U.S. air traffic hubs. The projections of annual operations are based on predictions of total traffic and fleet growth that have previously been accepted as useful for studies of the future ATC environment. Predictions of busy-hour operations are derived from historical relationships between annual and busy-hour operations at busy airfields. Total annual and representative busy-hour operations taken from the most recently distributed FAA *Terminal Area Relationships*, compiled for FY 1970 and FY 1971, are used as a starting point. It is assumed that data compiled for fiscal years closely represent the calendar years. From this point, for 1972 to 1984, air carrier operations are taken from FAA *Terminal Area Forecast*, which span these years. From 1984 through 1995, the rate of growth of air carrier operations is taken from the 1969 report of the Air Traffic Control Advisory Committee (ref. 6-7) and applied to the traffic at each individual airport. The simple calculations used for this phase are as follows:

Annual operations (in millions) in 1980 = 19.6 (ATCAC estimate)

Annual operations (in millions) in 1995 = 28.2 (ATCAC estimate)

28.2 - 19.6 = 8.6 increase in 15 years

Annual operations in 1984 = 19.6 + 4/15 x 8.6 = 21.9

Annual operations in 1995 = Annual operations in 1984 x 28.2/21.9
Annual operations in 1984 x 1.28

This ratio of growth (1.28) is then applied to traffic of all airports for the years from 1984 to 1995.

To project the number of annual air carrier operations beyond 1995 to 2005 the predictions on fleet size developed from the Advanced Air Traffic Management System (AATMS) study is used. The procedure called for the simplifying assumptions that traffic growth at individual airports is proportional to growth in total U.S. annual air carrier operations up to 1995 and to growth in total U.S. air carrier fleet size from 1995 and on. This growth of fleet size is reproduced in table 6-1.

TABLE 6-1.—ESTIMATIONS OF AIR CARRIER FLEET SIZE

	Year			
	1972	1995	2005*	2020
High estimate		9500	11,300	14,000
Medium estimate	2700	7000	8,000	9,500
Low estimate		5000	5,800	7,000

*Figures for the year 2005 are interpolations from the original AATMS data for years 1995 and 2020.

The forecasted (nominal or medium estimate) number of annual operations for 2005 at each airport was found by use of simple ratios as shown below:

$$\text{Ratio} \frac{2005 \text{ ops}}{1995 \text{ ops}} = \frac{8000}{7000} = 1.14$$

$$2005 \text{ ops} = 1995 \text{ ops} \times 1.14$$

To forecast the busy-hour operations at each airport the historical relationship between representative busy-hour operations and annual operations, as published annually in the FAA documents *Terminal Area Relationships*, was studied. Figure 6-1 is a scatter diagram

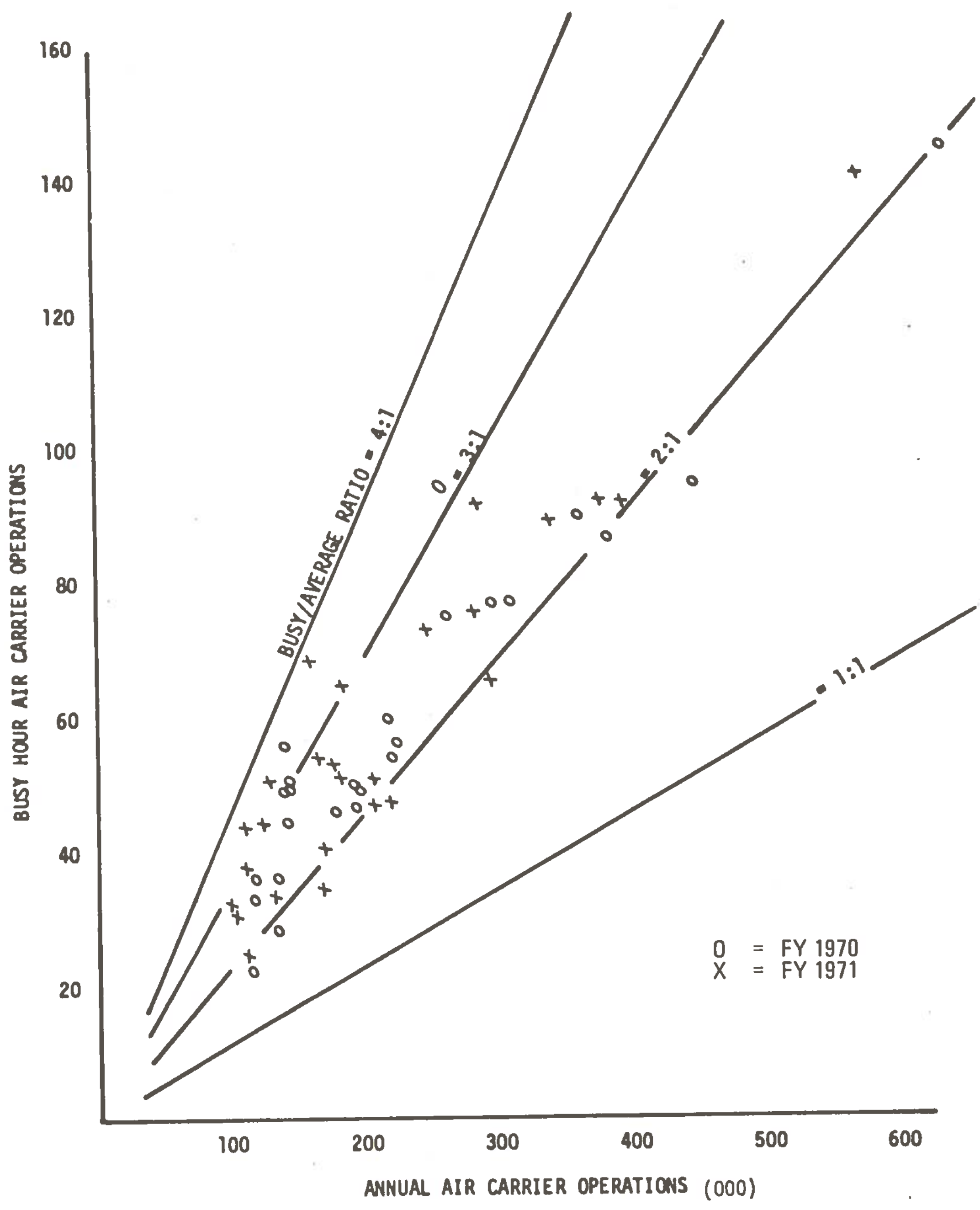


FIGURE 6-1.—TERMINAL AREA AIR TRAFFIC RELATIONSHIPS

showing this relationship for the fiscal years 1970 and 1971 for the airports having more than 100,000 annual operations. Less busy airports are eliminated from this chart for clarity. A refinement of these data shows that the ratio of busy to average hour operations is not a function of time. Figure 6-2 is a histrogram grouping this ratio by annual operations for the years 1960, 1970, and 1971. This, and continuous plotting of the same data, shows no pattern of change related to time. From this study the curve in figure 6-3 is constructed. It is used to estimate future busy-hour traffic from the forecast annual air carrier operations.

To evaluate the requirement for an improved control system at the principle airports of all large and medium air traffic hubs, forecasts are necessary for a large number of airports. To minimize calculations, a simple formula was developed for determining the year of airport capacity saturation at high and low levels of traffic growth. The formula makes use of the forecast growth in busy-hour operations from 1972 to 2005 for each airport modified in the same ratios as the high and low estimates of growth in total fleet size for the same period. This enables an estimation that is unique to each airport and within bounds set by estimates of fleet size growth considered acceptable for other studies. Simplifications required for this method include assumptions that high and low values of busy-hour operations increase in a straight-line manner and that the growth in busy-hour traffic at specific airports is related to the growth in total fleet size. Development of the formula used for this purpose is shown below.

Symbolism

Busy-hour operations (BHO) = V

BHO at airport capacity = V_c

Airport BHO in 1972 = V_{72}

Forecast airport BHO in 2005 = V_{05}

High estimate of airport BHO in 2005 = V_H

Low estimate of airport BHO in 2005 = V_L

Total fleet size in 1972 = F_{72} = 2,700

Forecast fleet size in 2005 = F_{05} = 8,000

High estimate fleet size in 2005 = F_H = 11,300

Low estimate fleet size in 2005 = F_L = 5,800

Assumption

Growth in V is result of growth in fleet size. V_H and V_L grow in proportion to high and low fleet estimates as V_{05} (which is determined by use of historical relationships) grew to the nominal forecast fleet size.

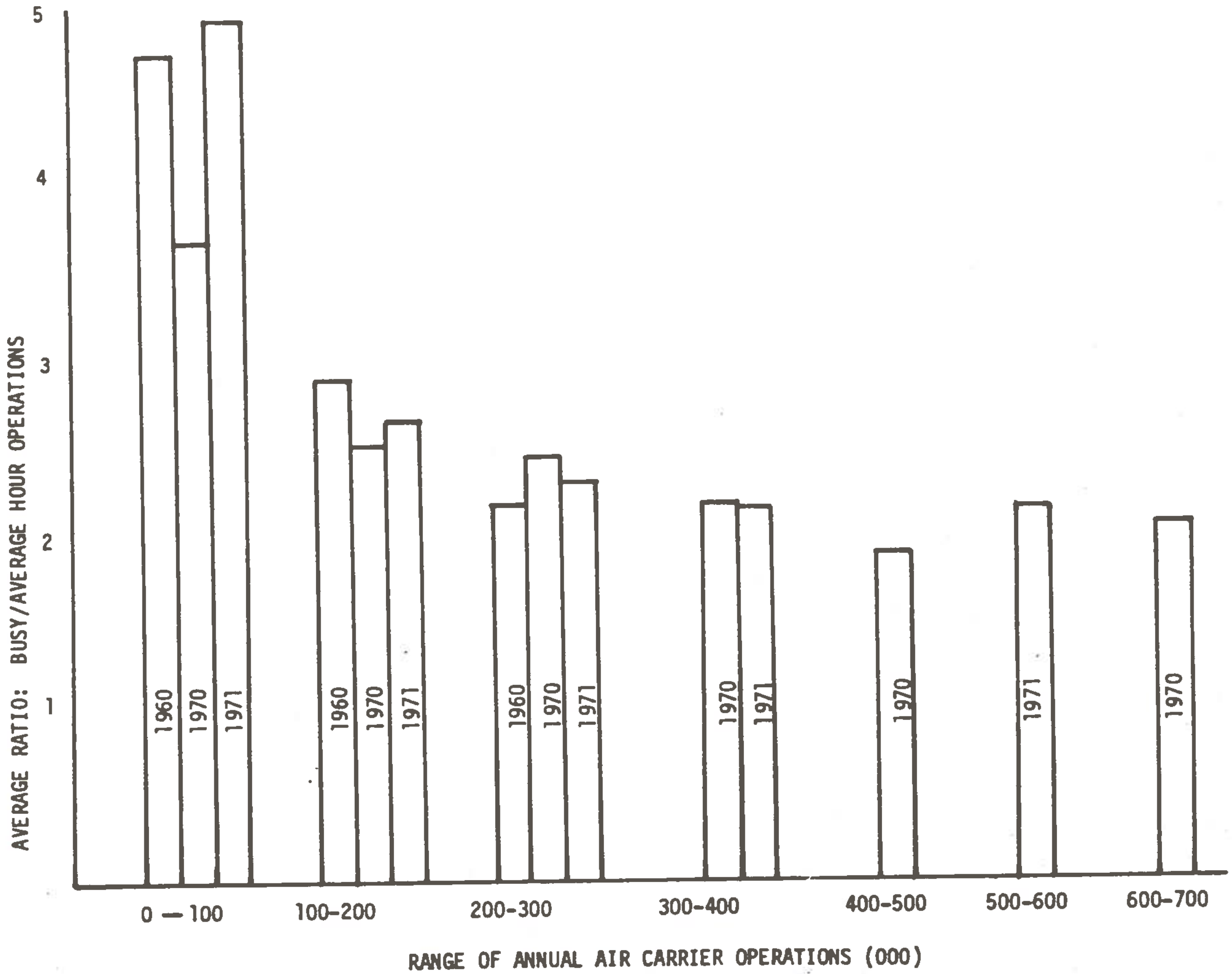


FIGURE 6-2.—TIME COMPARISON OF TERMINAL AREA TRAFFIC RELATIONSHIPS

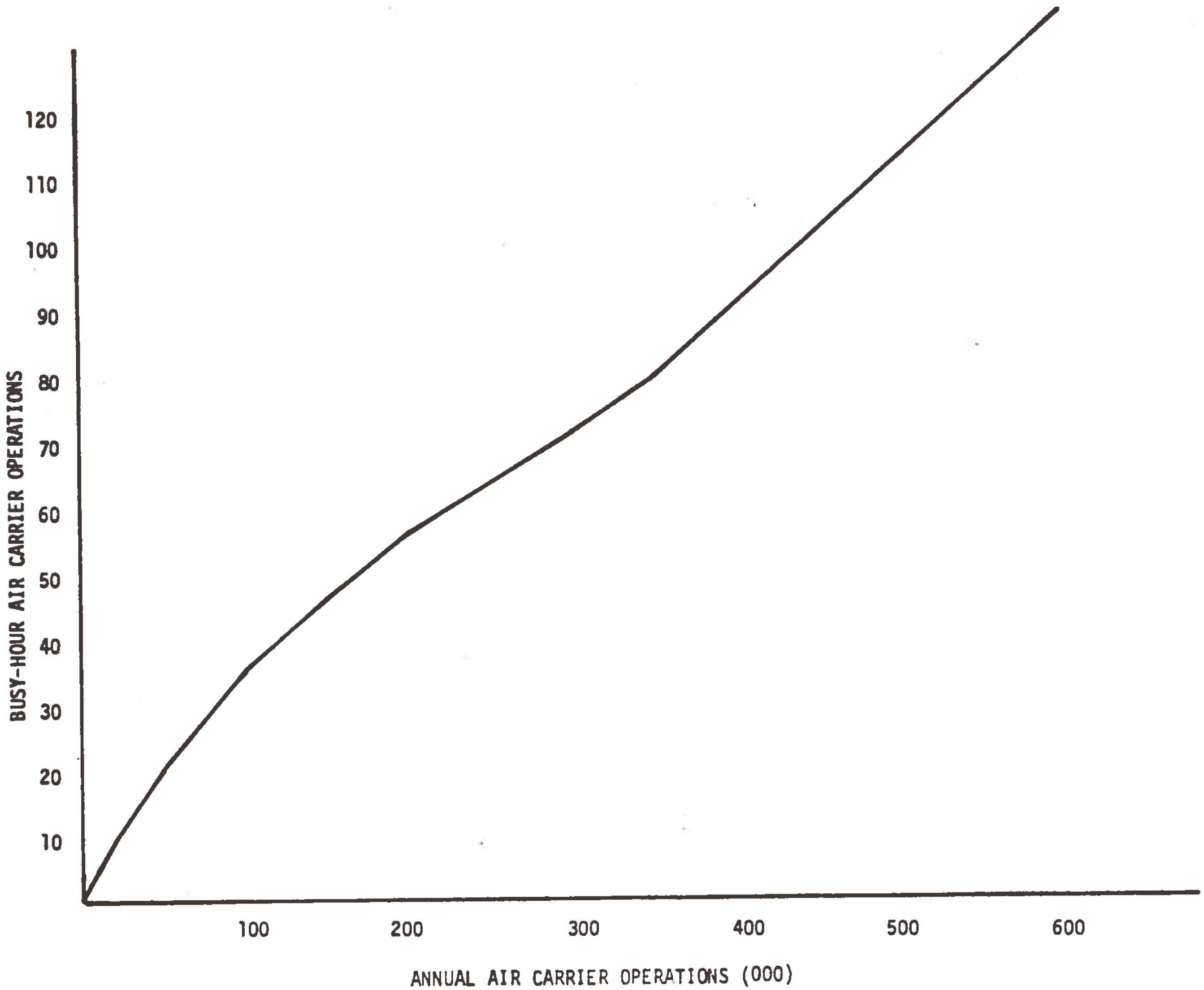


FIGURE 6-3.—ANNUAL BUSY-HOUR OPERATIONS RELATIONSHIP

Mathematical Development

$$\text{Forecast yearly BHO growth rate} = \frac{V_{05} - V_{72}}{33} = \frac{\Delta V}{33}$$

$$\text{High estimate yearly BHO growth rate} = \frac{\Delta V}{33} \times \frac{F_H - F_{72}}{F_{05} - F_{72}} = \Delta V \times 0.0488$$

$$\text{Low estimate yearly BHO growth rate} = \frac{\Delta V}{33} \times \frac{F_L - F_{72}}{F_{05} - F_{72}} = \Delta V \times 0.0179$$

If capacity saturation occurs at 1972 + h years, $V_c - V_{72} = h \times \text{yearly growth rate}$ and

$$h = \frac{V_c - V_{72}}{\text{yearly growth rate}}$$

$$\text{Then year of saturation is } 72 + \frac{V_c - V_{72}}{\text{yearly growth rate}}$$

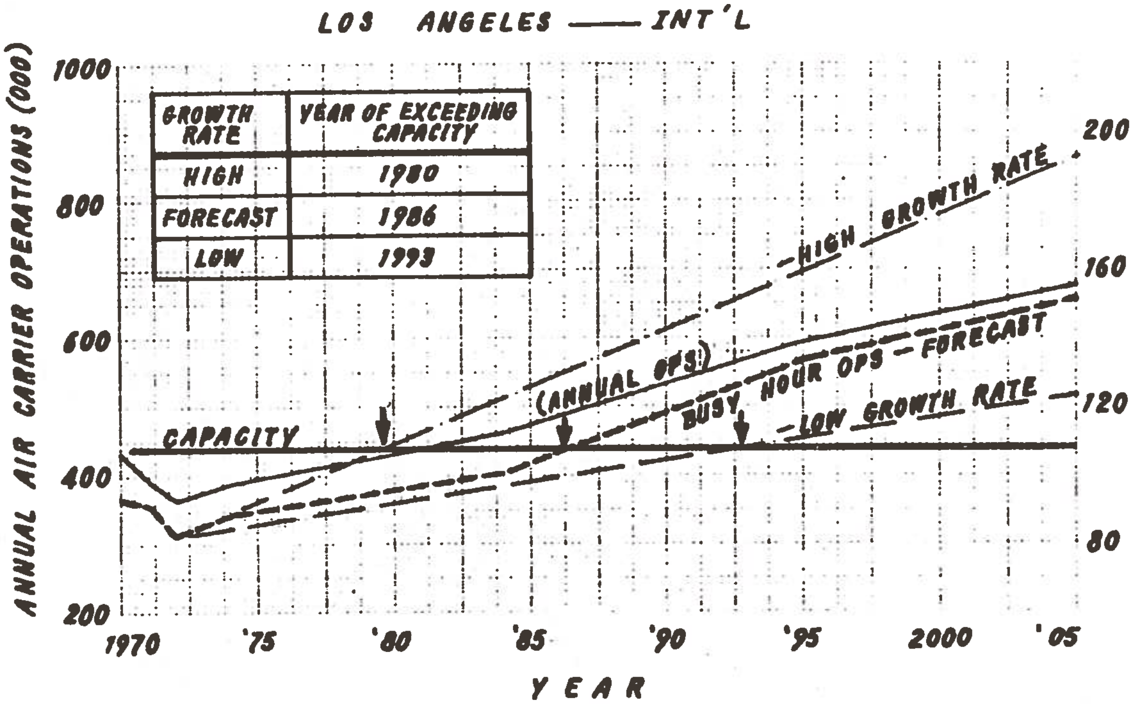
$$\text{For the high estimated growth rate year of saturation} = 72 + \frac{V_c - V_{72}}{0.0488 \times \Delta V}$$

$$\text{For the low estimated growth rate year of saturation} = 72 + \frac{V_c - V_{72}}{0.0179 \times \Delta V}$$

Thus, by inputting the capacity of a specific airport, its 1972 BHO, and its forecast growth in BHO to 2005, the years of saturation at high and low estimated growth rates can be calculated. Figure 6-4 plots the high and low estimates of busy-hour operations calculated in this manner superimposed on the forecast growth for Los Angeles and Atlanta. The years of saturation are tabulated on the traffic growth charts for all airports included in the supporting data (sec. 6.4).

6.1.4 Forecast Strategic Control Airports

Figure 6-5 shows the airports that are candidates for strategic control as a function of the year. Effects of high and low growth estimates are also shown but without designating the airports. Using the criteria proposed in this study, five of the nation's airports are presently candidates for strategic control. By 2005 this number will have grown to 27 for the nominal air traffic growth forecast. The supporting data of section 6.4 include charts of the forecast growth of each airport studied. Each chart also has a table of the years of capacity saturation for the corresponding airport. Section 6.4 also contains a list of all the airports studied, their effective runway configurations, IFR hourly capacity, and appropriate remarks.



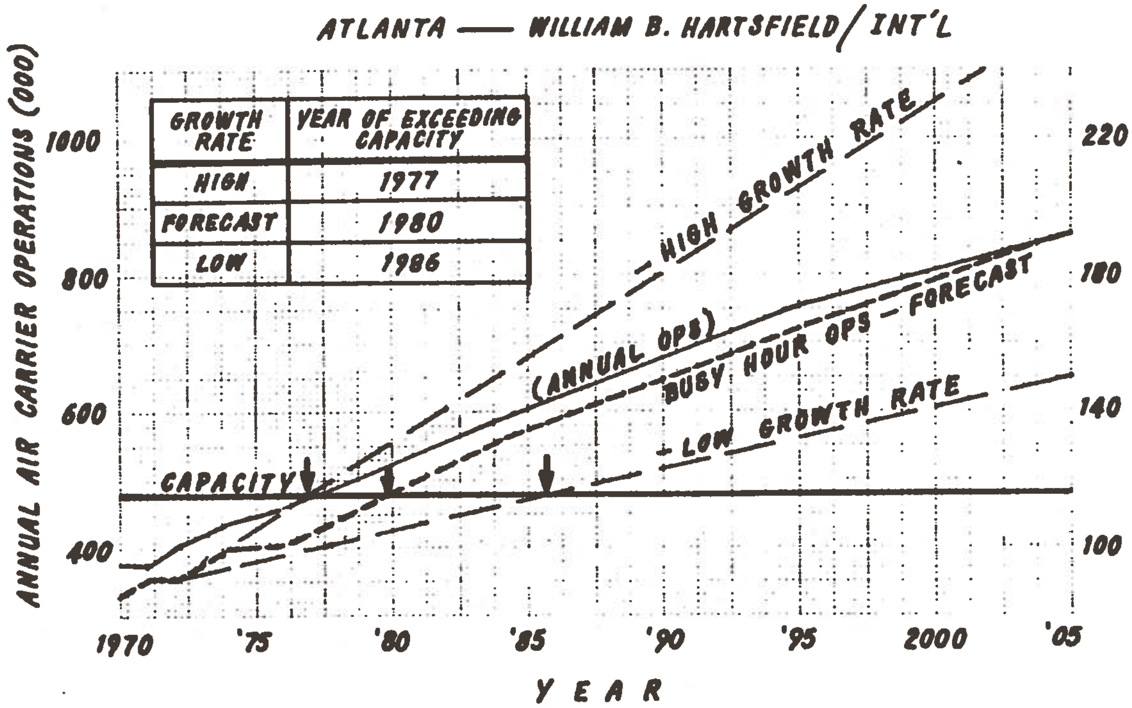


FIGURE 6-4.–AIRPORT GROWTH/CAPACITY RELATIONSHIPS

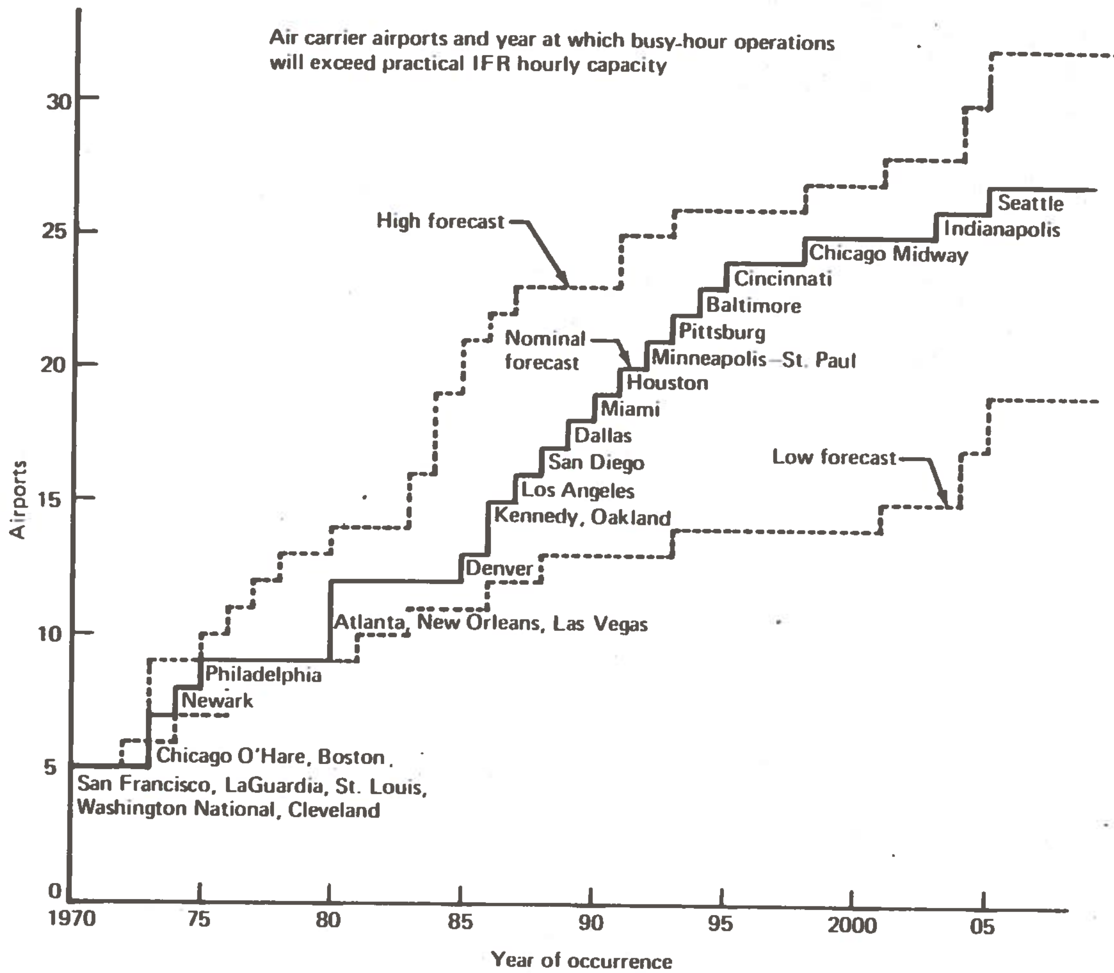


FIGURE 6-5.–STRATEGIC CONTROL AIRPORTS

6.2 STRATEGIC CONTROL EN ROUTE SEGMENTS

An obvious benefit to strategic control in terminal areas would be realized if flights on the heavily used routes could be spaced and guided to desired entry points while en route. Thus en route strategic control may have valuable advantages in addition to providing safety, decreasing controller load, and increasing capacity on route segments between terminal areas. This section discusses the requirement for its application.

6.2.1 Criteria for Application to En Route Segments

This section describes a rationale for application of strategic control between terminal areas and will summarize the results. The rationale is based on providing the best return for the overall system. Therefore, the tie-in with the terminal systems is of concern as well as en route traffic levels.

6.2.1.1 Tie-in With Strategic Control Terminal Areas

In studying the en route situation for strategic ATC requirements, it is evident that congestion in en route areas would not present the problem that it does in the terminal areas. Therefore, although complete automation would undoubtedly yield benefits along any extremely heavily traveled route, this study is confined to those en route segments that connect terminal areas with airports that are candidates for strategic control. It is felt that the greatest payoff from en route control would be in easing the situation within those terminal areas.

6.2.1.2 Overlap of Terminal Areas

The strategically controlled terminal areas are, at the present stage of concept development, nominally 175 nautical miles in radius. Because of this, several of the areas overlap and no en route segment exists between them; direct handoffs will take place. Thus, the second criteria for en route consideration is that the terminal areas connected do not overlap.

6.2.1.3 Level of Traffic

There are two considerations in determining the level of traffic at which en route strategic control would provide benefits. One is the premonition that at a certain level, the ordering, spacing, and accuracy of delivery to terminal entry points would assist, or even be necessary, in operation of the terminal control system. The other consideration is for safe and efficient operation along the route itself. The value of delivery accuracy versus traffic level is not known at the present. For this reason we establish a preliminary criterion that approximates the present FAA criteria for sectorization (as published in the NAS Ten-Year Plan) given as 180 operations per controller working shift. The concept of en route strategic control presently calls for en route segments to be isolated and treated separately, much as long thin sectors, and so the approximation has some validity. A sampling of scheduled flights between specific major hubs has shown that approximately 15% of the flights during day and evening 8-hour shifts occur in the busiest hour. Thus, the busy-hour traffic in a representative sector might consist of 27 flight operations. For the present this has been rounded to 25 busy-hour flights and accepted as the criteria for application of strategic control to en route segments.

6.2.1.4 Summary

The greatest benefits from en route strategic control occur by applying it to segments between strategic control terminals where control areas do not overlap and where busy-hour equipped flights exceed the workload level expected in a control sector. As in the case of the terminals, air carrier traffic is expected to approximate total equipped traffic.

6.2.2 En Route Demand Determination

This section describes the method of forecasting en route traffic and reveals the en route segments that qualify for strategic control. Qualification is given by year of occurrence.

6.2.2.1 Projection of Traffic Levels

In forecasting flight operations on route segments, the scheduled airline flights for a Friday in May of 1972 were taken as a baseline. These scheduled flights were then multiplied by the high, nominal, and low estimates of fleet growth factors as shown in table 6-2.

TABLE 6-2.—EN ROUTE TRAFFIC GROWTH ESTIMATION FACTORS

Year	Fleet size	Growth factor
1972	2,700	1.0
Low 1995	5,000	1.86
Medium 1995 Low 2020	7,000	2.58
High 1995 Medium 2020	9,500	3.52
High 2020	14,000	5.20

For the expanded traffic, the flights were dispersed in time as would actually be necessary to space departures. An analysis of the flights at the low 1995 level shows that the busy-hour/total-day flights relationship is not unduly changed by the expansion. The busy-hour and total daily flights were calculated for each level of traffic for each route that is qualified by the other criteria.

6.2.2.2 Criteria Qualification

There are 27 airports that will exceed their capacity by the year 2005 and are consequently suggested for strategic control. They are in 19 of the present 21 large hub areas. As seen by a study of the supporting data in section 6.4, no airports in large hubs other than the first 19 will be qualified for strategic control by the year 2005. The airports in medium hubs that exceed their capacity are considered, for the present, to be able to solve congestion problems by less sophisticated means. After combining airport-to-airport schedules to obtain hub-to-hub traffic, it was found that only 25 pairs of the hubs had 50 or more direct flights between them on their peak day of 1971. The others were dropped from consideration as, by our method of estimation, they would not meet the traffic load criteria in any of the future estimates. Of the 25 hub pairs that were qualified by traffic level only nine do not have overlapping terminal areas. The resulting requirements by year of occurrence are discussed in the next section.

6.2.3 Forecast Strategic Control En Route Segments

The busy-day (a Friday in May) and busy-hour flights between the nine qualified city pairs for 1972 and for all estimated levels of future traffic are shown in table 6-3. Using this table the traffic loads were interpolated for intermediate years. Figure 6-6 illustrates the results for the three forecast levels. Using similar graphs for all three levels of estimated growth, table 6-4 and figure 6-7 were constructed for presentation of the final results. Figure 6-8 shows the effect on requirements of varying the busy-hour traffic load criteria using the medium forecast.

6.3 STRATEGIC CONTROL AIRSPACE PLANS

This section discusses the configurations of airspace for terminal and en route strategic control. The Los Angeles terminal is used as an example. This plan is also used as the terminal geometry inputs for the evaluation model described in volume IV of this report.

6.3.1 Terminal Airspace Structure

The terminal airspace must be configured to satisfy geometric considerations for the strategic control concept as discussed in section 2.0 of volume III. At the same time it must allow for the specific geography of any terminal such as Los Angeles, which is modeled for this study.

6.3.1.1 Geometric Considerations

Routing within the terminal areas must be of sufficient length to provide for derandomization of arriving flights by speed control and for descent from cruise altitudes to the initial approach fix and thence to the runway. Distance along track from each entry fix to an initial approach fix must be reserved for deceleration to descent speed at high-entry altitudes. The route distance to the initial approach fix is further dictated by the maximum descent rate of 250 feet per mile and the need for another 10-mile level deceleration segment before reaching the initial approach fix. Arrival at the initial approach fix must be at 10,000, 11,000, or 12,000 feet, depending upon which entry fix a flight has used. After passing the initial approach fix descent rates up to 300 feet per mile are allowed through a turn fix, merge fix, final approach fix, and outer marker, in that order, to touchdown. The entry fixes are placed to coincide with routes from connecting cities. Placing of the other fixes can be influenced by the presence of high terrain and busy neighboring airports as long

TABLE 6-3.—FORECAST EN ROUTE FLIGHT OPERATIONS

ENROUTE SEGMENT	1972 OPERATIONS		FORECAST OPERATIONS 1995		FORECAST OPERATIONS 2020	
	BUSY DAY	BUSY HOUR	BUSY DAY HIGH MEDIUM LOW	BUSY HOUR HIGH MEDIUM LOW	BUSY DAY HIGH MEDIUM LOW	BUSY HOUR HIGH MEDIUM LOW
NEW YORK–CHICAGO	138	10	486 343 266	35 26 19	718 486 343	52 35 26
NEW YORK–MIAMI	83	10	292 213 158	35 26 19	432 292 213	52 35 26
CHICAGO–LOS ANGELES	60	5	211 155 116	18 13 10	310 211 155	26 18 13
SAN FRANCISCO–CHICAGO	43	5	151 111 87	18 13 10	224 151 111	26 18 13
BOSTON–WASHINGTON	65	8	229 168 127	28 21 15	338 229 168	42 28 21
CHICAGO–DENVER	38	5	134 98 76	18 13 10	198 134 98	26 18 13
NEW YORK–LOS ANGELES	50	6	176 129 95	21 15 12	260 176 129	31 21 15
CHICAGO–WASHINGTON	56	5	197 144 106	18 13 10	291 197 144	26 18 13
SAN FRANCISCO–SEATTLE	37	4	130 95 71	14 10 7	192 130 95	21 14 10

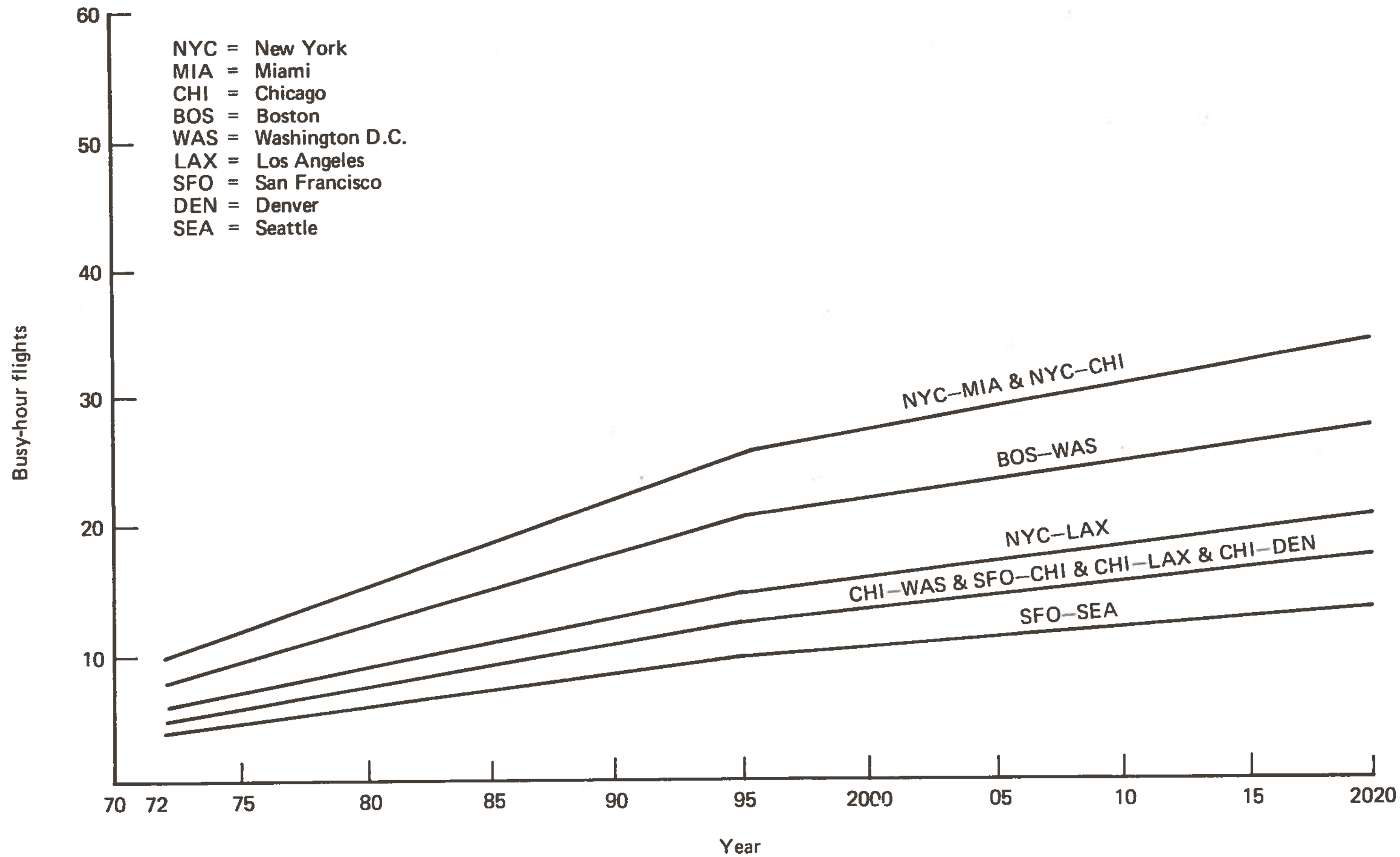


FIGURE 6-6.–BUSY-HOUR EN ROUTE TRAFFIC

NOMINAL FORECAST

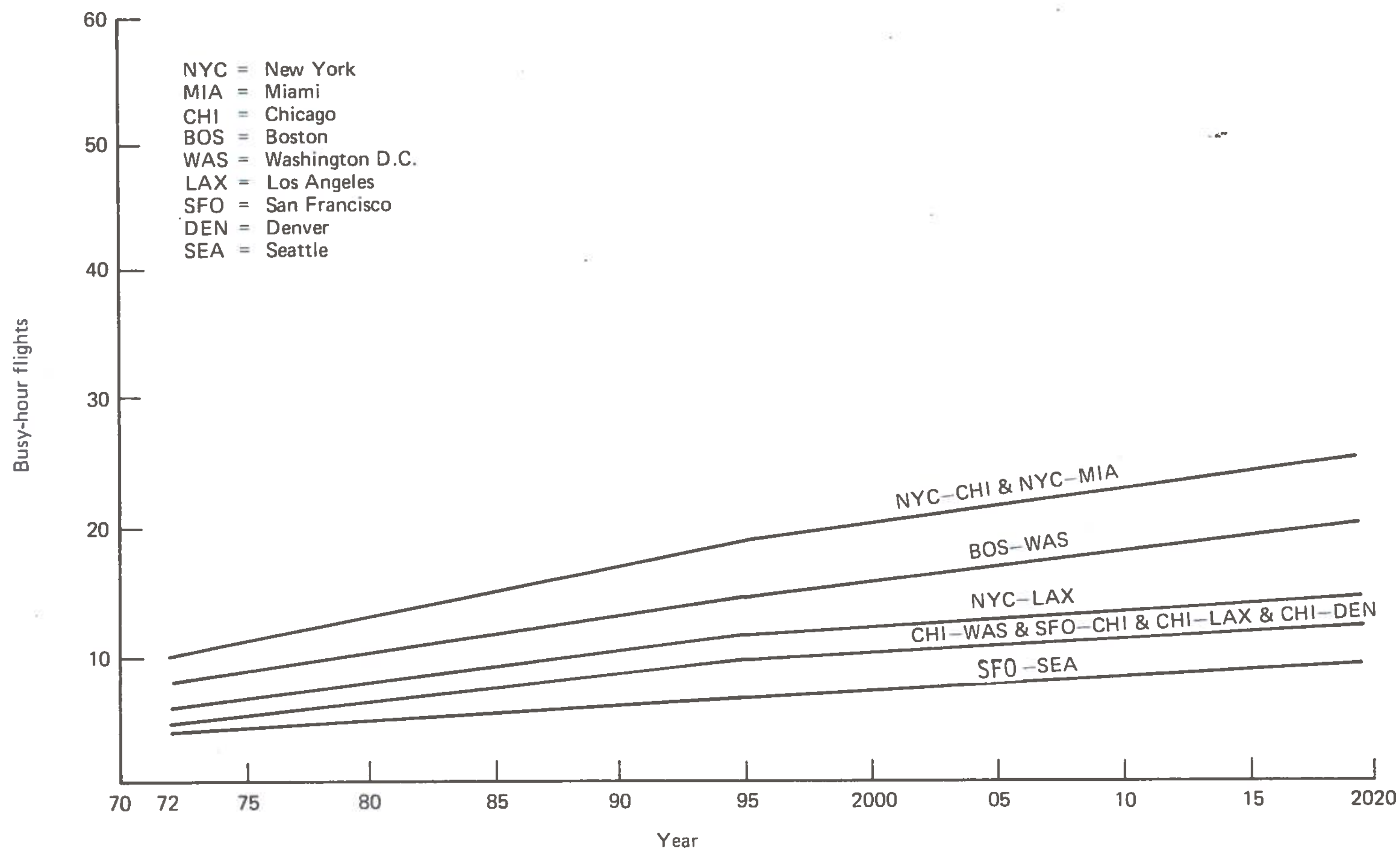


FIGURE 6-6.—CONTINUED

LOW FORECAST

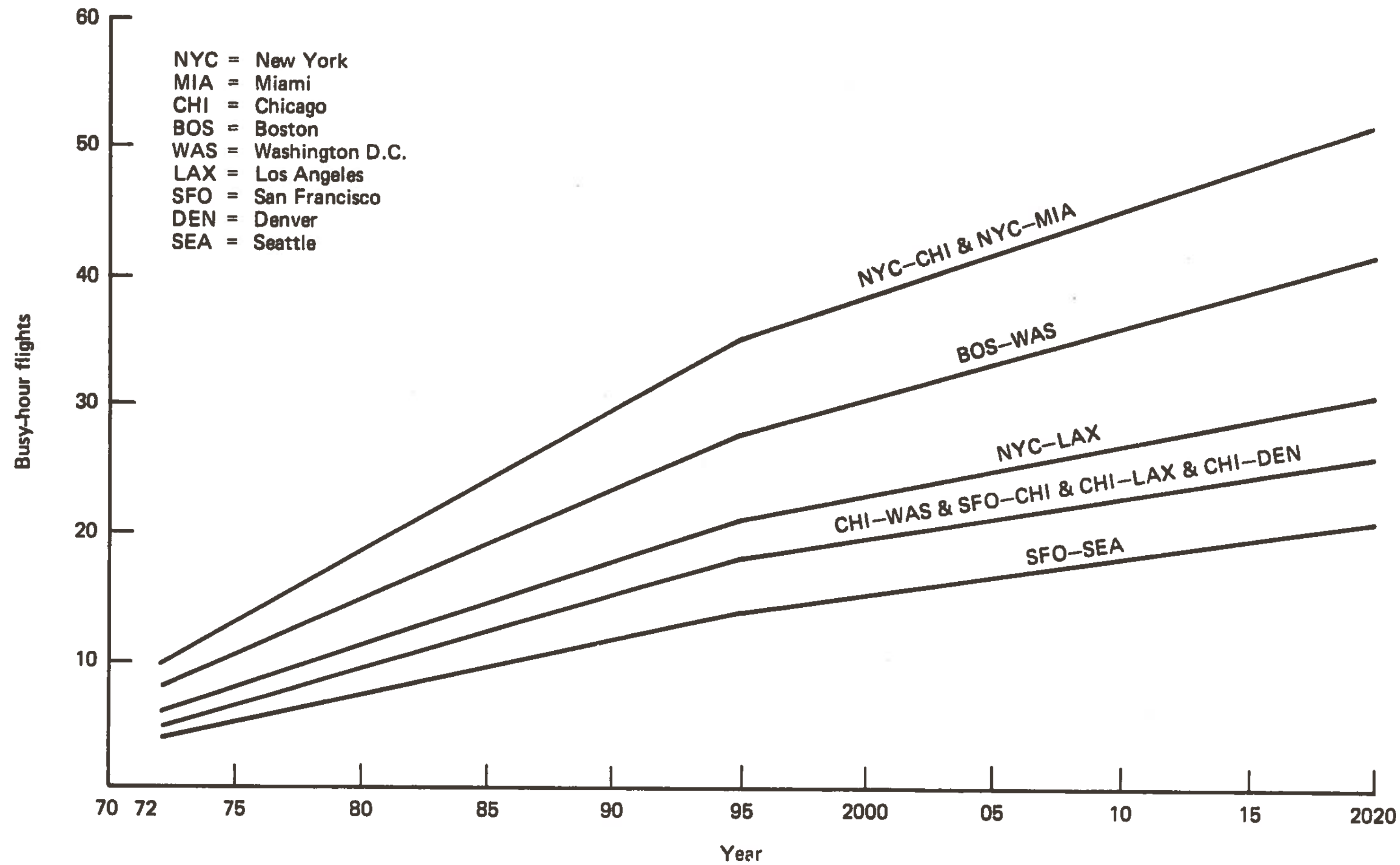


FIGURE 6-6.—CONCLUDED

HIGH FORECAST

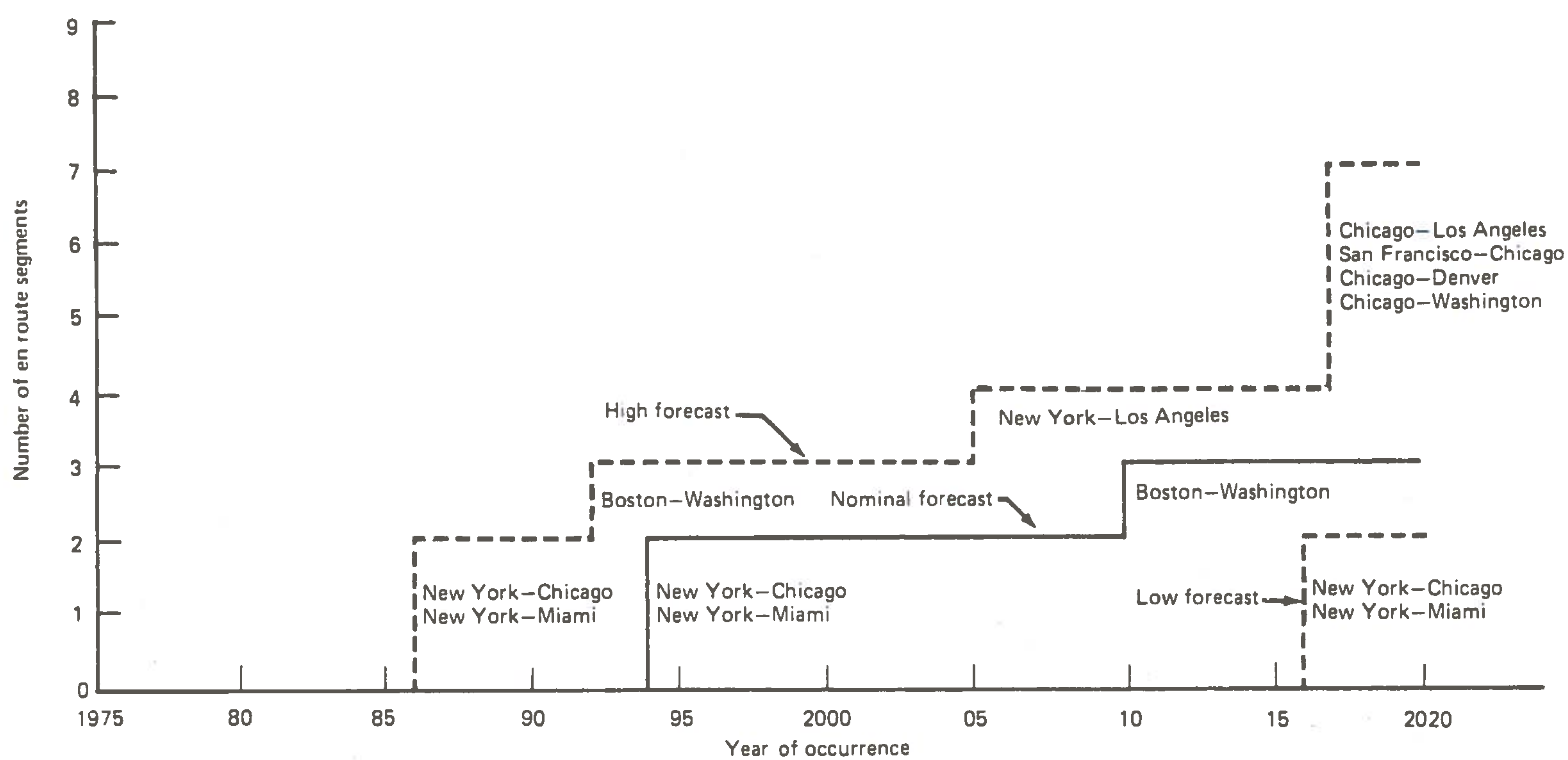


FIGURE 6-7.–EN ROUTE STRATEGIC CONTROL REQUIREMENT

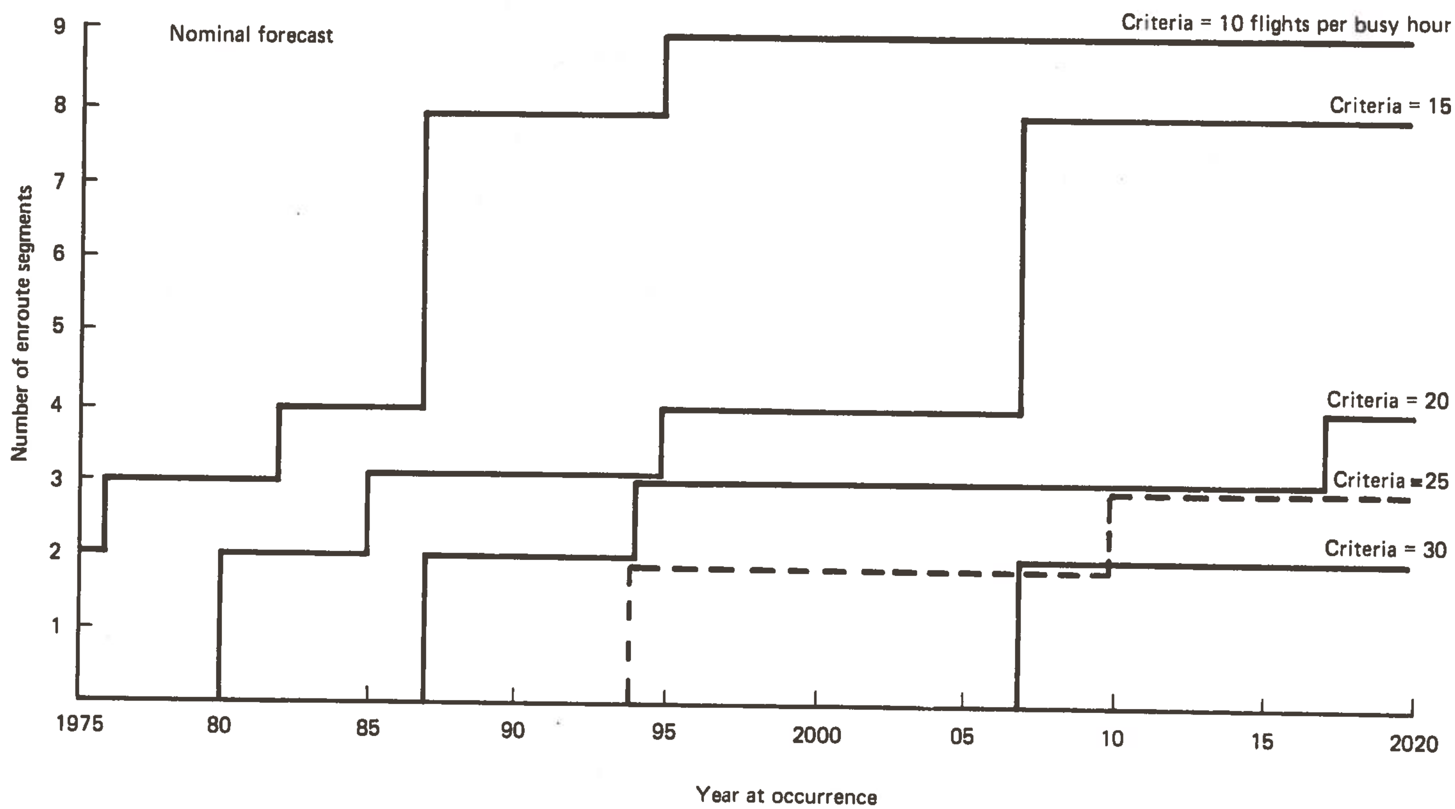


FIGURE 6-8.—EFFECT OF BUSY HOUR LOAD CRITERIA ON REQUIREMENT FOR EN ROUTE STRATEGIC CONTROL

TABLE 6-4.–EN ROUTE STRATEGIC CONTROL REQUIREMENTS–YEAR OF OCCURRENCE

En route segment	Year in which busy hour flights exceed criteria		
	Low forecast	Medium forecast	High forecast
New York–Chicago	2016	1994	1986
New York–Miami	2016	1994	1986
Chicago–Los Angeles	–	–	2017
San Francisco–Chicago	–	–	2017
Boston–Washington	–	2010	1992
Chicago–Denver	–	–	2017
New York–Los Angeles	–	–	2005
Chicago–Washington	–	–	2017
San Francisco–Seattle	–	–	–

as the along-track distances satisfy the above constraints imposed by descent rates. The routing space and distance allowed for radii of turns reflects the speeds at different arrival stages. These radii are 18.6 nautical miles for a speed of 500 knots at the entry fixes: 5.0 nautical miles for 300 knots at the initial approach fix and other intermediate points; and 2.25 nautical miles for 200 knots turning on the final approach.

6.3.1.2 Considerations for the Los Angeles Terminal Area

The Los Angeles basin contains the greatest concentration of general aviation airplanes in the United States. From table 6-5, it can be seen that it contains four of the five busiest airports in the nation in terms of total annual operations. This results in one of the most severely congested airspace areas in the world. By the year 2000 it is projected that annual operations in the Los Angeles hub will increase by 50% to exceed 4.5 million. In terms of total air carrier operations, Los Angeles International Airport (LAX), is rated second in the nation. LAX has severe noise problems, possibly more critical than any other airport in the United States.

There are five parallel east-west runways but, for practical purposes, LAX can be regarded as two pairs of parallel runways since runway 26 is restricted to light general aviation airplanes and is used only infrequently. The outside runways of the two main sets of parallels are spaced so that under present rules they can be operated as one pair of independent parallel runways. This is done in bad weather, although use of the northernmost runway is undesirable because of the noise problem.

The Los Angeles International Airport is geographically situated such that it is provided both advantages and constraints. Located on the coast, there are clear paths to the west and southwest and, except for the Palos Verdes Point area (rising to 1300 feet 10 miles away), nothing but water exists to the southeast. At bearings from north to east, high ground is encountered but only at one point are massive hills close enough to affect close-in maneuver patterns. San Gabriel Peak and adjacent Mt. Wilson, both standing slightly over 6000 feet, are barely within a 25-mile radius of the airport. Beyond the areas of initial climbout and final approach, arrival and departure routes are affected. The bulk of the San Gabriel Mountains, including 10,000-foot Mt. San Antonio, lies to the northeast with the

TABLE 6-5.—TOWER AIRFIELDS IN LOS ANGELES BASIN (1971)

Civil airfields	Annual air carrier operations	Total annual operations	National rank order (TAO)
Burbank	29,622	215,501	73
El Monte	0	88,528	263
Hawthorne	4	226,087	59
Fullerton municipal	0	190,940	94
Hughes (non federal tower)	No data available		
Long Beach	6,923	565,102	2
Los Angeles International	397,650	516,057	5
Ontario	30,662	147,381	157
Riverside Municipal	10,232	122,889	199
Santa Ana (Orange County)	19,557	520,593	4
Santa Monica	0	301,487	29
Torrance Municipal	0	388,492	12
Van Nuys	16	558,812	3
Palmdale	8	86,314	271
Military airports			
El Toro MCAS			
Los Alamitos NAS (closed)			
March AFB			
Norton AFB			
George AFB			

highest peaks about 40-45 miles away. On a bearing of 75° magnetic, lowlands form a corridor through the communities of Riverside and Palm Springs. At a distance of 80 miles, the corridor narrows as it passes between 11,000-foot peaks. Low altitude traffic to and from the east funnels through this pass. Jet traffic is more affected by the much nearer San Gabriel Mountains, which prevent either climbout or descent in the northeast quadrant. Table 6-6 tabulates prominent features.

Present traffic flow into Los Angeles can be grouped into eight main streams as shown in figure 6-9. Approximately 70% of the traffic comes in from the east. This eastern traffic is picked up by the ARTCC controllers while still at a distance and merges with flights from the southeast and northeast. The stream thus formed is brought straight in and handed off to the Los Angeles approach control after being lined up and spaced for a direct approach to the International Airport. Traffic coming down the coast from the north and coming in from the Pacific Ocean are merged into a stream at points in the northwest quadrant. When the flow is to the west, this traffic is vectored north of the airport to merge with traffic from the east. Flights from the southern coast are brought inland to join the eastern traffic on a long final approach. Departure traffic, either for east or west flow, is normally turned wide to skirt satellite airfields and kept low until passing under incoming streams.

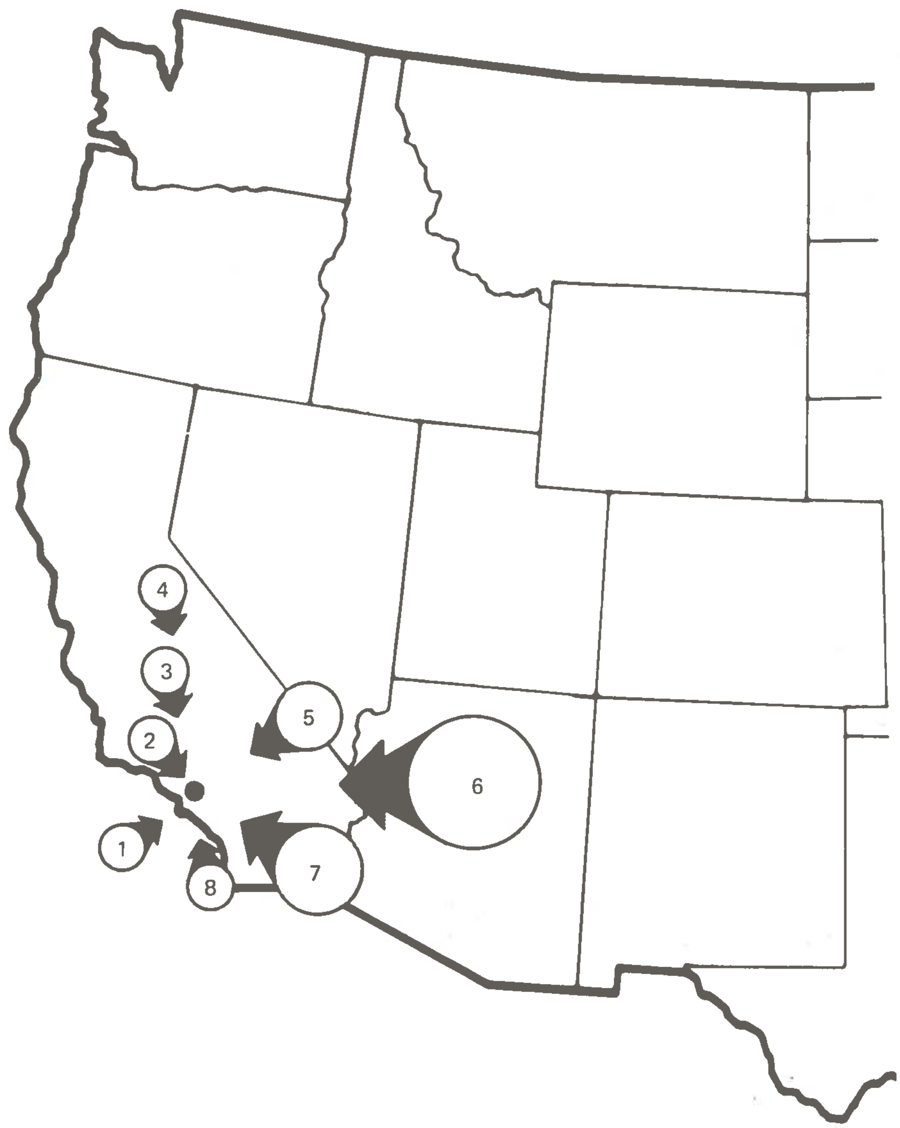


FIGURE 6-9.—LOS ANGELES INBOUND TRAFFIC FLOWS

TABLE 6-6.–PROMINENT TERRAIN FEATURES RELATIVE TO LOS ANGELES INTERNATIONAL AIRPORT

Feature	Bearing (degree magnetic)	Distance (nautical mile)	Elevation (feet)
San Gabriel Peak	22	25	6161
Pacifico Mt.	22	33	7124
Mt. Wilson Observatory	24	25	6172
Mt. Baden-Powell	37	43	9399
Peak	39	28	5409
Peak and tower	41	39	5698
Mt. San Antonio	46	43	10064
San Gorgonio Peak	67	81	11502
San Jacinto Peak	80	87	10831
Palos Verdes Area	150	10	1310
Palos Verdes Point	160	10	Sea level
Open water	160-270	—	Sea level
High ground north of Saddle Intersection	280	20	2824

6.3.1.3 Strategic Control Airspace Configuration for LAX

The example plan for the Los Angeles terminal area was constructed to handle the flow of traffic in a manner very similar to the present generalized patterns except that traffic will be directed over more definitely specified routes. Figure 6-10 shows the planned arrival routing.

In order to assign coordinates to locations for use of the computer, the area has been divided into quadrants with the origin at the threshold of the southernmost runway (25L), the y-axis is aligned with the runway, and the x-axis perpendicular to it. All entry fixes (not shown because of scale) are located on the arc of a circle 175 nautical miles from the origin to provide the needed track distance.

The plan is organized for use as either a single or dual parallel runway situation. Since a large part of the traffic approaches directly from the east, three entry fixes are placed east of the airport from which traffic merges at an initial approach fix and tracks directly into runway 25L.

A turn fix is placed along this route to satisfy programming requirements but is not used in this instance. Three entry fixes are placed in the northwest corridor, two to collect traffic from the north and one from an ADIZ corridor to the west. Flights from these fixes merge at an initial approach fix in the same quadrant; pass south of the Van Nuys and Burbank airports in order to stay clear of high terrain in the northeast quadrant; and turn right to intercept the final approach. Separation from nonstrategic Van Nuys and Burbank traffic is by altitude. An entry fix in the southwest quadrant allows arrival through another ADIZ corridor for flights from South America and the Pacific, which merge at an initial approach fix in the vicinity of Santa Ana with airplanes from Mexico and the southwest

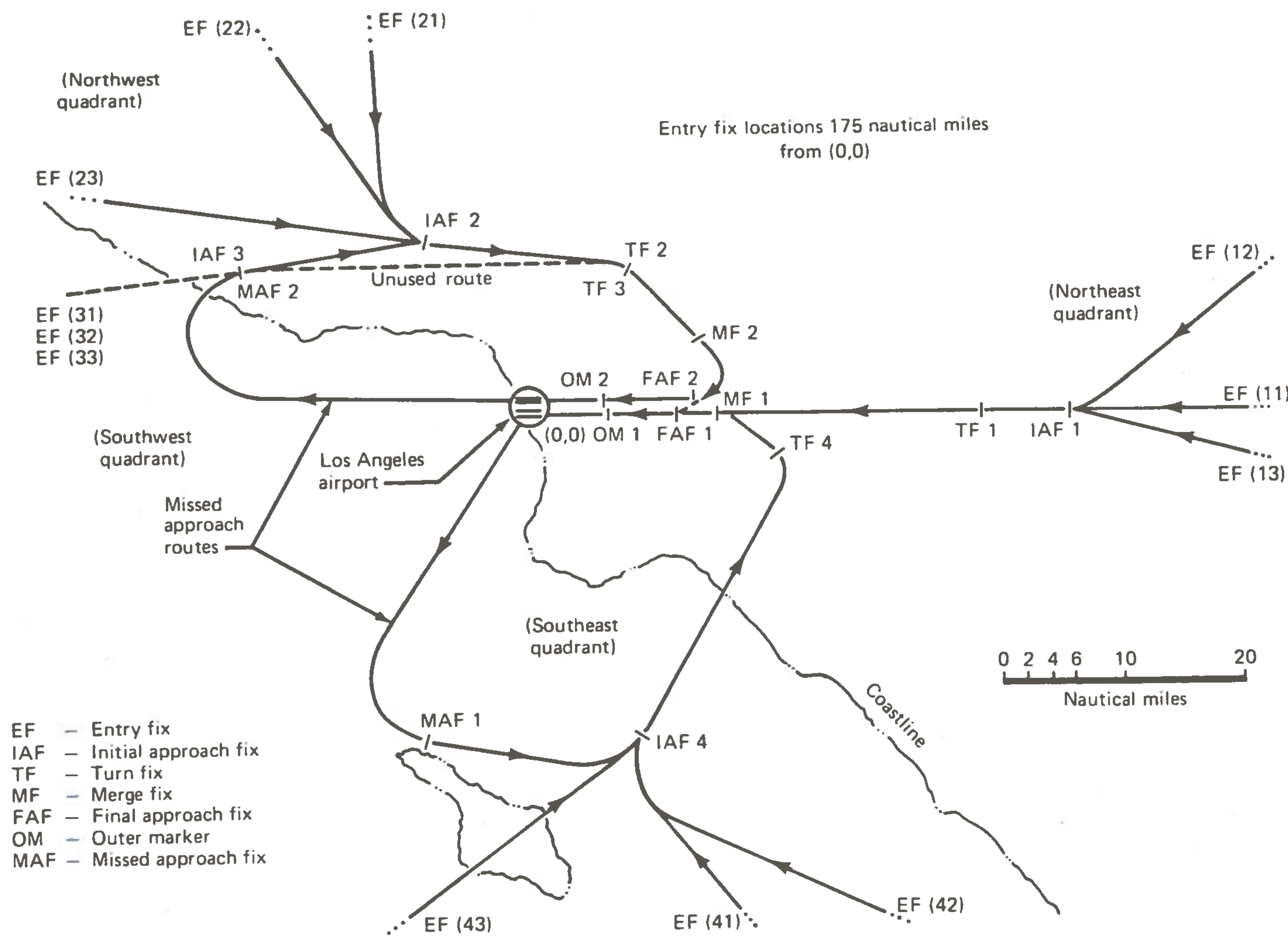


FIGURE 6-10.—LOS ANGELES STRATEGIC ARRIVAL GEOMETRY

U.S. These streams are merged on the final with flights from the east as shown in the figure. Note that, for safety, a straight-line segment 30° off the final heading is flown for at least 2 miles before intercepting the final approach. Note also that the airplanes intercepting the final from the north are separated from those from the south, both in altitude and along track at the points of interception. An unused dummy route (dashed line) is included because the program requires a total of 12 entry fixes with an initial approach fix for each set of three. Missed approach routes are constructed to return an airplane to the closest initial approach fix.

6.3.2 En Route Airspace Structure

At the present stage of concept development the strategically controlled en route airspace is viewed simply as RNAV type routes existing from one terminal area and connecting at an entry point of another. Separate routes, or separate altitudes for opposite direction traffic will probably be used. Only nine routes meet the present criteria (discussed in section 6.2) for designation as strategic routes. These routes, and the terminal areas meeting strategic control criteria, are shown on a map of the United States in Figure 6-11.

6.4 SUPPORTING DATA

Supporting data for the developments in section 6.0 are supplied as follows:

- Figure 6-12, IFR Practical Hourly Capacity of Selected Runway Configurations
- Table 6-7, Airport Air Carrier IFR Capacity
- Comments on capacity of specific airfields for table 6-7
- Figure 6-13, Airport Traffic Growth Charts
- Table 6-8, index to figure 6-13, Airport Traffic Growth Charts

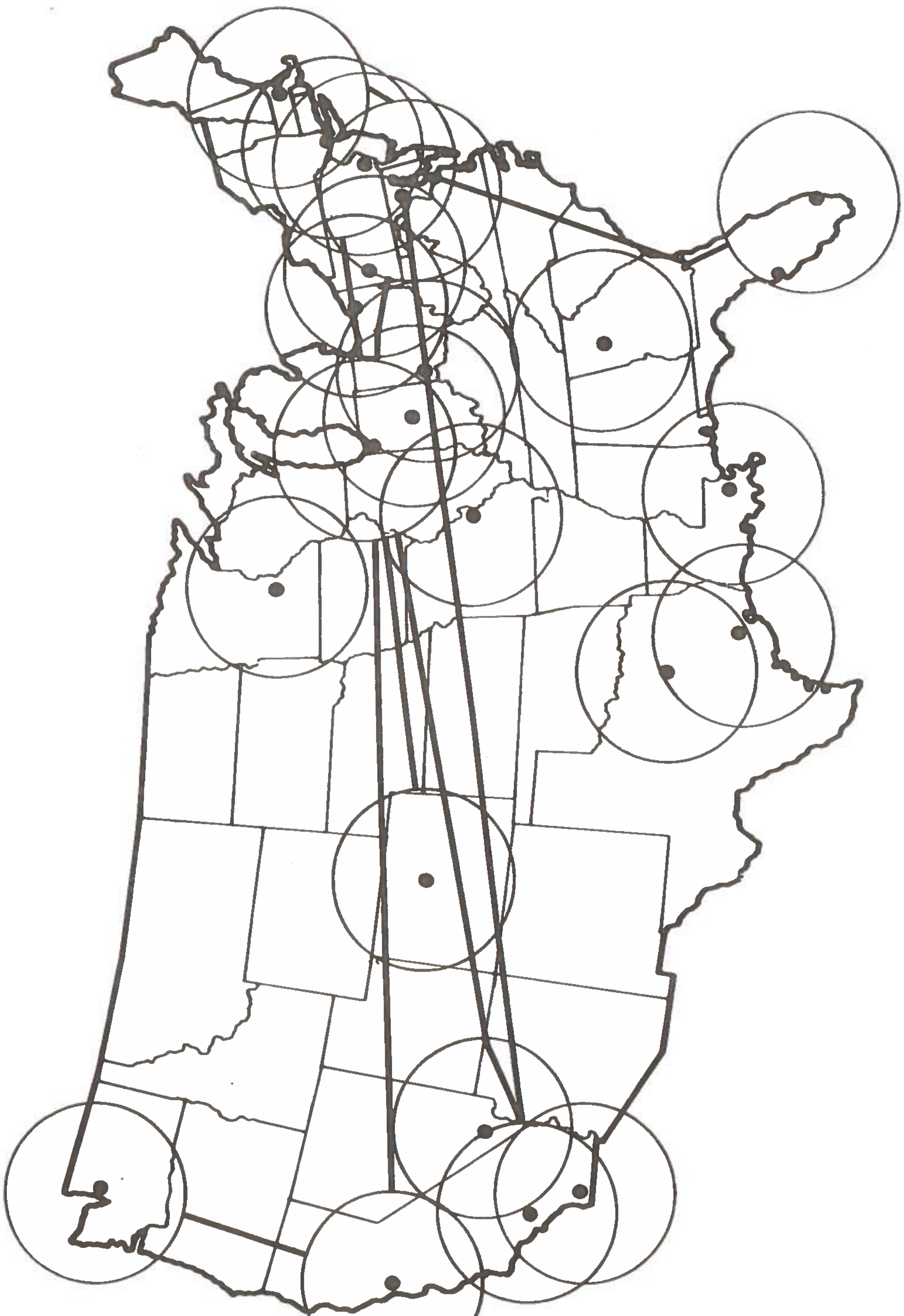


FIGURE 6-11.—TERMINAL AND EN ROUTE AREAS MEETING CRITERIA FOR STRATEGIC CONTROL

RUNWAY CONFIGURATION		IFR PRACTICAL HOURLY CAPACITY (MIX 4)
LAYOUT	DESCRIPTION	
(A)	SINGLE RUNWAY (ARRIVALS-DEPARTURES)	42
(B) LESS THAN 3500'	CLOSE PARALLELS (IFR DEPENDENT)	54
(C) 3500' TO 4999'	INDEPENDENT IFR ARRIVAL/DEPARTURE PARALLELS	74
(D) 5000' OR MORE	INDEPENDENT IFR ARRIVALS AND DEPARTURES	84
(E) 5000' OR MORE	INDEPENDENT PLUS ONE CLOSE PARALLEL	96
(F) 5000' OR MORE; 3500' TO 4999'	INDEPENDENT PLUS SIMULTANEOUS DEPARTURE RUNWAY	133

FIGURE 6-12.–IFR PRACTICAL HOURLY CAPACITY OF SELECTED RUNWAY CONFIGURATIONS (PER FAA AC 150/5060-3)

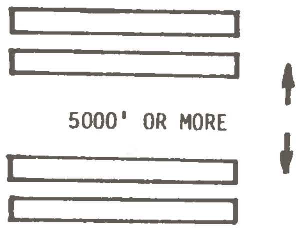
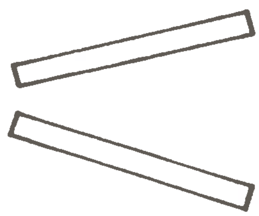
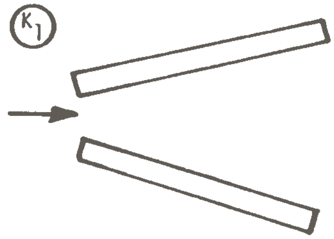
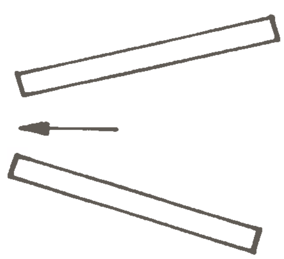
RUNWAY CONFIGURATION		IFR PRACTICAL HOURLY CAPACITY (MIX 4)
LAYOUT	DESCRIPTION	
(H) 	INDEPENDENT PARALLELS PLUS TWO CLOSE PARALLELS	108
(J) 	WIDELY SPACED OPEN V WITH INDEPENDENT OPERATIONS	74
(K_1) 	OPEN V, DEPENDENT, OPERATIONS AWAY FROM INTERSECTION	60
(K_2) 	OPEN V, DEPENDENT, OPERATIONS TOWARD INTERSECTION	50

FIGURE 6-12.–CONTINUED

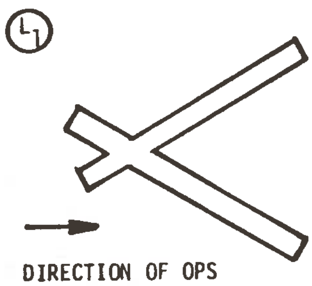
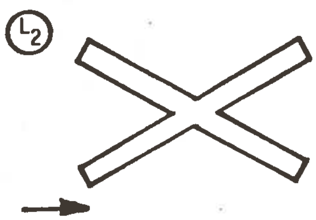
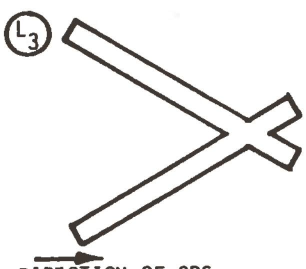
RUNWAY CONFIGURATION		IFR PRACTICAL HOURLY CAPACITY (MIX 4)
LAYOUT	DESCRIPTION	
 DIRECTION OF OPS	TWO INTERSECTING AT NEAR THRESHOLD	60
 DIRECTION OF OPS	TWO INTERSECTING IN MIDDLE	47
 DIRECTION OF OPS	TWO INTERSECTING AT FAR THRESHOLD	42

FIGURE 6-12.—CONCLUDED

TABLE 6-7.—AIRPORT AIR CARRIER IFR CAPACITY

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
1. Chicago-O'Hare International (ORD)	F	133	O'Hare is a complex operation often involving the use of six runways. Operations rates of 150 to 200 per hour are experienced. It was roughly equated to independent parallels plus a simultaneous departure runway yielding 133 IFR operations per hour, which approximates the scheduling limit of 135 operations per hour.
2. Los Angeles International (LAX)	H	108	Los Angeles International Airport runway operations are subject to several special considerations: • Most operations are under VMC conditions. • Simultaneous approaches to 25R and 25L are routinely used based on visual contact between aircraft. • Aircraft over 350,000 pounds actual weight cannot use 25R or 25L due to the Sepulveda Boulevard underpass and must use 24L. • 24R is usually not used (except for a few small private aircraft) due to sideline noise effect on the neighborhood. • When the weather is close to minimums, 24R is used so that independent parallel pair operation is in effect. • Many aircraft are classified as "heavy" requiring wake turbulence spacing. • Minimum capacity occurs under these IFR conditions when 24R is not used. Considering (1) the gains due to VFR operations, (2) actual operations of 79 air carrier flights in 1 hour with 99 total operations, and (3) the various constraints, the effective runway configuration was defined as independent parallel pairs.
3. Atlanta Municipal (ATL)	E H	[a] 96 [b] 108	The Atlanta basic configuration has parallel runways separated by about 4500 feet, with a special dispensation for simultaneous approaches to the east using 2-mile longitudinal separation. A third outside parallel is being placed into operation that is over 5000 feet from the opposite parallel. This was equated to independent parallels plus an independent departure runway. It is planned to construct a fourth outside parallel runway providing parallel pairs with about 4500 feet between the inside runways. This was equated to independent parallel pairs.

[a] See text
[b] Post-1975

TABLE 6-7.—CONTINUED

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
4. New York J. F. Kennedy International (JFK)	C D	74 [c] 84	J. F. Kennedy has one pair of parallel runways (13L/31R, 13R/31L) separated by over 5000 feet and another pair (4L/22R, 4R/22L) separated by about 3000 feet. Today's operations were equated to independent approach/departure parallels. This is substantiated by the peak hour schedule limits of 80 air carrier/90 total operations. In the future, possibly by 1975, the 13L/31R, 13R/31L combination could be provided landing guidance systems to support simultaneous independent arrivals.
5. San Francisco International (SFO)	L_2	47	San Francisco's principal mode of air carrier IFR operation is landing on runway 28L and R and departure on runway IR. These two runways intersect near the middle.
6. Dallas Love/S.W. Regional (DAL)	C D H	[d] 74 [e] 84 [f] 108	Air carrier operations in the Dallas/Fort Worth area use Love Field, which has parallel runways that support independent arrival/departure operations. The Dallas/Fort Worth Regional Airport will open soon. The Regional Airport will initially have two primary runways separated by 6400 feet providing independent arrivals and departures. Ultimate growth (possibly by 1980) would add a run-way 1200 feet outside of each primary runway providing independent parallels plus two close parallels.
7. New York-La Guardia (LGA)	L_1	60	La Guardia has intersecting runways with optimum operations by landing on runway 22 and taking off on runway 13. This is crossing at near threshold.
8. Miami International (MIA)	C D	74 [b] 84	Miami has primary runways that are parallel and separated by 5000 feet. They are operated as independent IFR approach/departure parallels. Addition of landing guidance systems could provide independent IFR arrivals and departures, possibly by 1975 or beyond.
9. Detroit Metropolitan-Wayne County (DTW)	C D	74 [g] 84	Primary IFR runways are parallel 3/21R and L separated by 3800 feet allowing independent IFR arrival/departure operations. Future construction may provide a new 3R/21L separated by 5000 feet from the existing 3L/21R and thereby allowing independent IFR arrivals and departures.
10. Washington National (DCA)	A	42	Under instrument conditions, air carrier operations are normally conducted on one runway.

[b] Post-1975
[c] Approximately 1975
[d] Love Field
[e] Regional airport
[f] Regional post-1980
[g] By 1975

TABLE 6-7.—CONTINUED

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
11. Boston Logan International (BOS)	L_1	60	Typical IFR operations are arrivals on 4R and departures on 9 which are runways intersecting near the threshold end.
12. St. Louis Lambert Field (STL)	A	42	Air carrier operations are conducted primarily on the 30L/12R runway.
13. Newark (EWR)	B	54	Newark has been equated to the IFR capacity of a set of close parallels considering (1) currently aircraft can arrive on 4L and depart on 11, and (2) the rehabilitation of 4R/22L would provide a set of close parallels.
14. Philadelphia International (PHA)	B	54	Runways 9R/27L and 9L/27R provide close parallels that are used for most air carrier operations.
15. Greater Pittsburgh (PIT)	C	74	Pittsburgh has a set of parallel runways that are operated as independent IFR arrival/departure parallels.
16. Denver Stapleton International (DEN)	J	74	Denver has two long runways forming an open "T." Primary air carrier operations are independent arrivals on 8R/26L and departures on 35L. This is equated to an open "V" with independent operations (equivalent to independent IFR arrival/departure parallels).
17. Minneapolis-Wold Chamberlain(MSP)	B	54	Under VMC conditions Minneapolis has been observed handling arrivals on 29R, VFR arrivals on 29L and departures on 29L and 22. Under IMC 29L/11R and 29R/11L are used as close parallels.
18. Cleveland-Hopkins International (CLE)	A	42	For air carrier IFR operations Cleveland-Hopkins can be operated as either a single runway or as runways intersecting at the far threshold.
19. San Juan International (SJU)	A	42	As far as air carrier operations are concerned San Juan is a single runway (7/25) airport.
20. Houston International (IAH)	K_1	60	
21. Kansas City International (Mid Continent) (MCI)	J D	[h] 74 84	
22. Baltimore International (BAL)	L_2	47	
23. Honolulu (HON)	A	42	
24. New Orleans-Moisant (MSY)	A	42	
25. Memphis International (MEM)	C	74	

[h] MCI initial configuration planned by 1975

TABLE 6-7.—CONTINUED

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
26. Seattle-Tacoma International (SEA)	B	54	
27. Greater Cincinnati (CVG)	A	42	
28. Las Vegas-McCarran International (LAS)	L_3	42	
29. Portland International (PDX)	C	74	
30. Indianapolis Municipal (IND)	L_2	47	
31. Phoenix-Sky Harbor International (PHX)	C	74	
32. Louisville-Standisford Field (SDF)	L_2	47	
33. Tampa International (TPA)	C	74	
34. Greater Buffalo International (BUF)	A	42	
35. Milwaukee-General Mitchell Field (MKE)	L_2	47	
36. San Diego-Lindbergh Field (SAN)	A	42	
37. Oakland-Metropolitan International (OAK)	A	42	
38. Salt Lake City International (SLC)	B	54	
39. Port Columbus International (CMH)	B	54	
40. Nashville Metropolitan (BNA)	L_2	47	
41. Dulles International (IAD)	D	84	
42. Charlotte-Douglas Municipal (CTL)	L_3	42	
43. San Antonio International (SAT)	L_3	42	
44. Syracuse Hancock International (SYA)	A	42	
45. Rochester-Monroe County (ROC)	A	42	
46. Windsor Locks-Bradley International (BDL)	A	42	
47. Dayton Municipal (DAY)	A	42	
48. Providence-Theodore F. Green State (PVD)	A	42	
49. Oklahoma City-Will Rogers(OKC)	C	74	
50. Albany County (ALB)	A	42	
51. San Jose (SJC)	A	42	
52. Jacksonville International (JAX)	J	74	

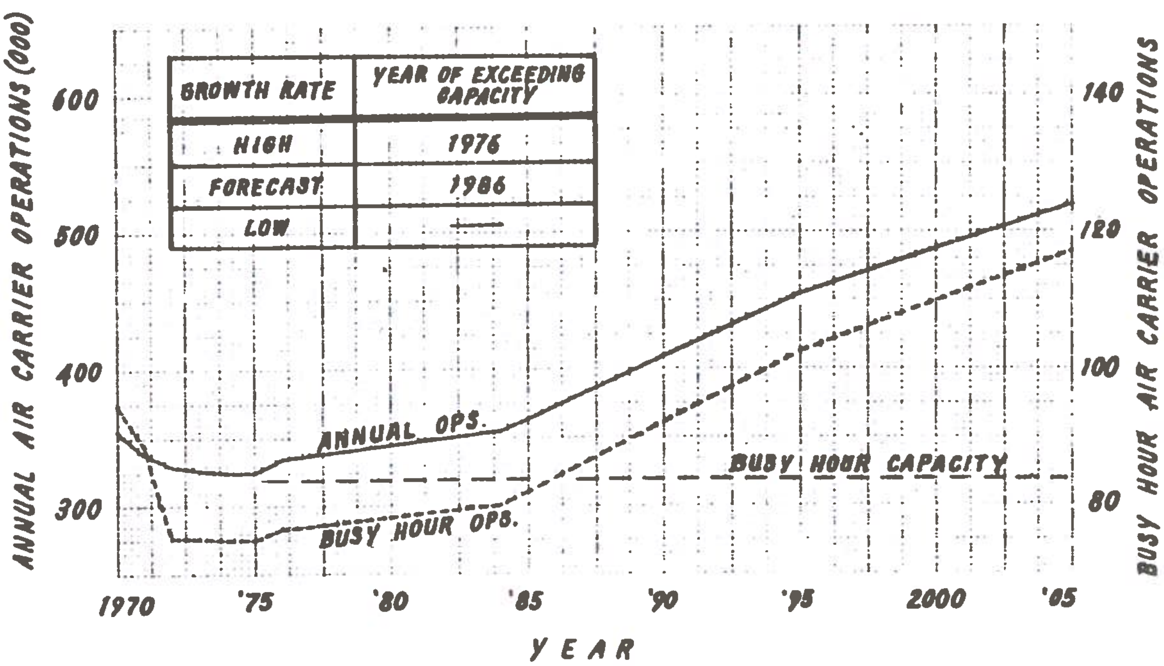
TABLE 6-7.—CONTINUED

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
53. Tulsa International (TUL)	A	42	
54. Birmingham Municipal (BHM)	A	42	
55. Omaha-Eppley Airfield (OMA)	A	42	
56. Albuquerque International (ACQ)	L_2	47	
57. Fort Lauderdale-Hollywood International (FLL)	A	42	
58. Palm Beach International (PBI)	L_2	47	
59. Norfolk Regional (ORF)	A	42	
60. Wichita Municipal (ICT)	C	74	
61. El Paso International (ELP)	A	42	
62. Shreveport Regional (SHV)	A	42	
63. Chicago-Midway (MDW)	B	54	
64. Tucson International (TUS)	A	42	
65. Knoxville-McGhee-Tyson(TYS)	A	42	
66. Des Moines Municipal (DSM)	A	42	
67. Roanoke Municipal (ROA)	L_3	42	
68. Detroit City (DET)	A	42	
69. Jackson-Allen C. Thompson Field (JAN)	C	74	
70. Raleigh-Durham (RDU)	A	42	
71. Burbank, Hollywood-Burbank (BUR)	L_3	42	
72. Spokane International (GEG)	L_3	42	
73. Greensboro-High Point/Winston-Salem Regional (GSO)	L_3	42	
74. Little Rock-Adams Field (LIT)	A	42	
75. Richmond-R. E. Byrd International (RIC)	K_2	50	
76. Charleston S.C. AFB/Municipal (CHS)	A	42	
77. Madison-Truax Field (MSN)	A	42	
78. Columbia Metropolitan (CAE)	A	42	
79. Billings-Logan Field (BIL)	A	42	

TABLE 6-7.—CONCLUDED

Airport	Effective runway configuration	IFR practical hourly capacity	Comments
80. Grand Rapids-Kent County (GRR)	A	42	
81. Sioux Falls-Joe Foss Field (FSD)	A	42	
82. Ontario International (ONT)	A	42	
83. Charleston W. Va.-Kanawha (CRW)	A	42	
84. Reno International (RNO)	A	42	
85. Midland Odessa Regional (MAF)	A	42	
86. Moline Quad City (MLI)	A	42	
87. Green Bay Austin Straubel (GRB)	A	42	
88. Greater Peoria (PIA)	A	42	
89. Chattanooga-Lovell Field (CHA)	A	42	
90. Augusta-Bush Field (AGS)	A	42	
91. Bristol Tenn-Tri City (TRI)	A	42	
92. South Bend-St. Joseph County (SBN)	A	42	
93. Middleton Pa.-Harrisburg Int/ Olmsted AFB (MDT)	A	42	

NEW YORK —— KENNEDY INTERNATIONAL



NEW YORK —— LAGUARDIA

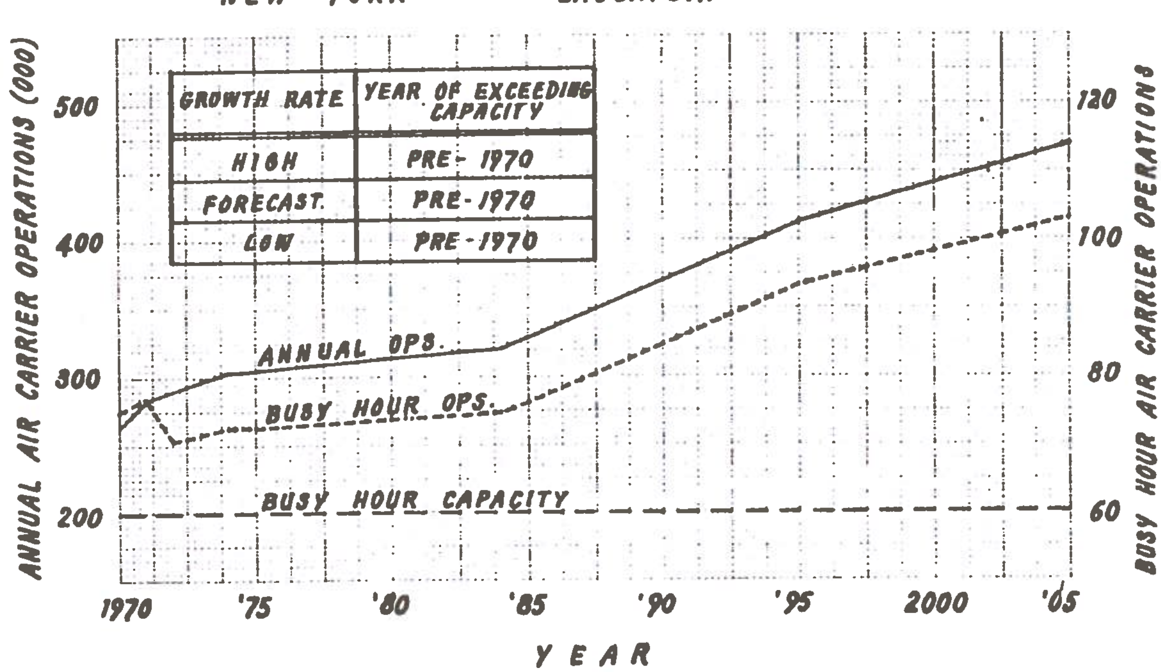
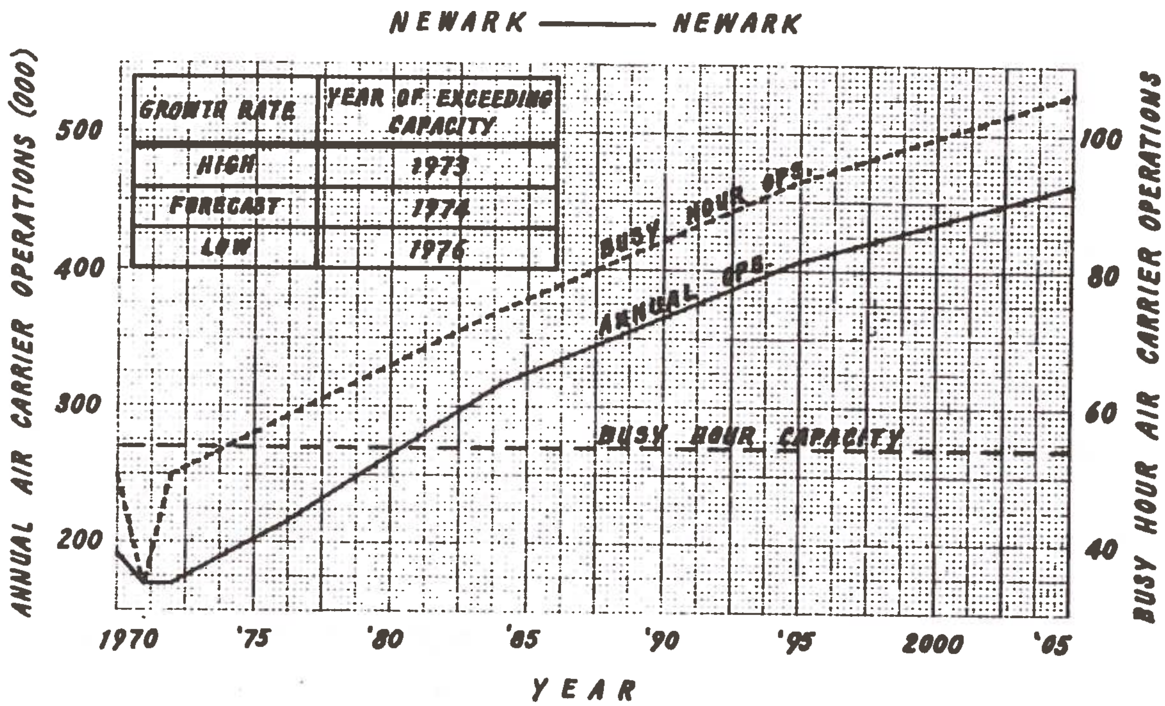


FIGURE 6-13.—AIRPORT TRAFFIC GROWTH CHARTS (SHEET 1)



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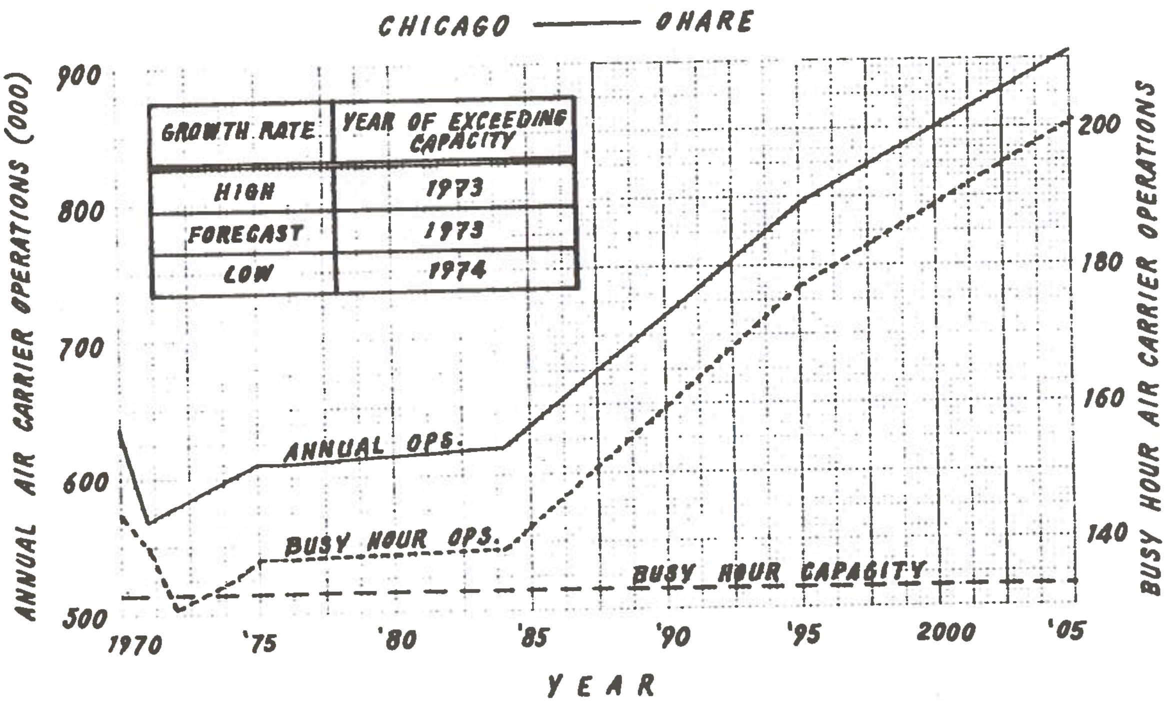


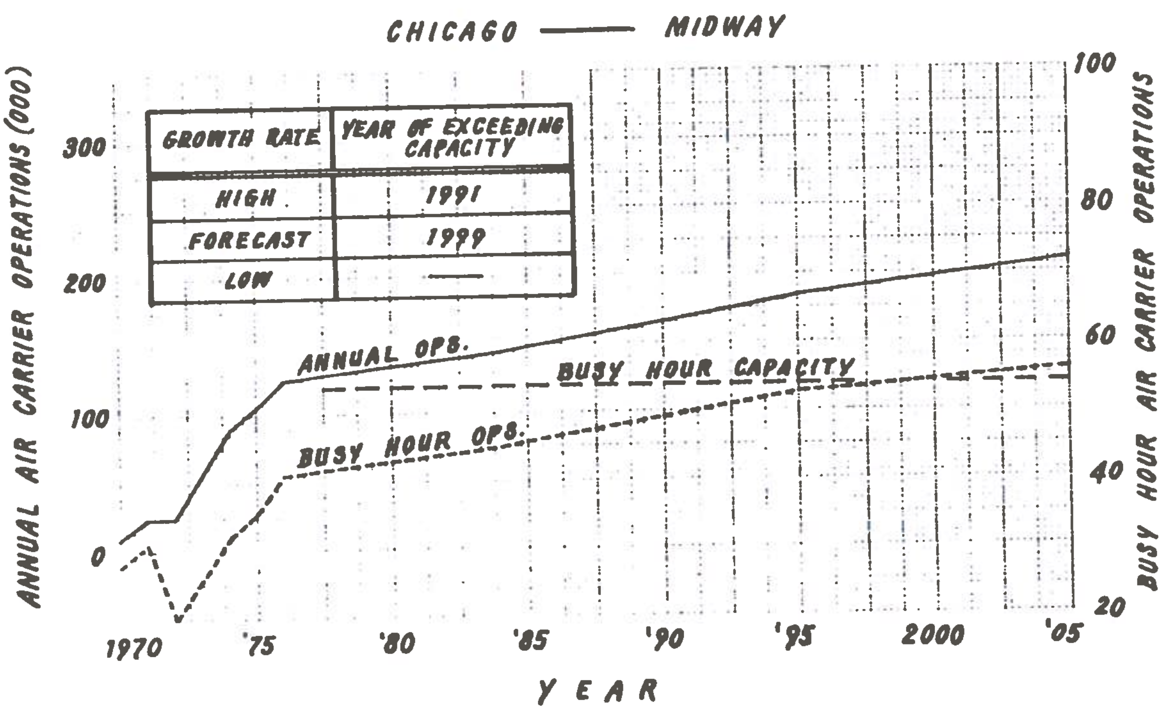
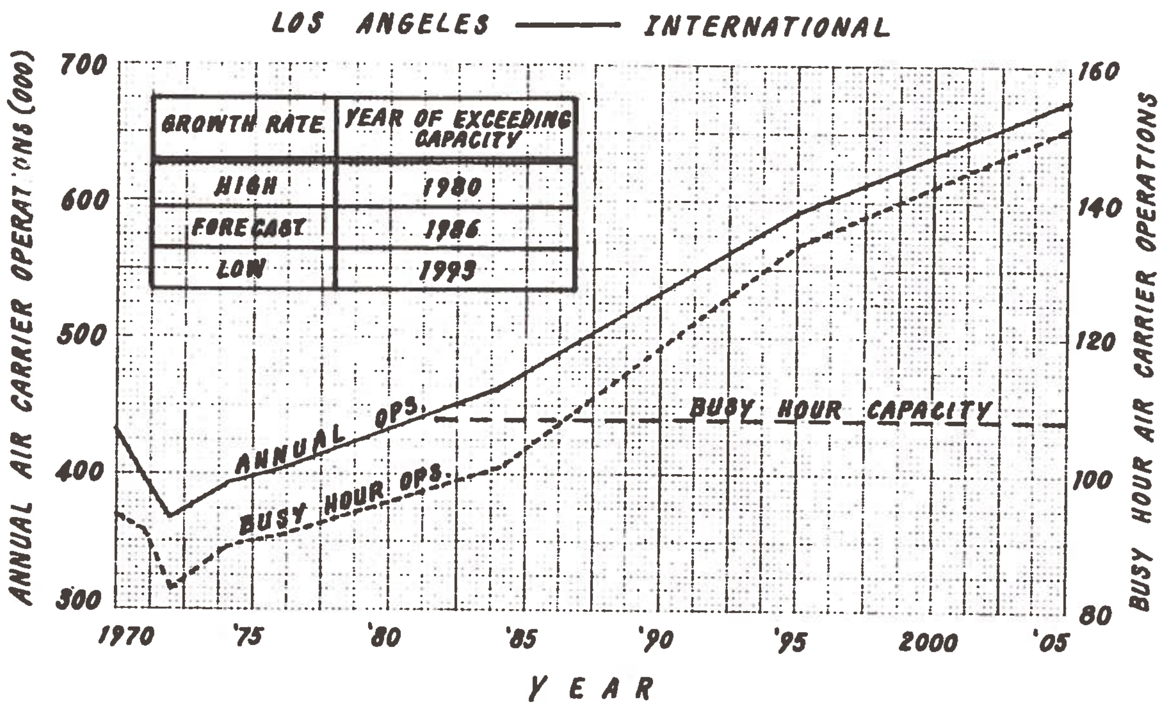


FIGURE 6-13.—CONTINUED (SHEET 3)



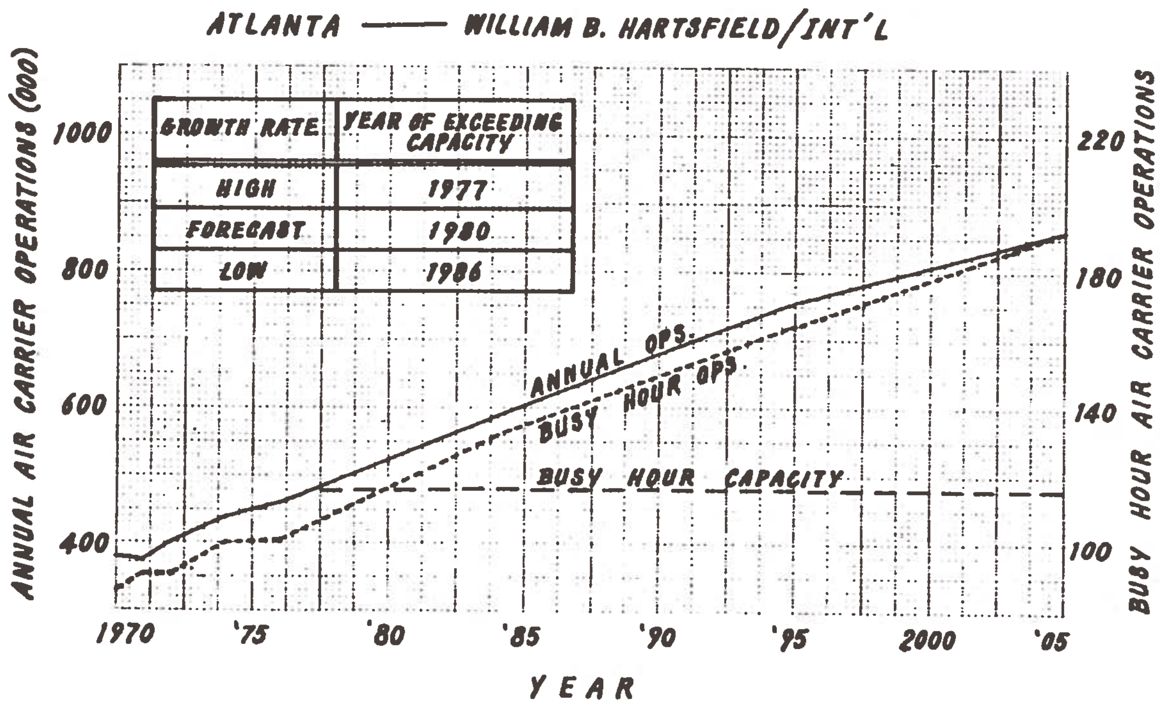
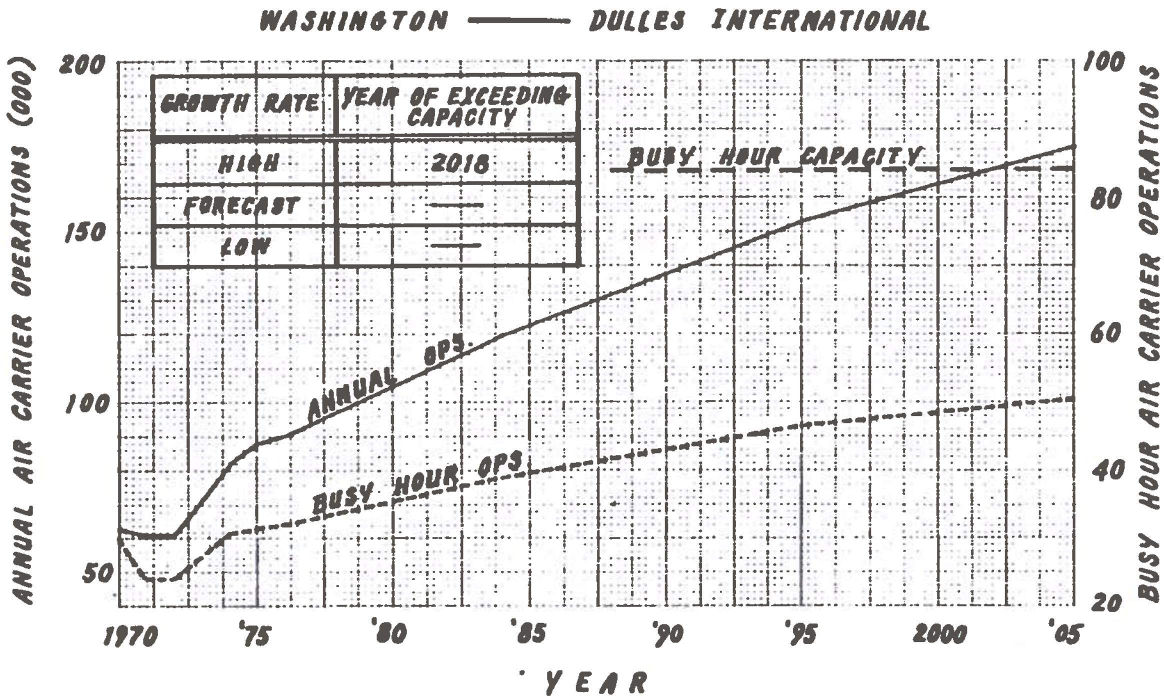
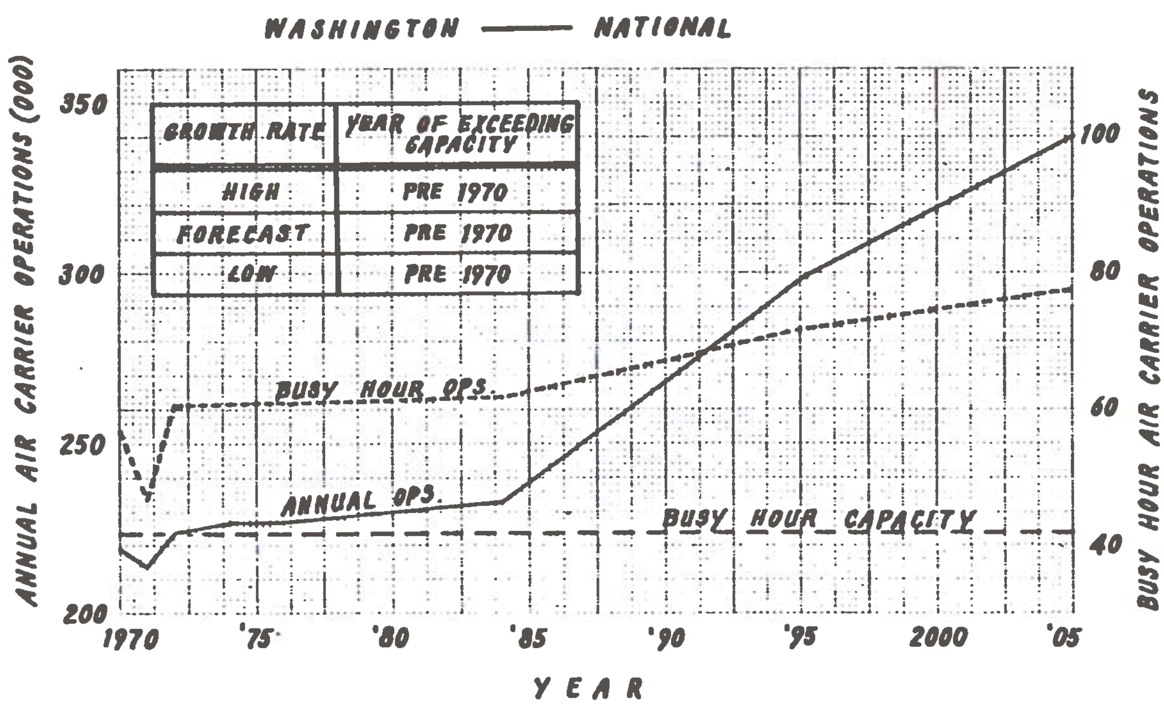


FIGURE 6-13.—CONTINUED (SHEET 4)





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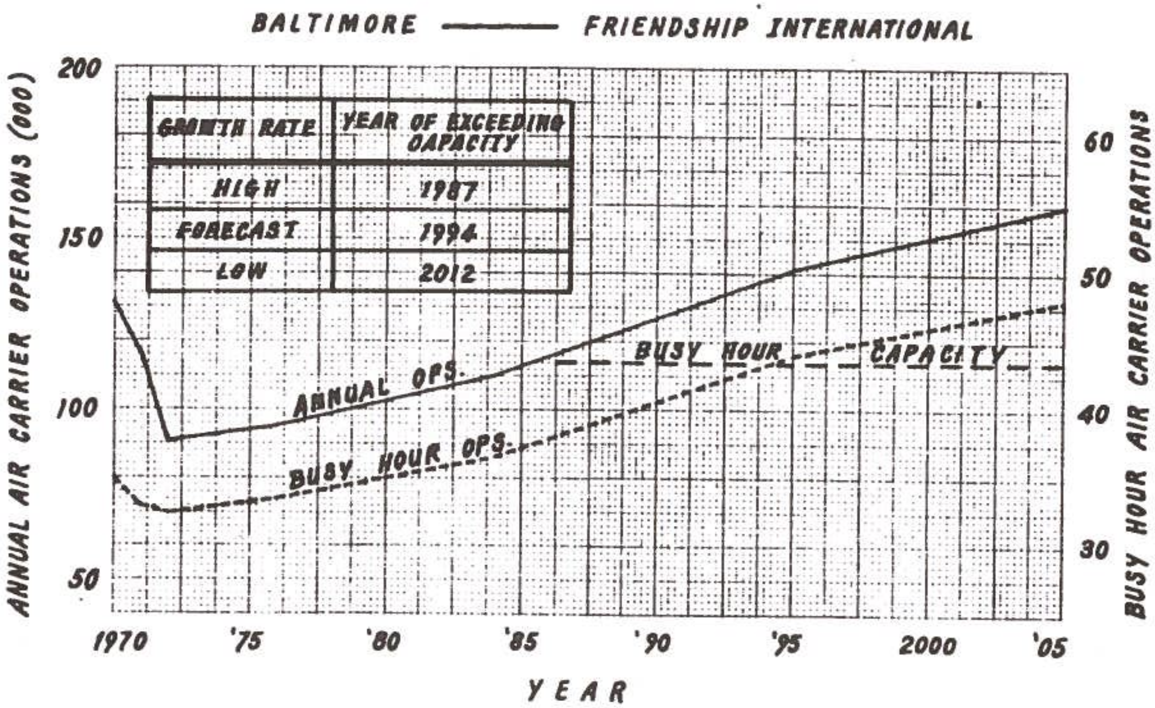

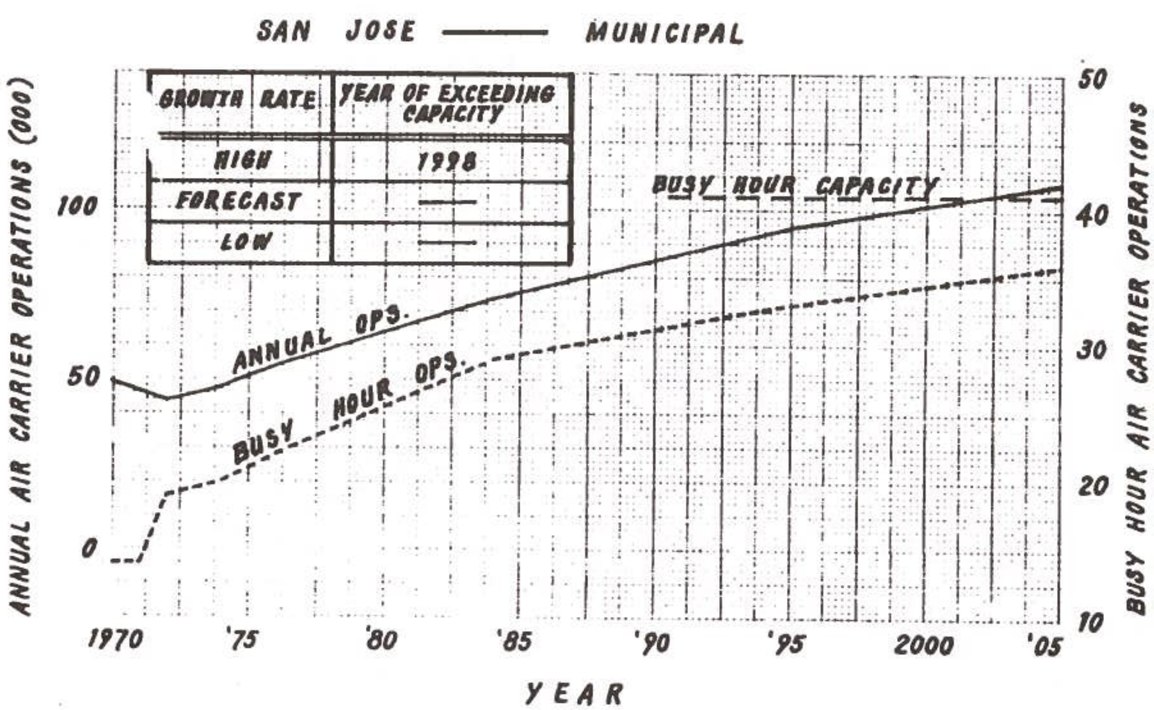

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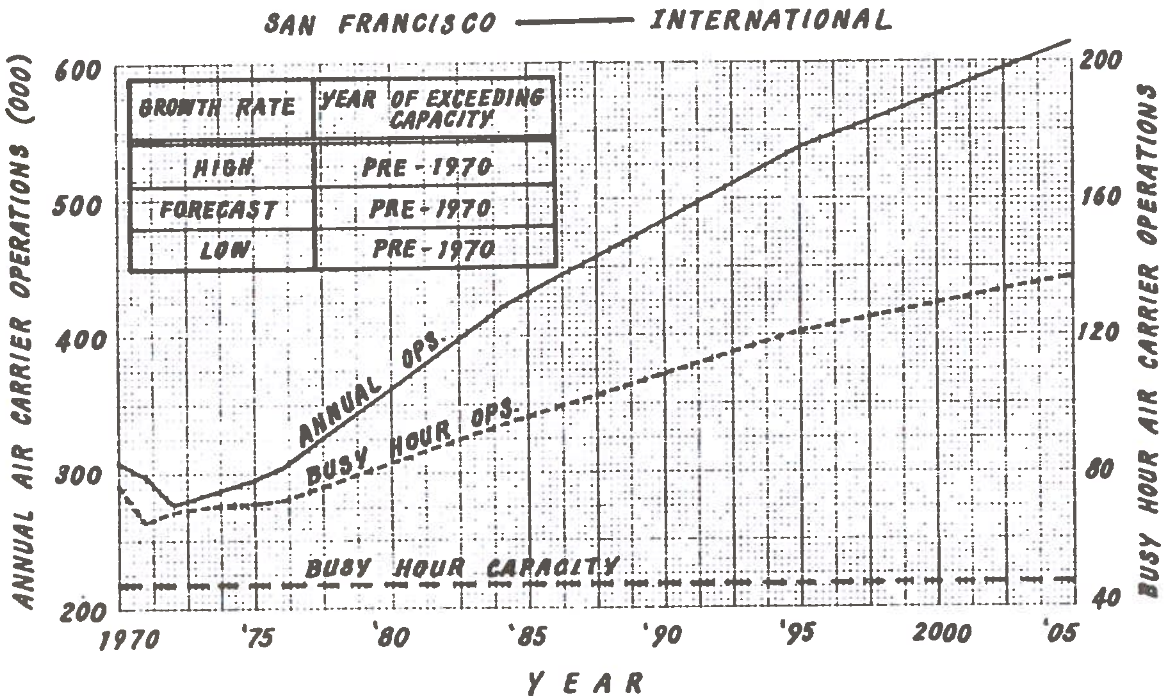

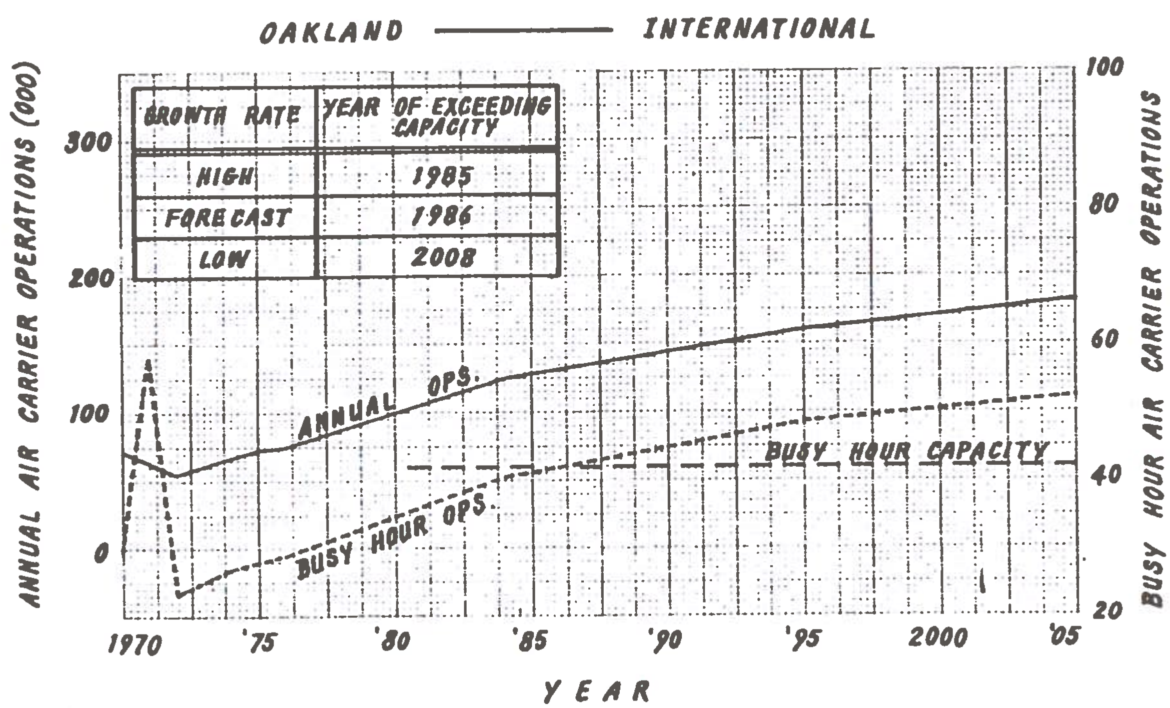

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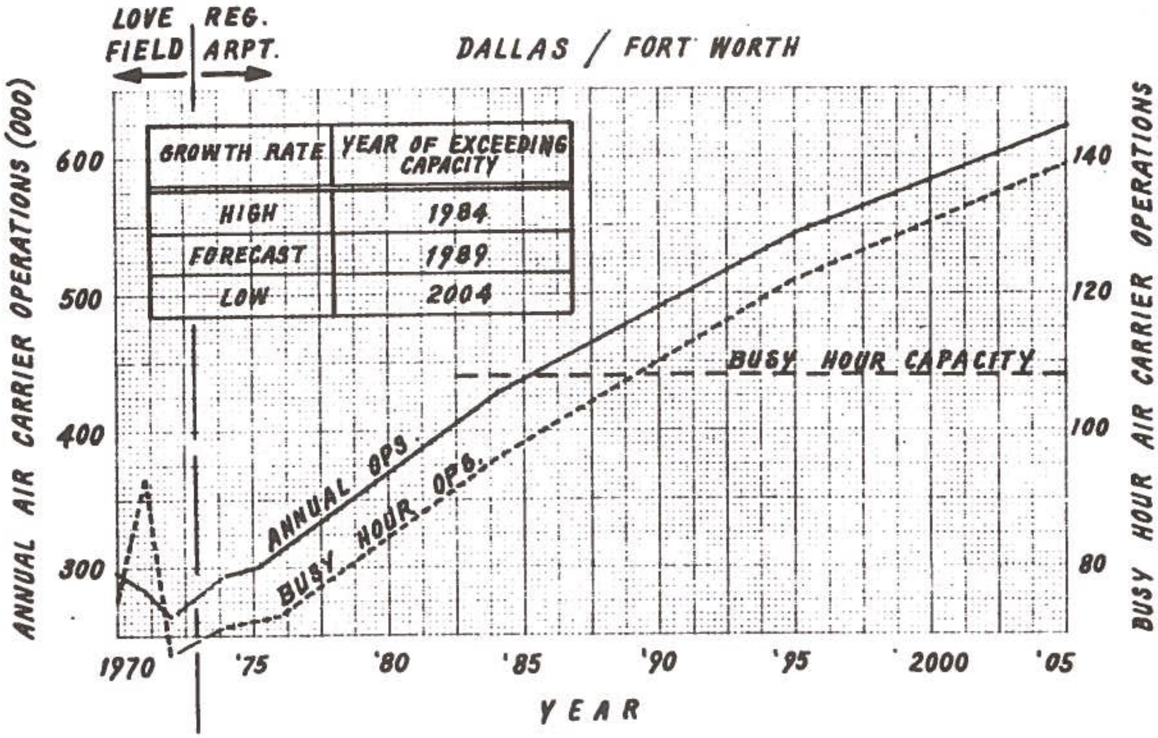

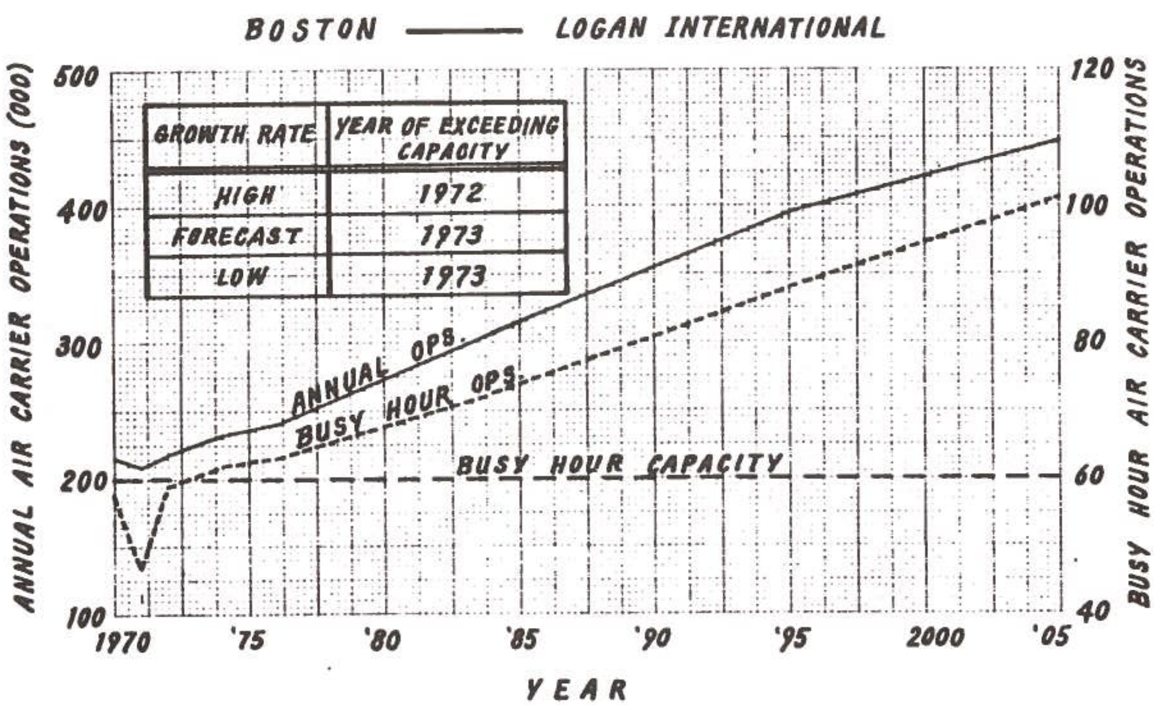

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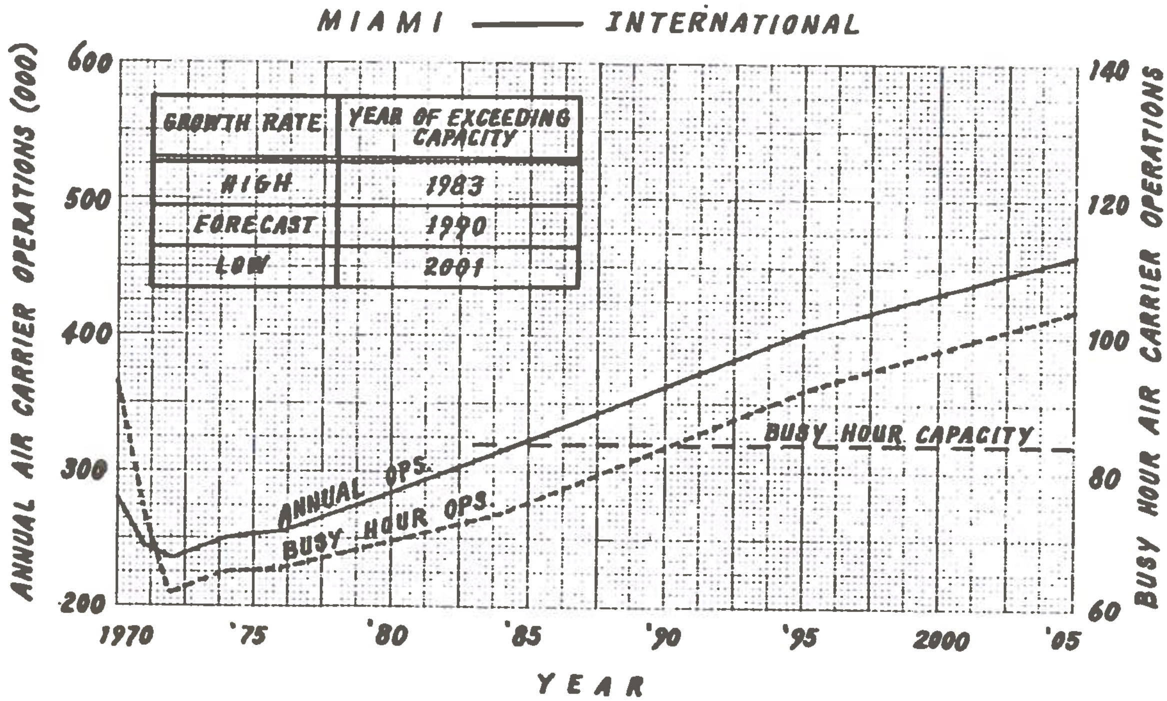

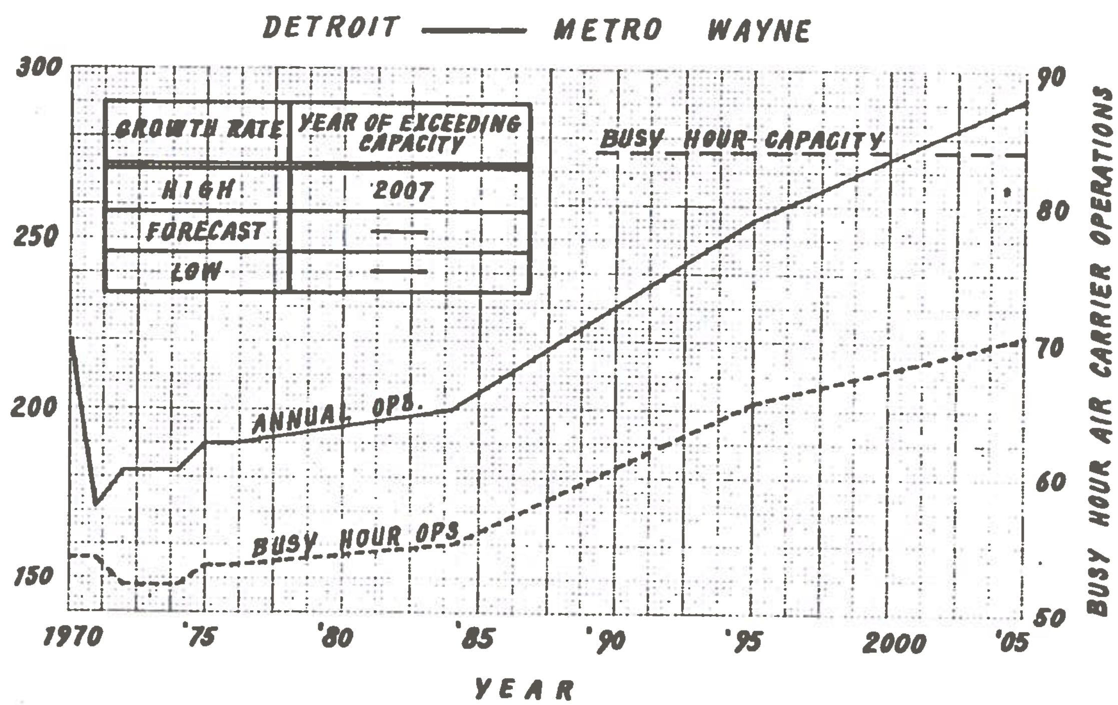

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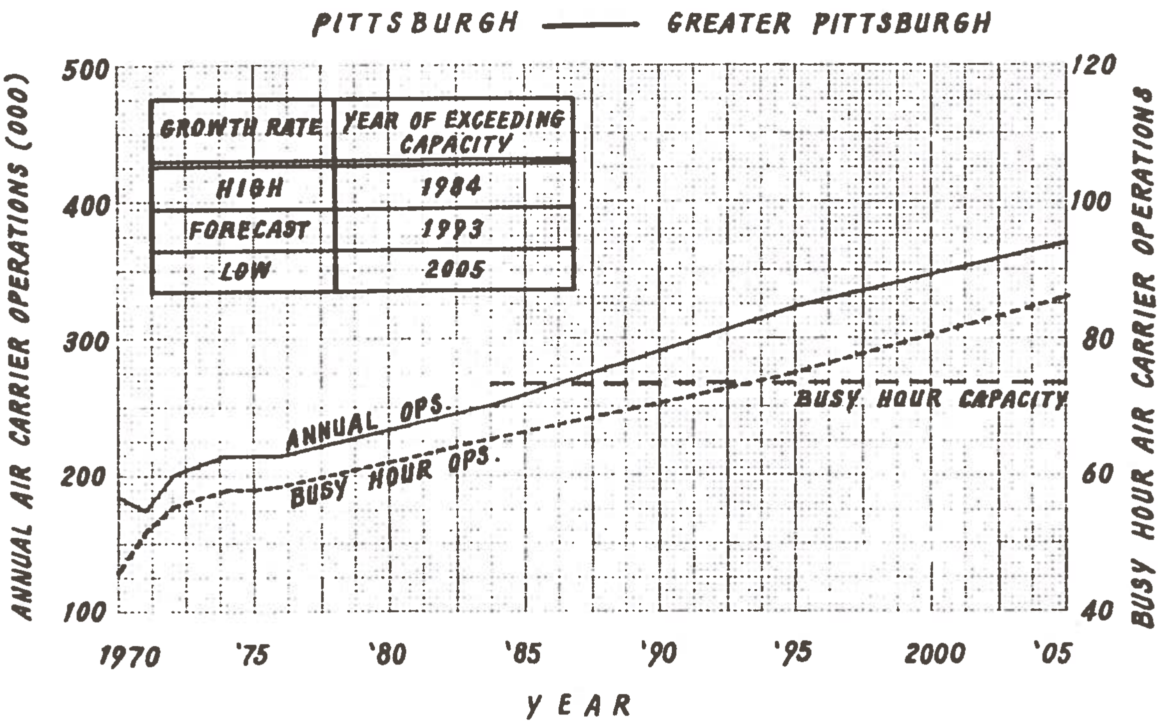

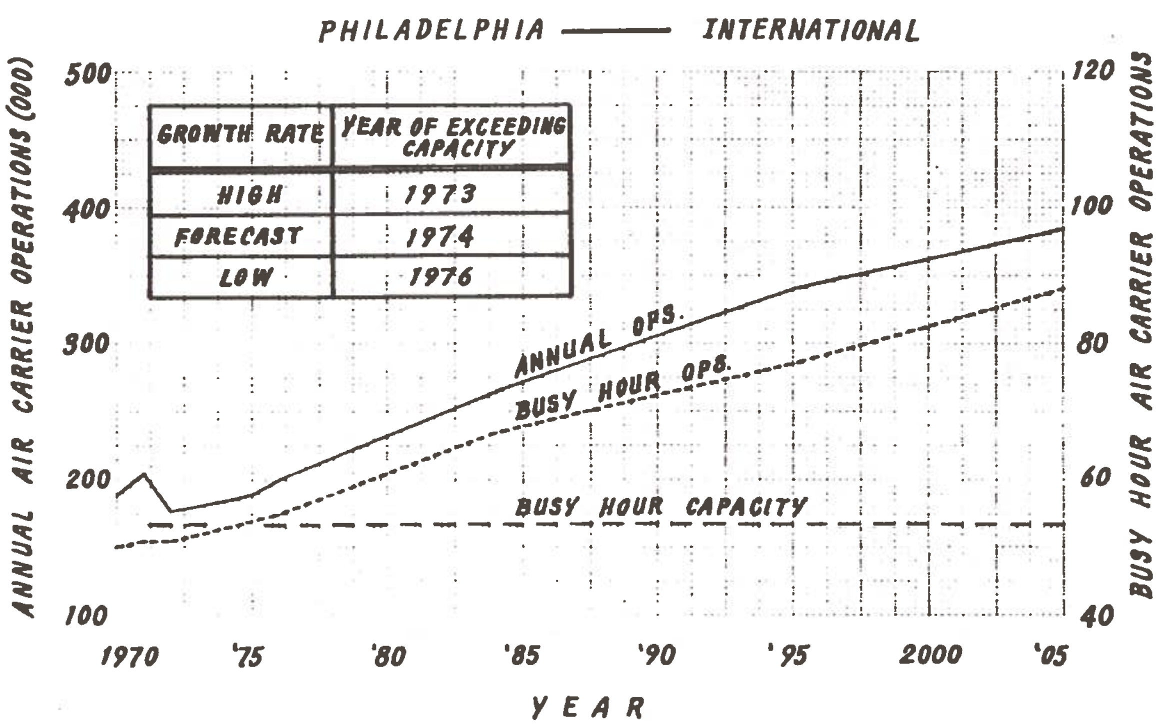

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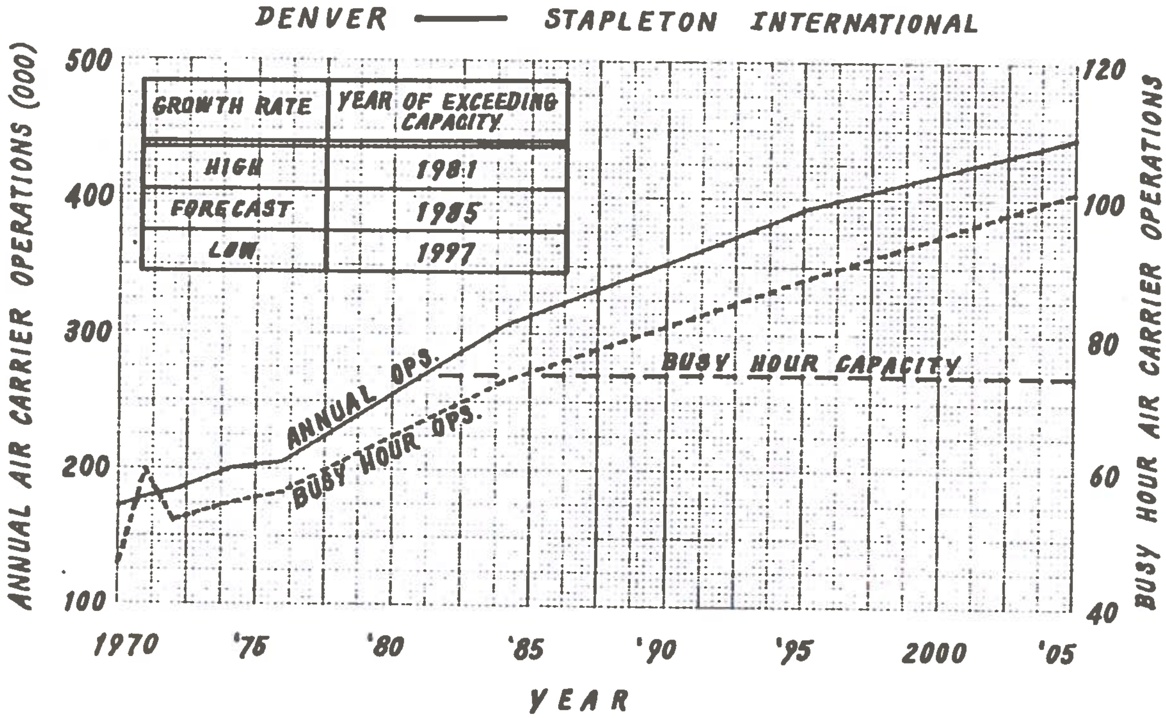

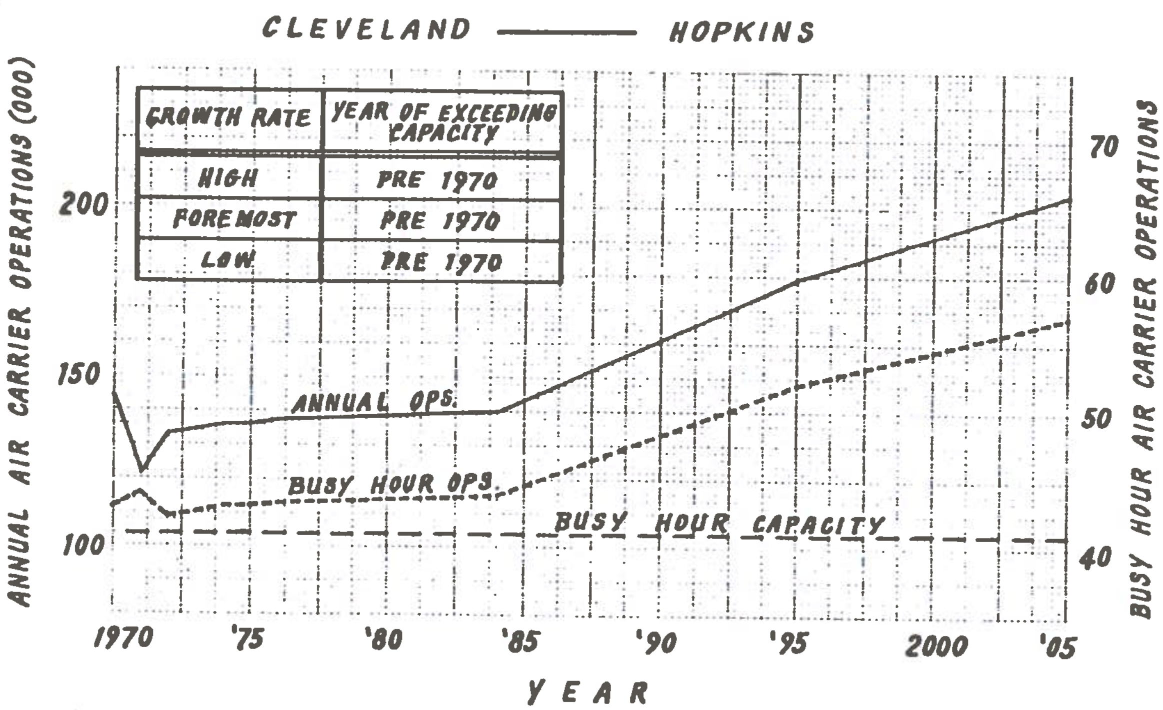

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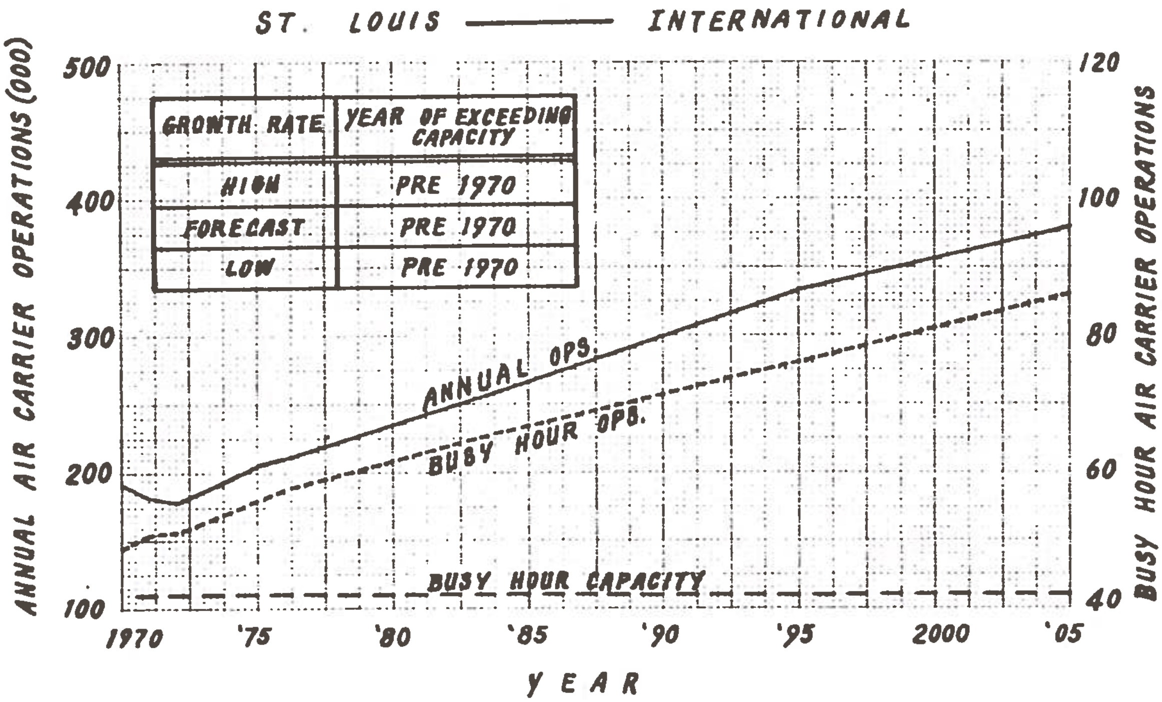

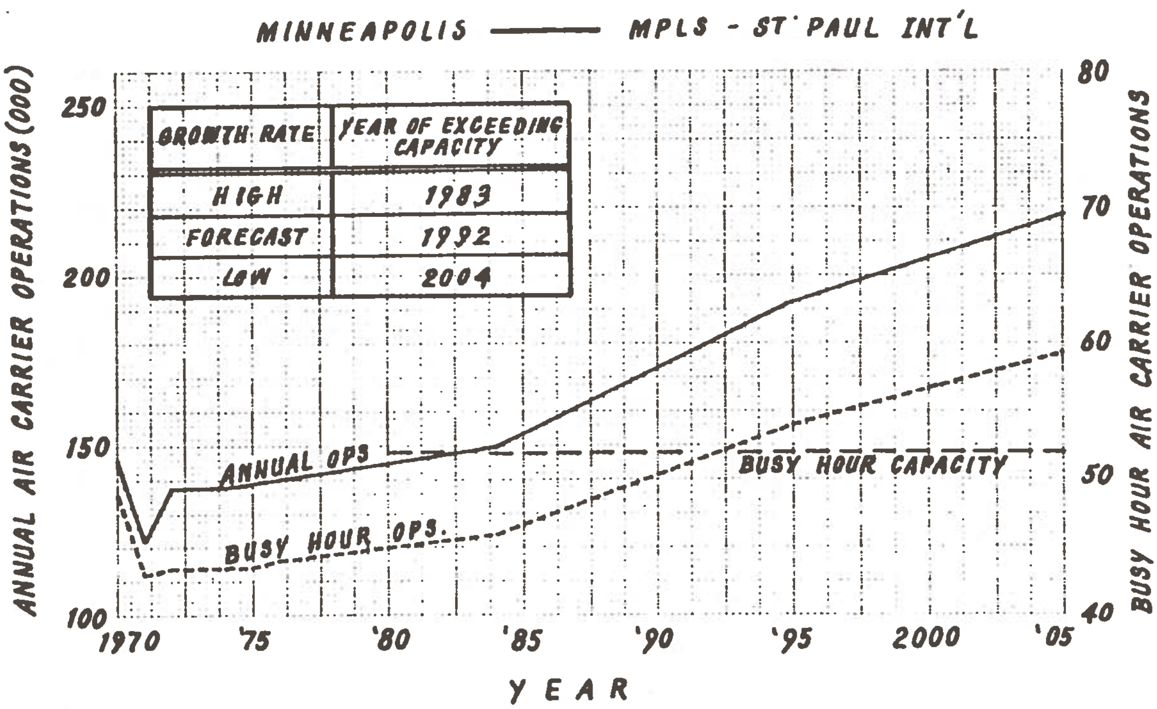

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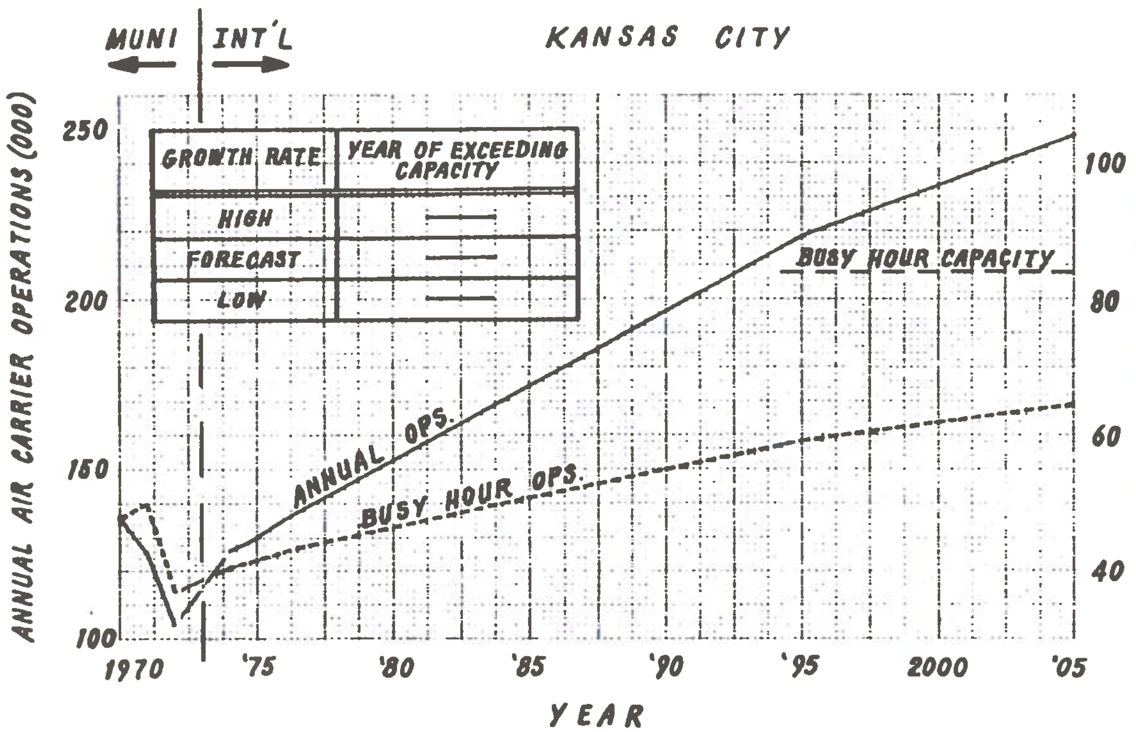


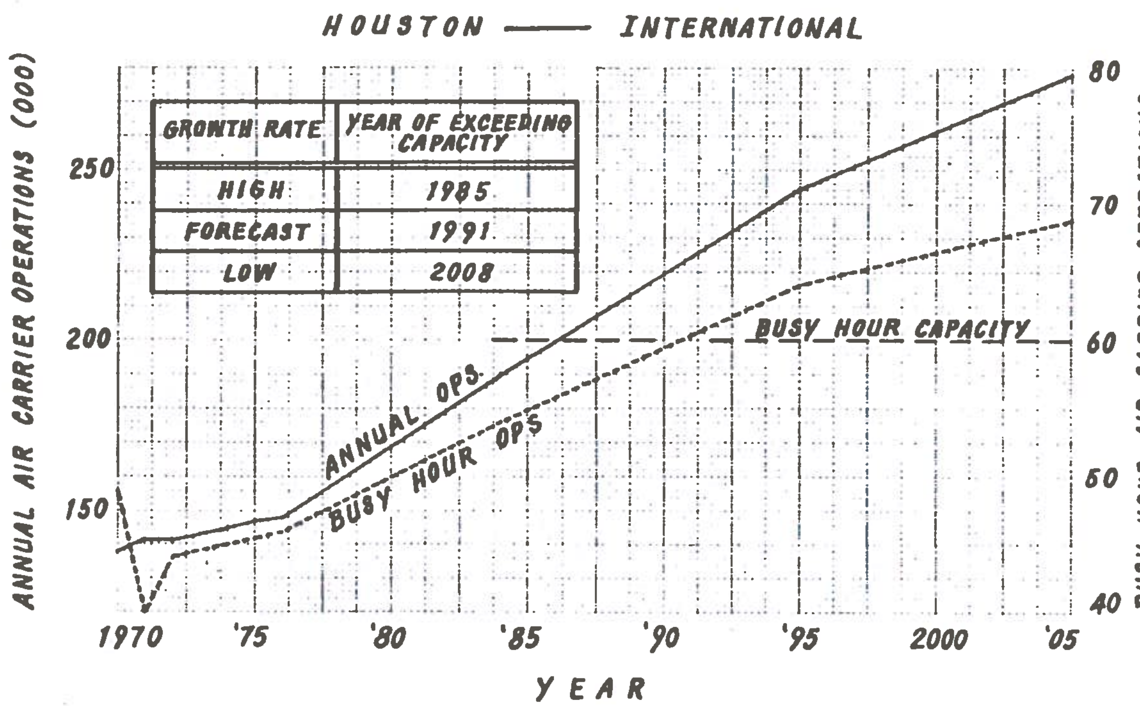
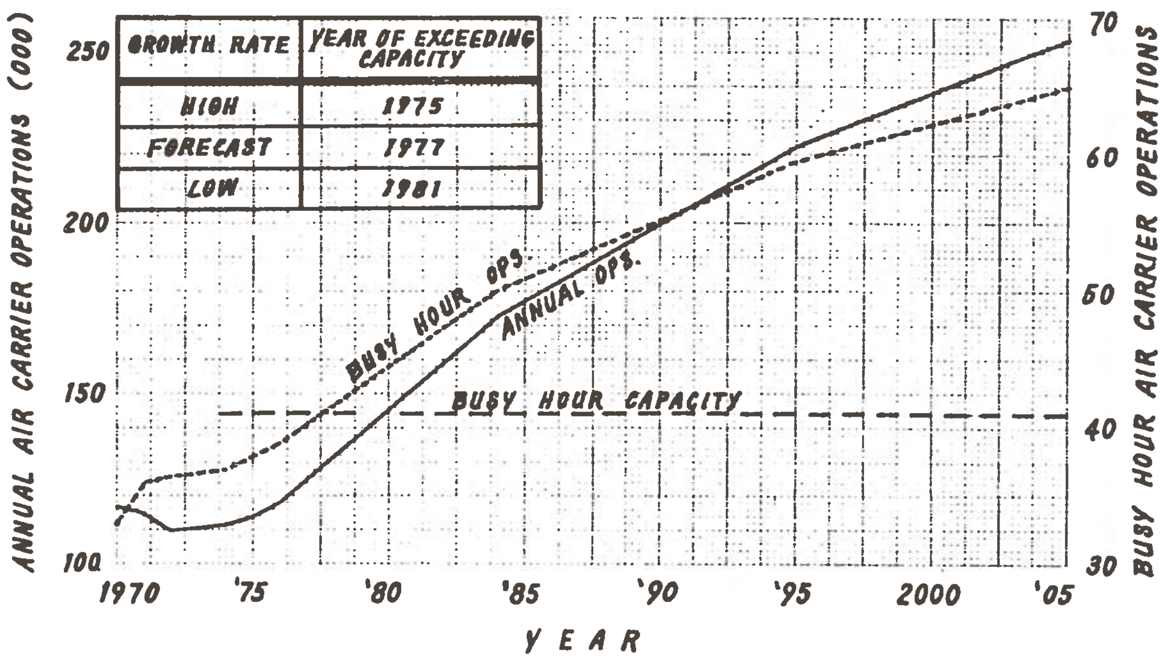


FIGURE 6-13.--CONTINUED (SHEET 13)

NEW ORLEANS — INTERNATIONAL



SEATTLE — SEATTLE/TACOMA

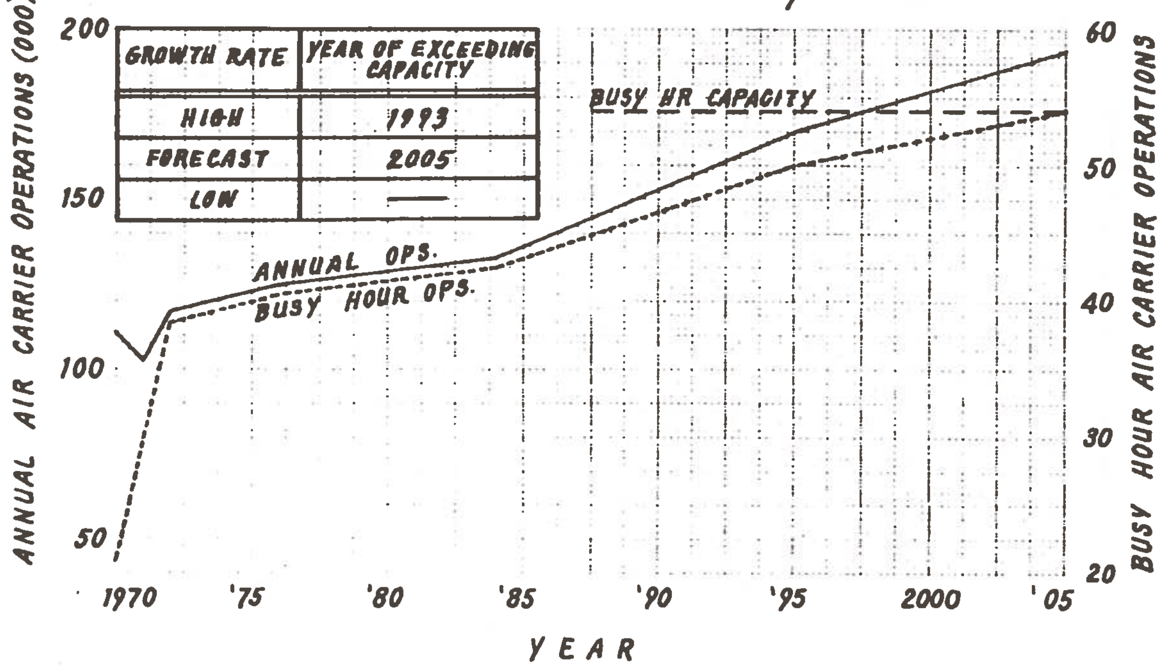
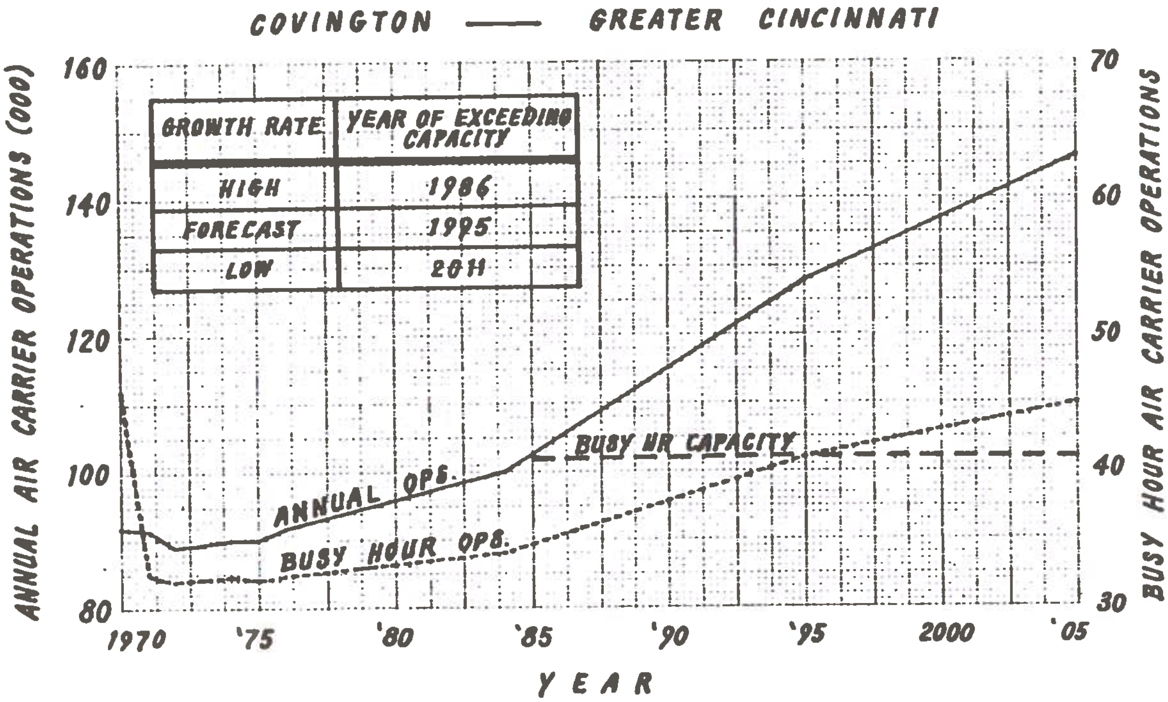


FIGURE 6-13.—CONTINUED (SHEET 14)



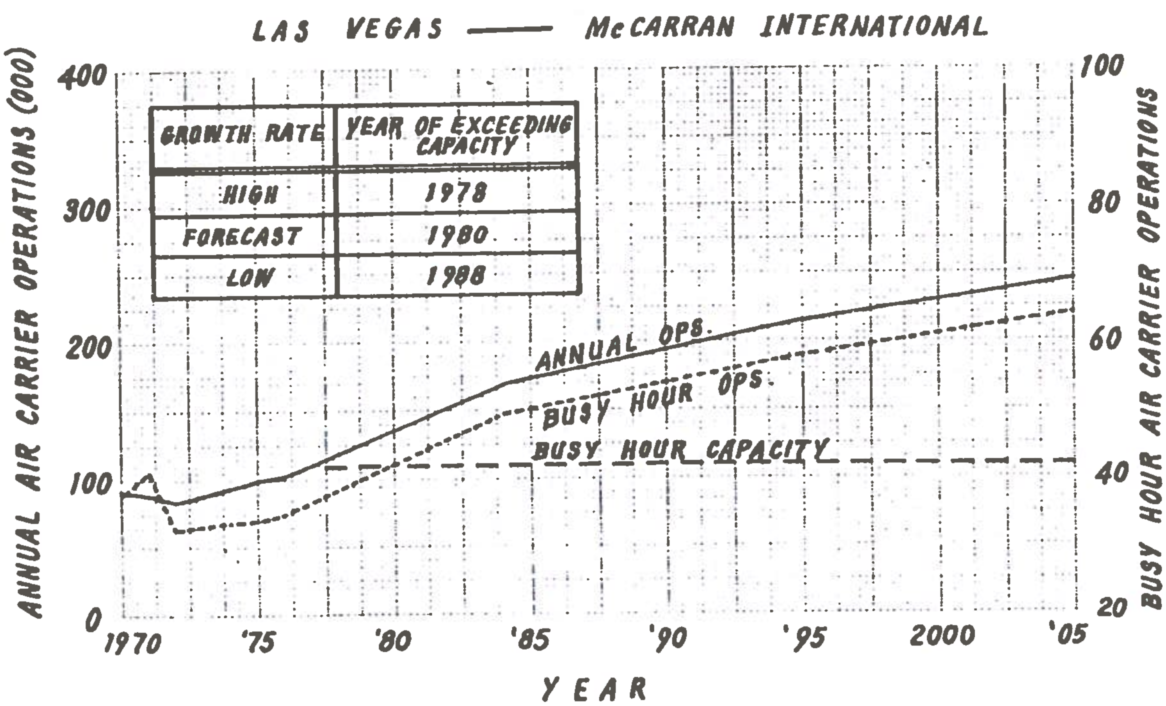
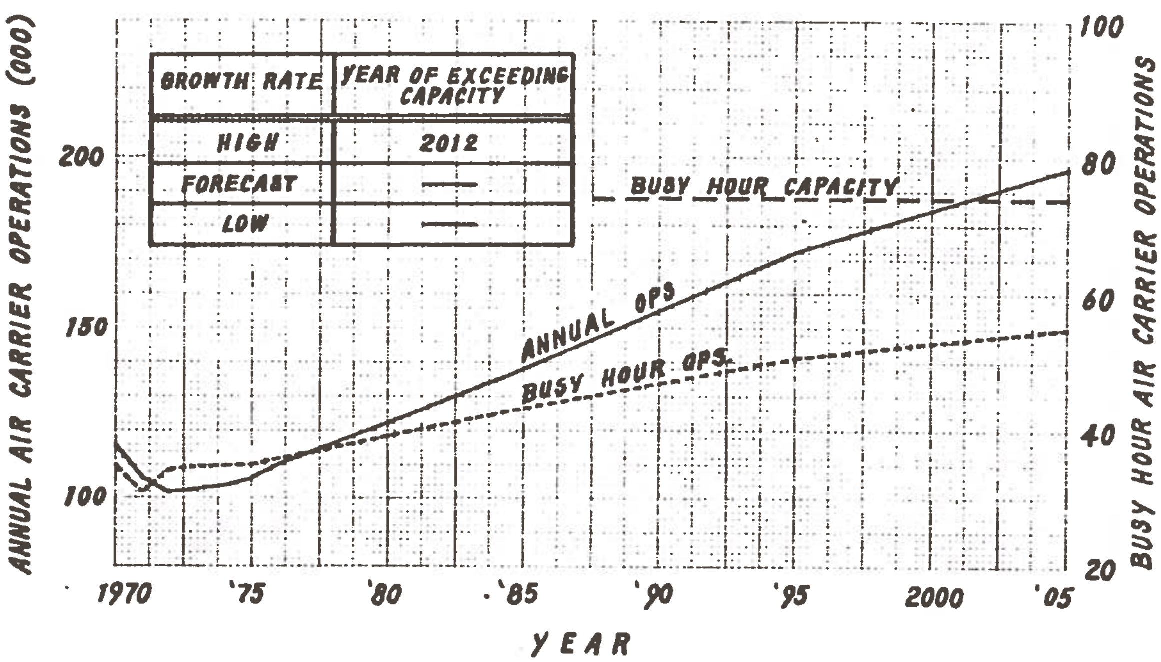
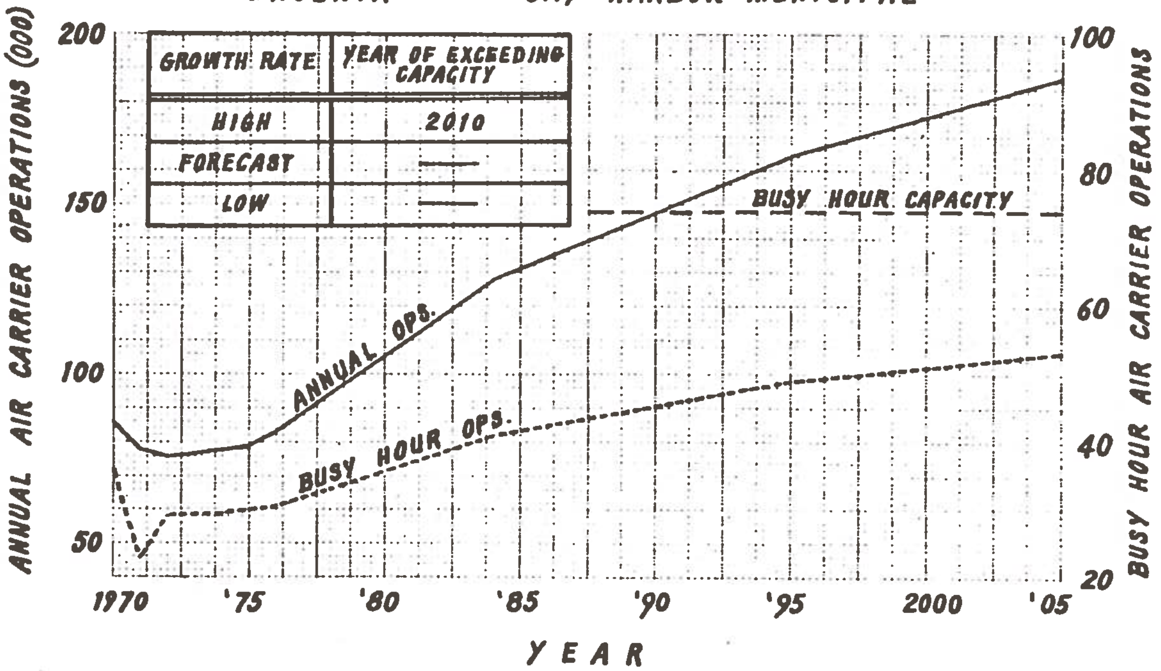


FIGURE 6-13.—CONTINUED (SHEET 15)

MEMPHIS — INTERNATIONAL



PHOENIX — SKY HARBOR MUNICIPAL



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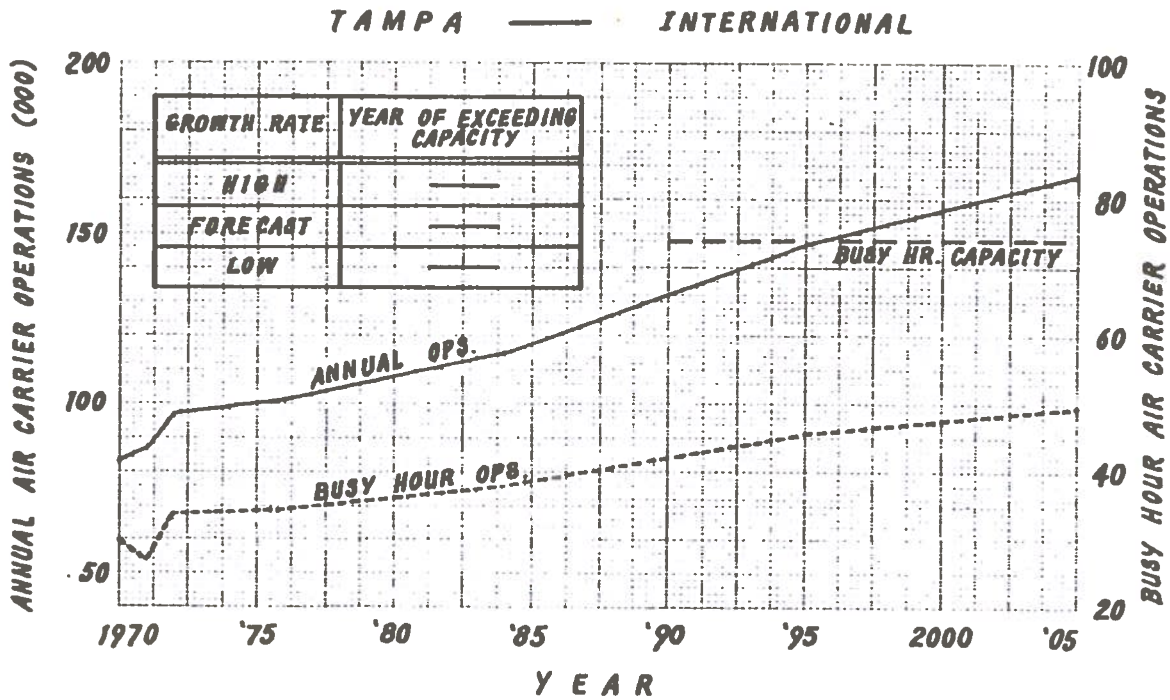


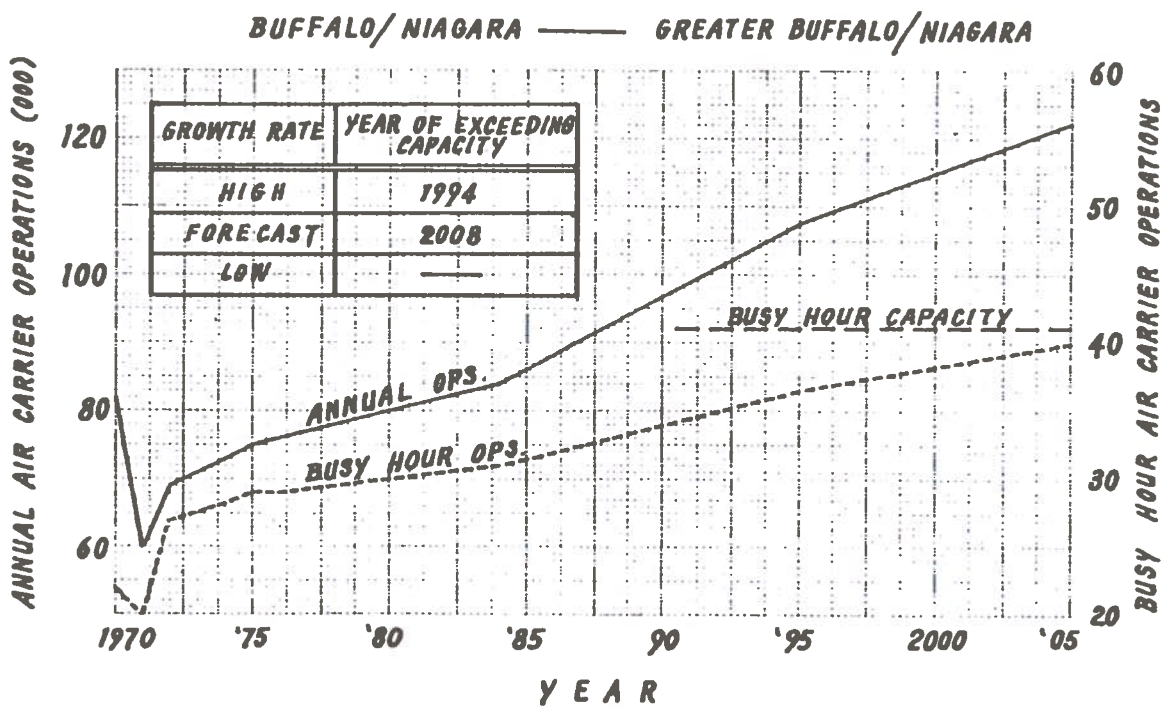
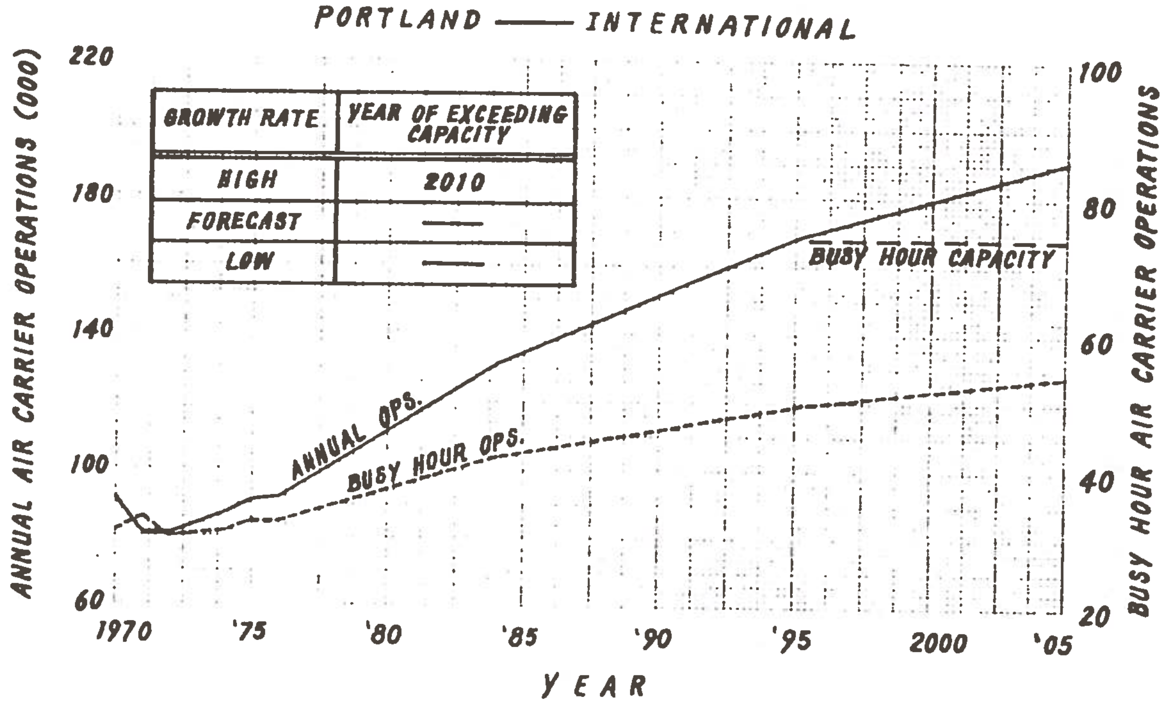


FIGURE 6-13.—CONTINUED (SHEET 17)



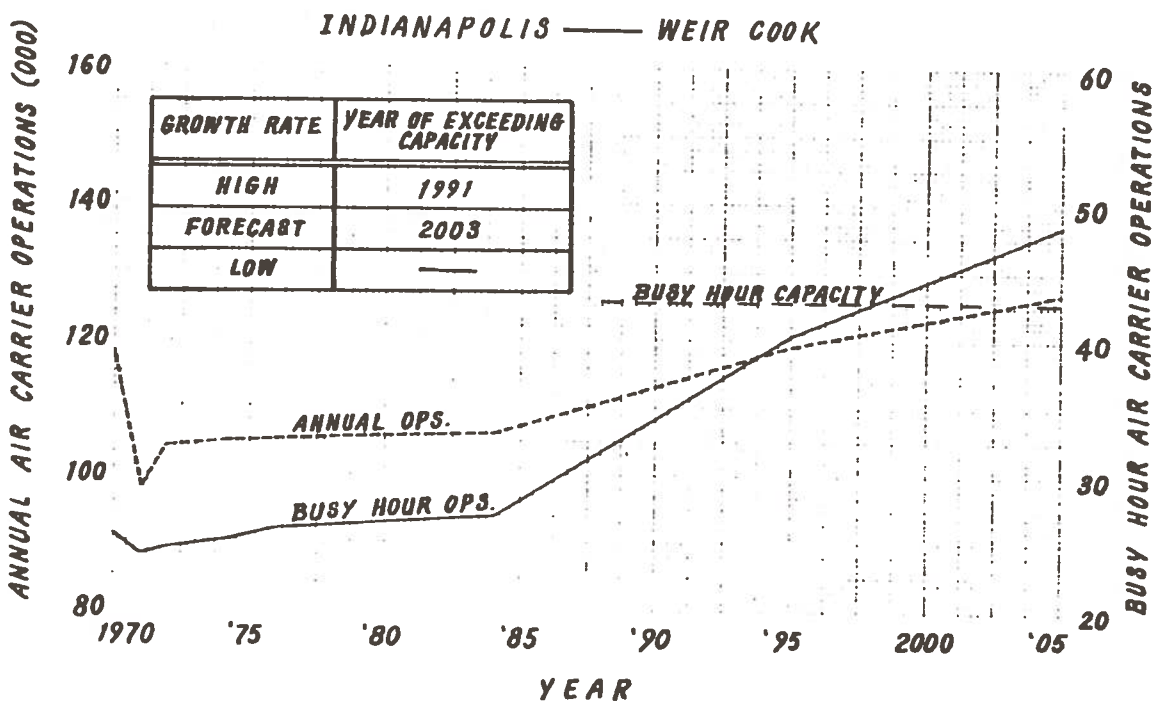
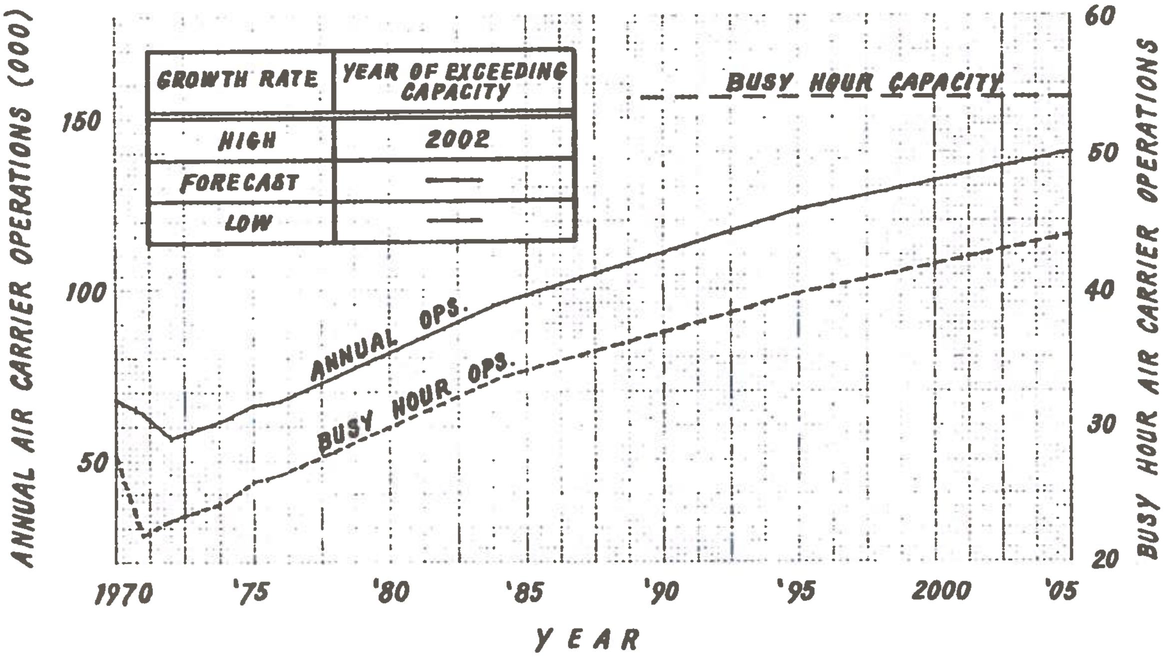


FIGURE 6-13.—CONTINUED (SHEET 18)

SALT LAKE CITY — INTERNATIONAL



LOUISVILLE — STANDIFORD FIELD

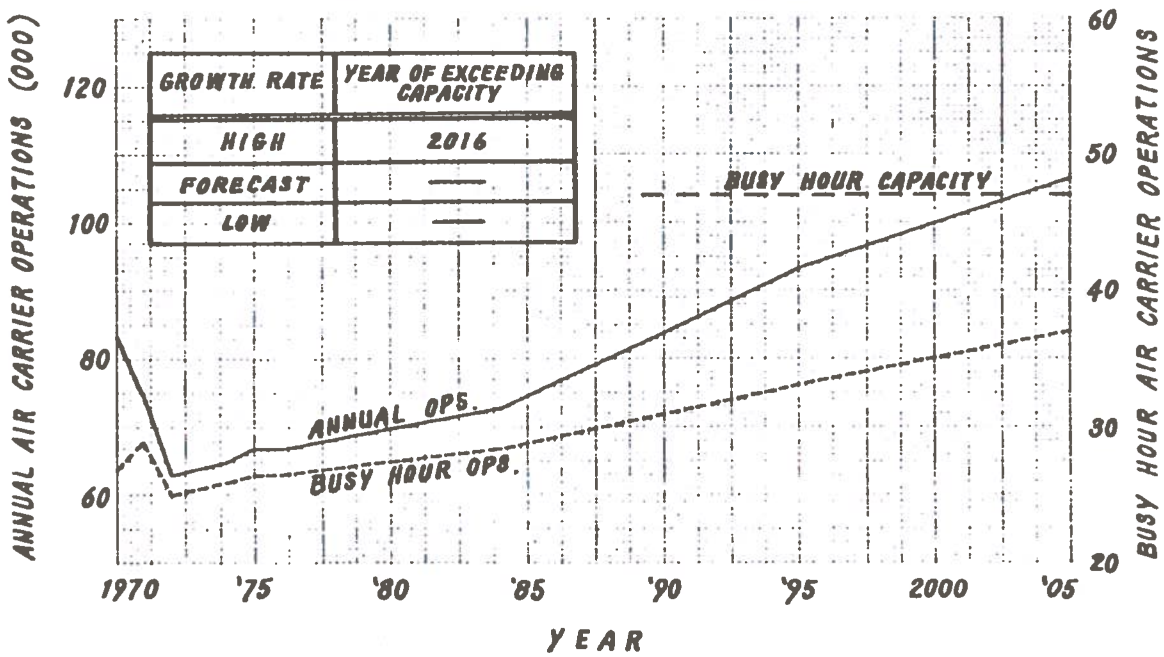
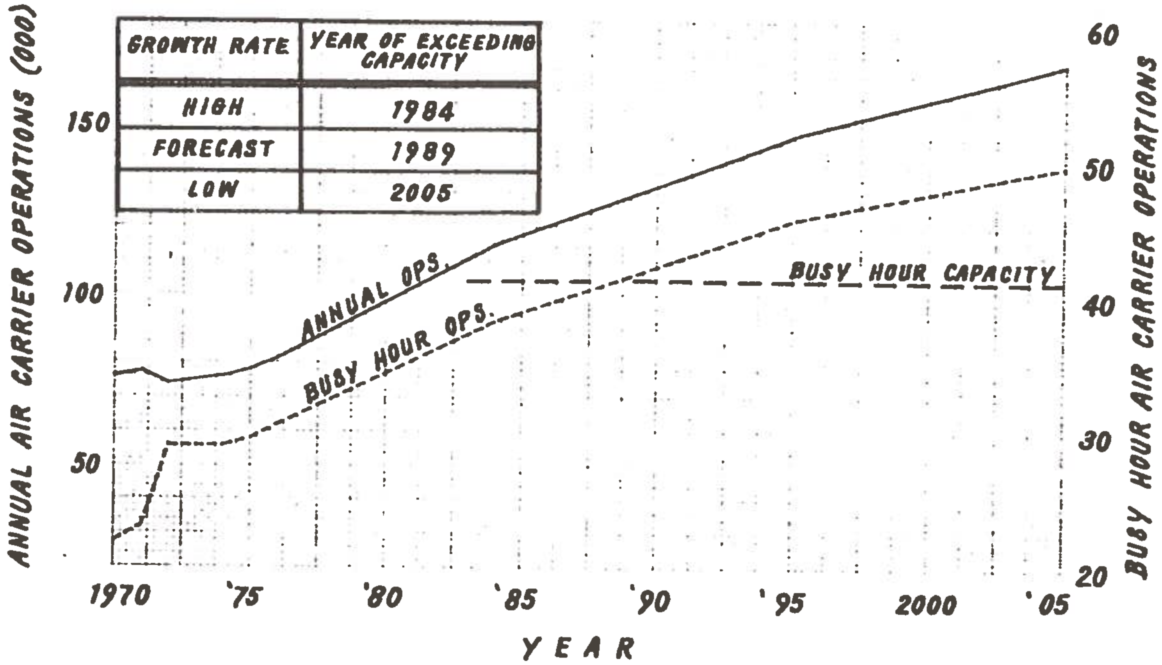


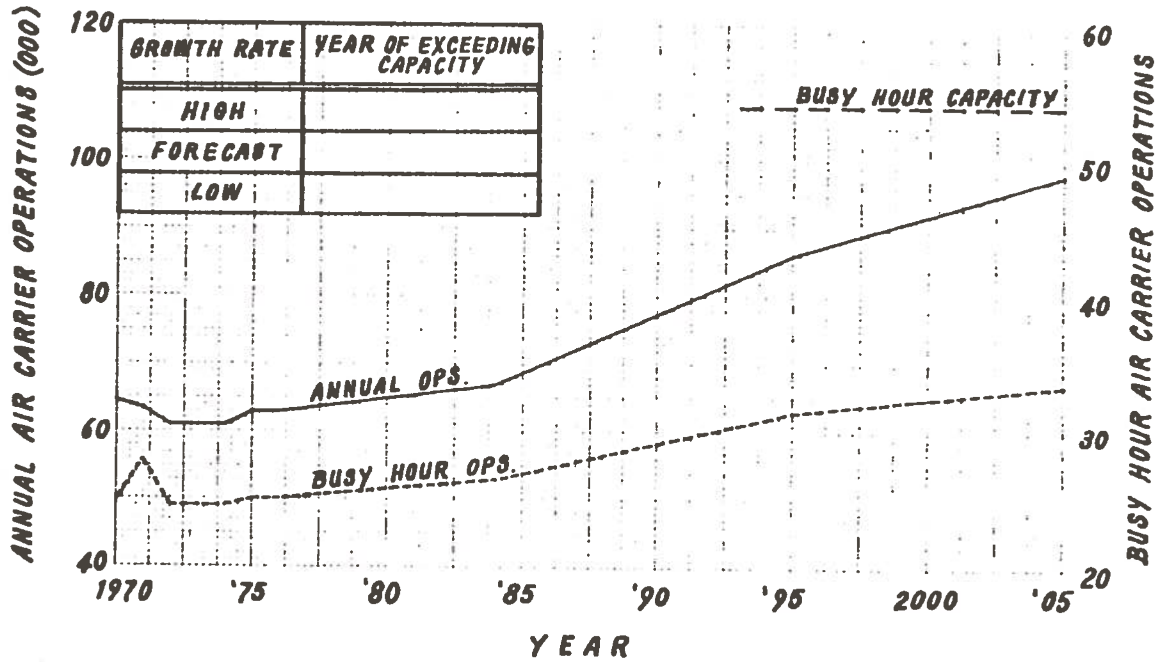
FIGURE 6-13.—CONTINUED **(SHEET 19)**

SAN DIEGO —— INTERNATIONAL



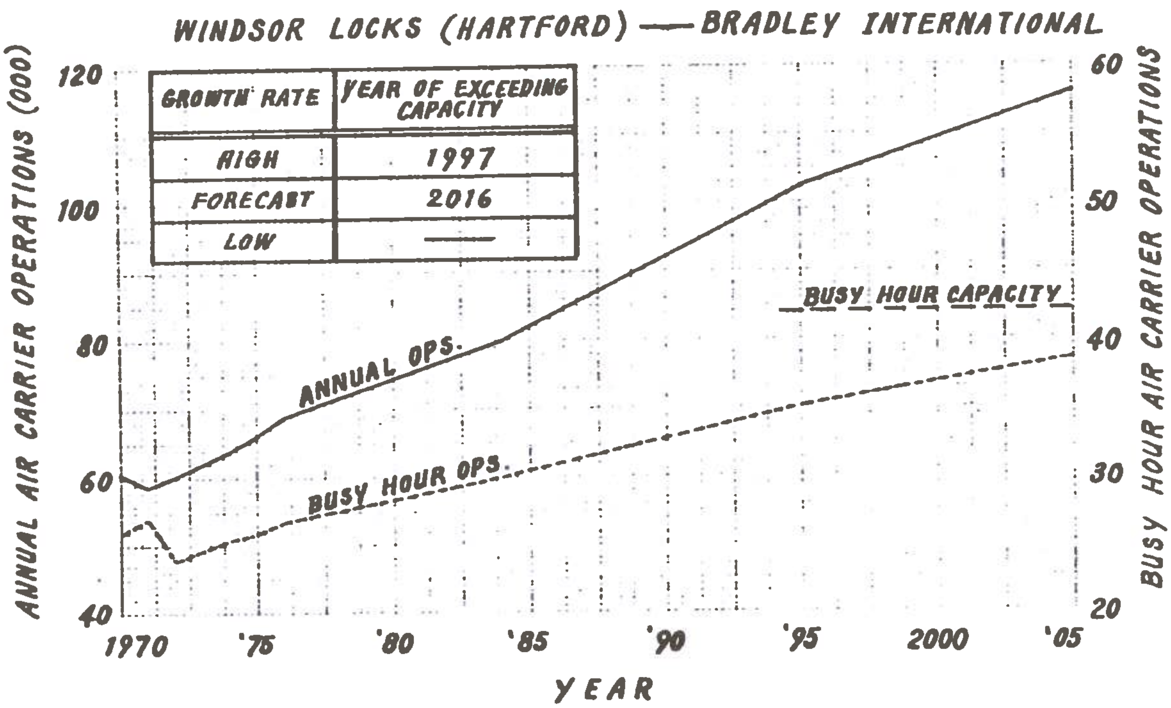
GROWTH RATE	YEAR OF EXCEEDING CAPACITY
HIGH	1984
FORECAST	1989
LOW	2005

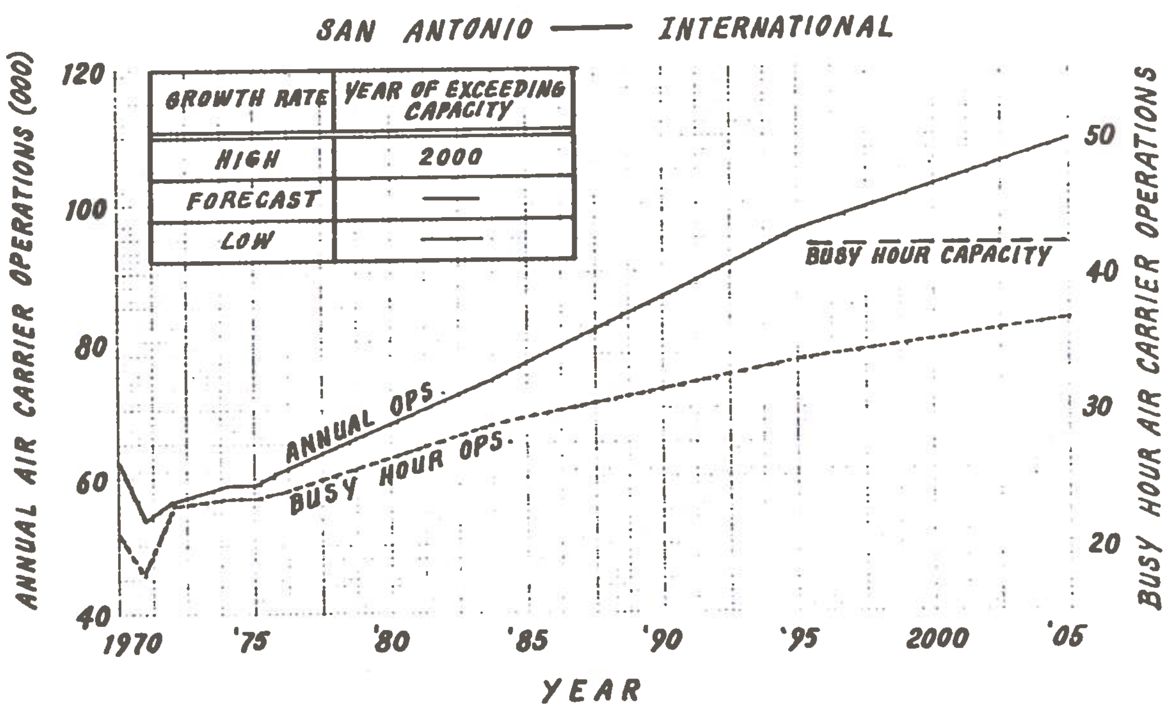
COLUMBUS —— PORT COLUMBUS



GROWTH RATE	YEAR OF EXCEEDING CAPACITY
HIGH	
FORECAST	
LOW	

FIGURE 6-13.—CONTINUED (SHEET 20)





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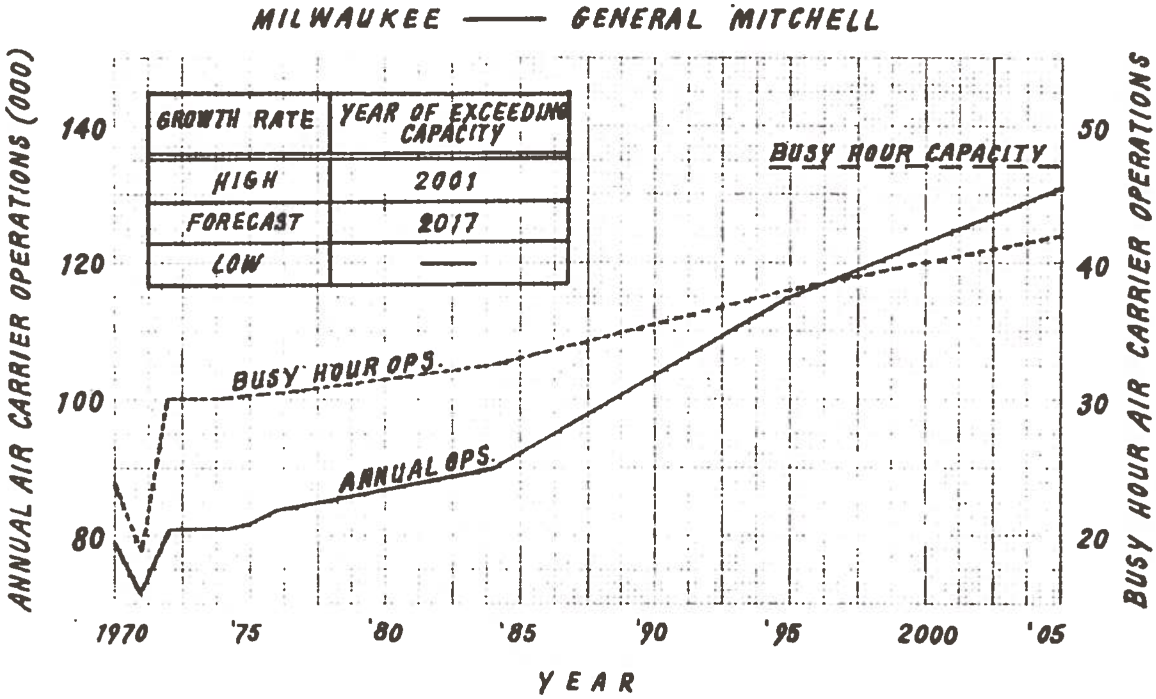


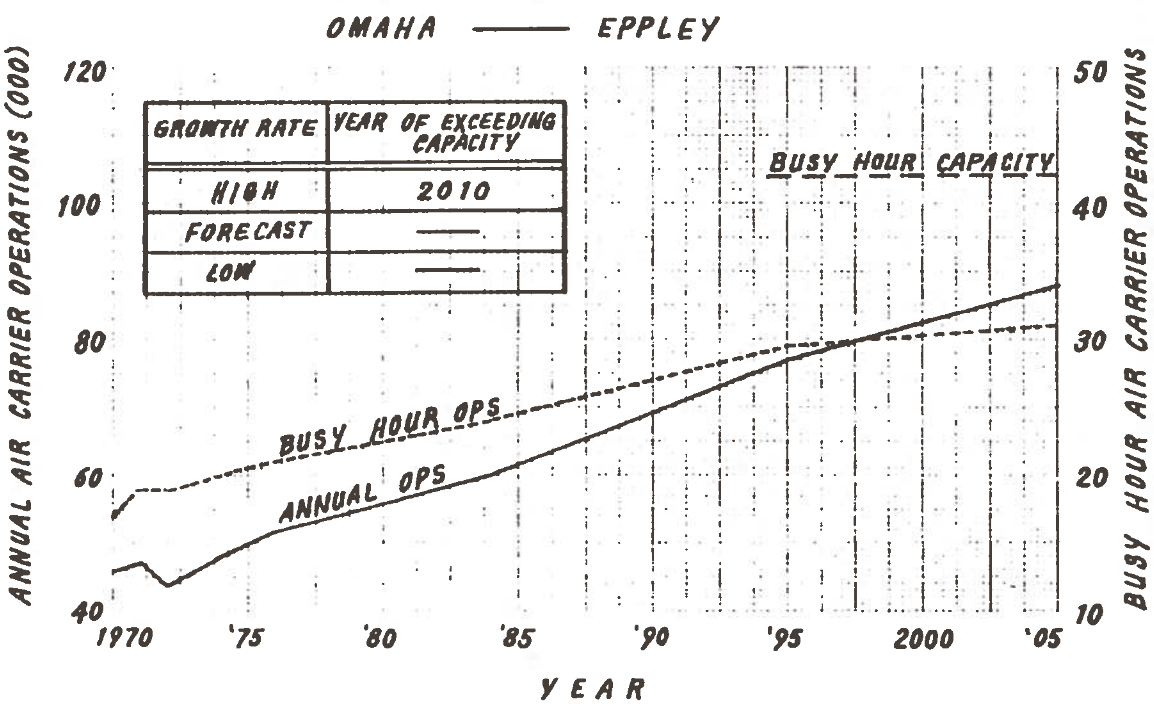
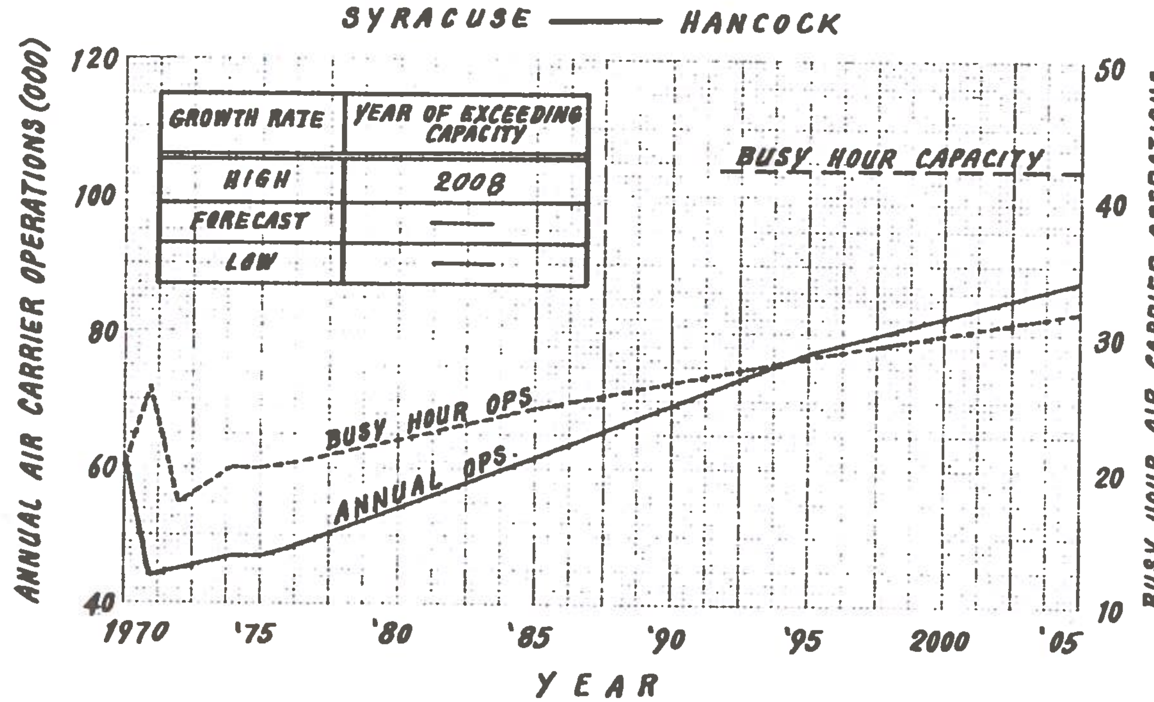


FIGURE 6-13.—CONTINUED (SHEET 22)



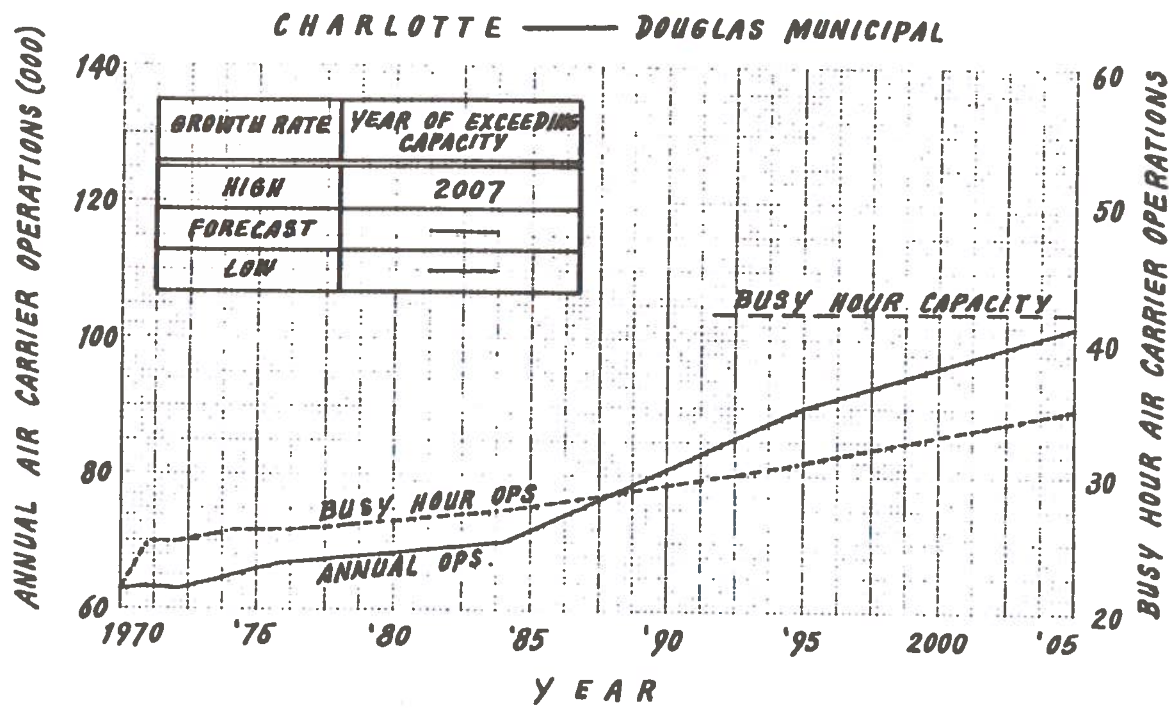
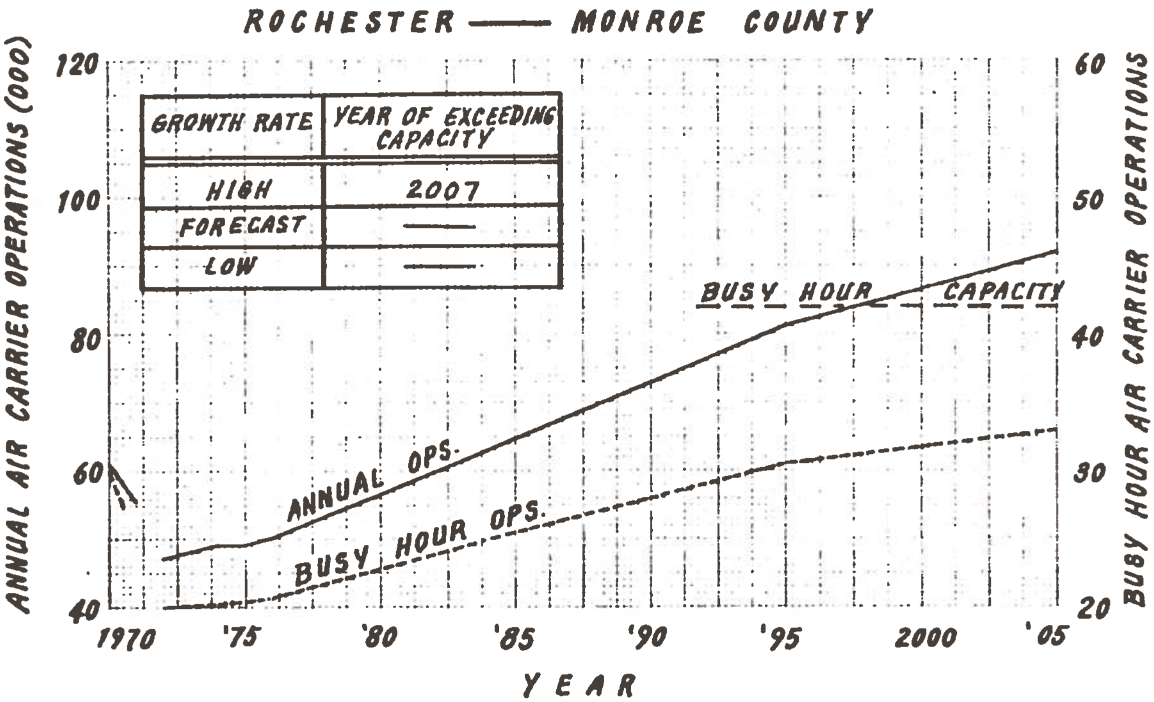


FIGURE 6-13.—CONTINUED (SHEET 23)



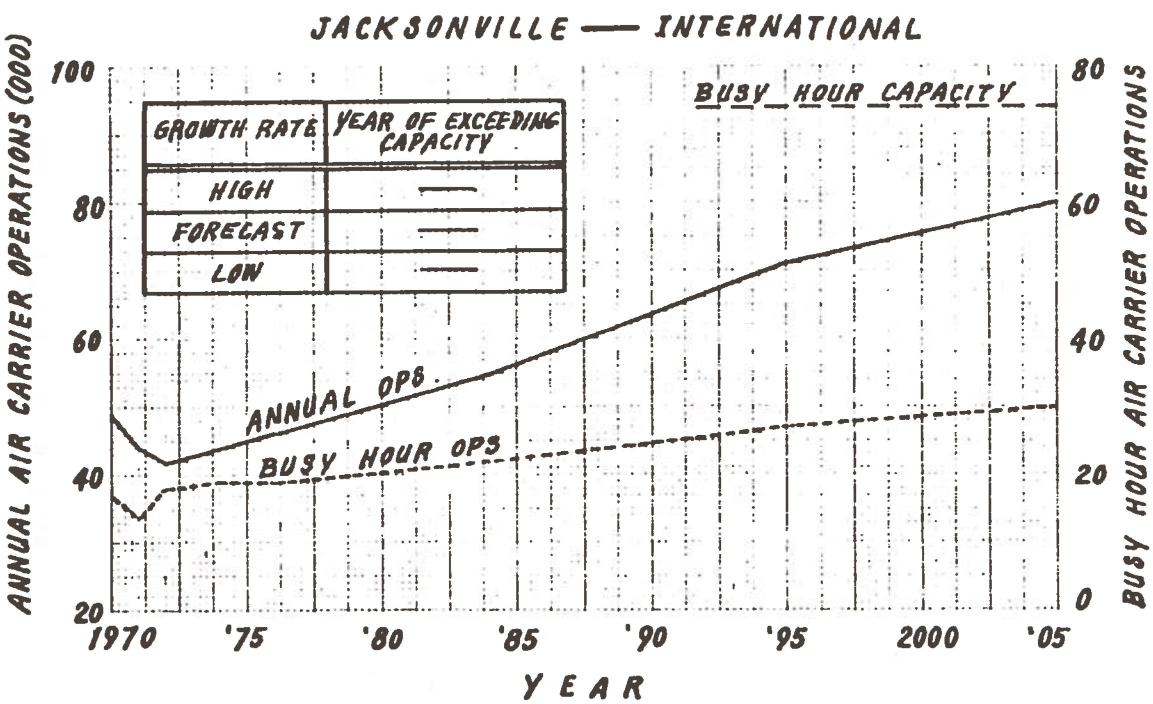
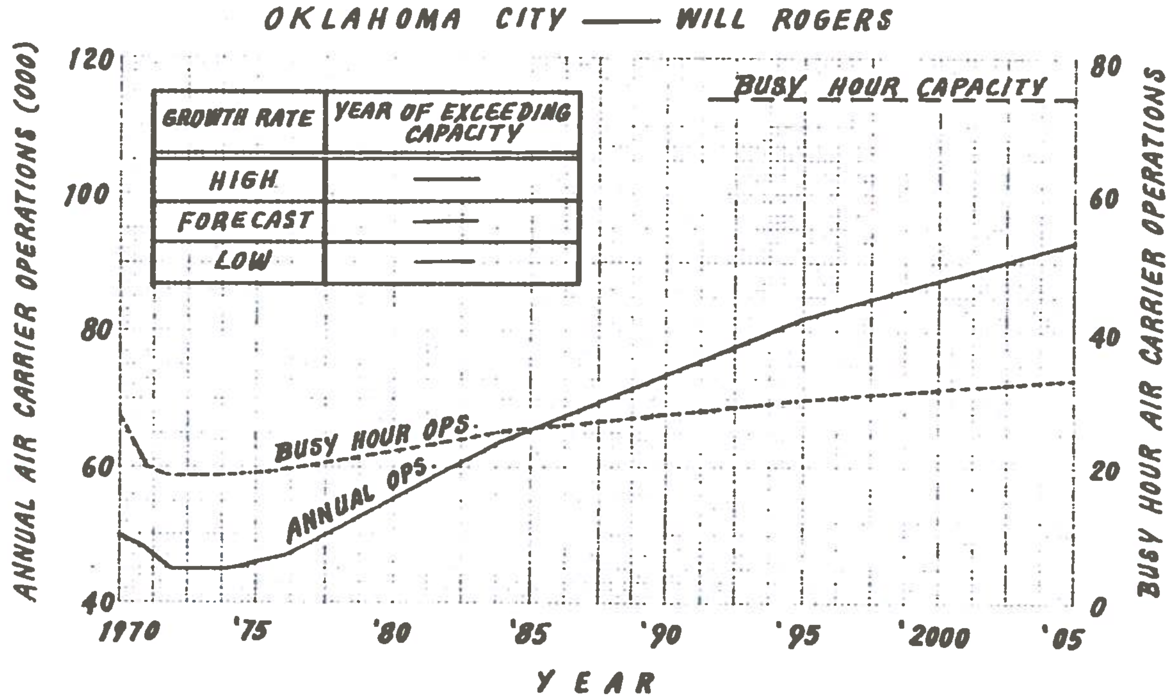


FIGURE 6-13.—CONTINUED (SHEET 24)



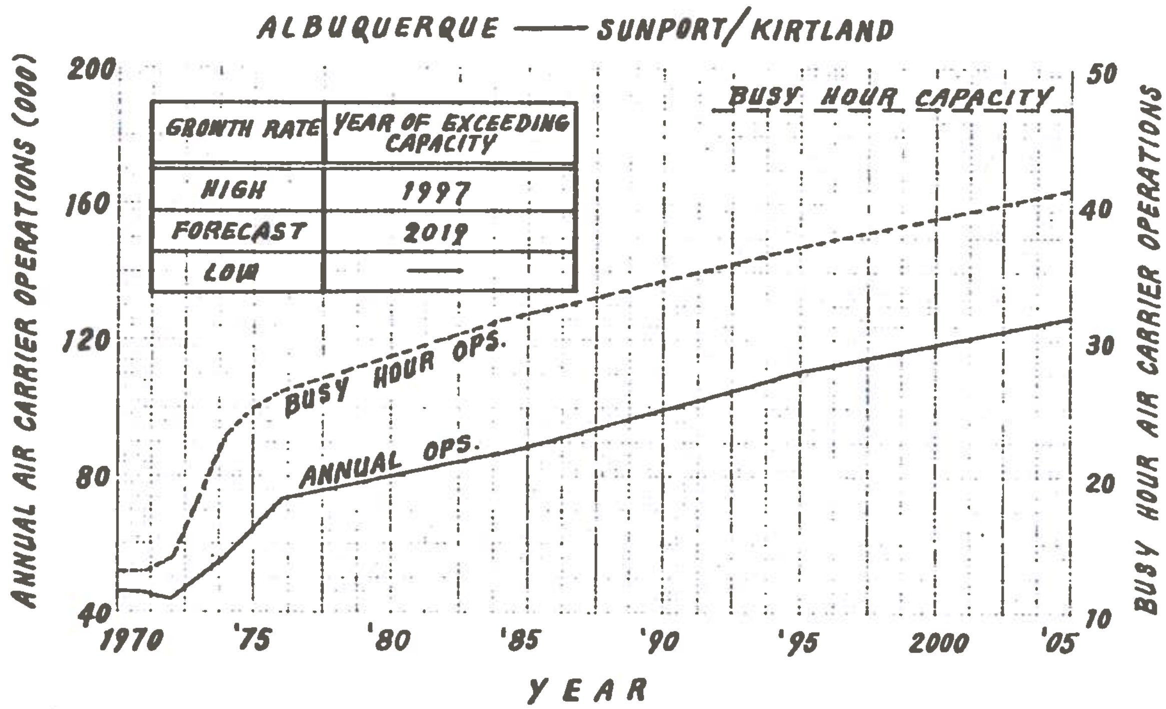
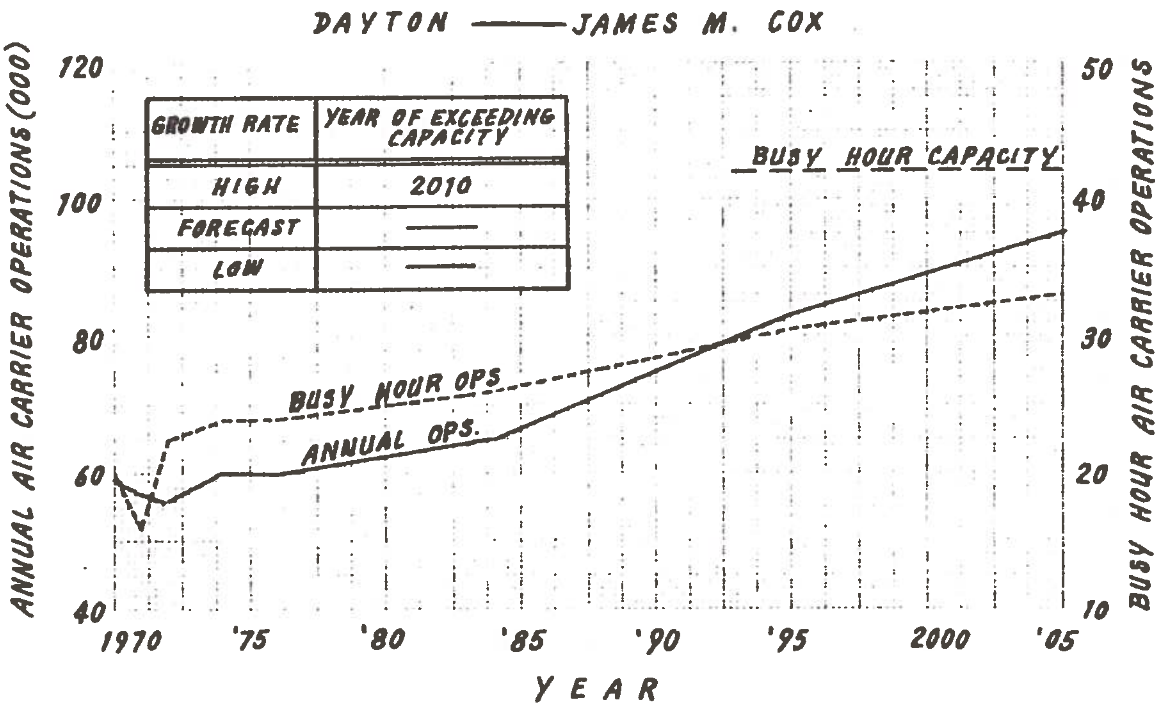


FIGURE 6-13.—CONTINUED (SHEET 25)



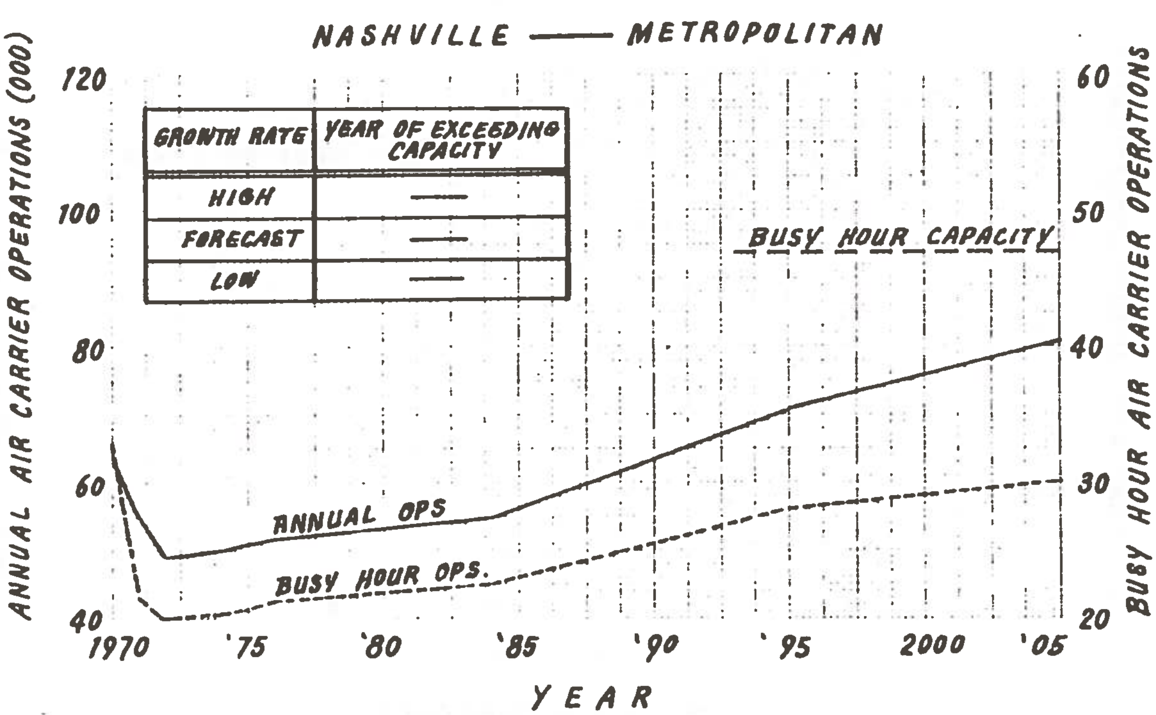
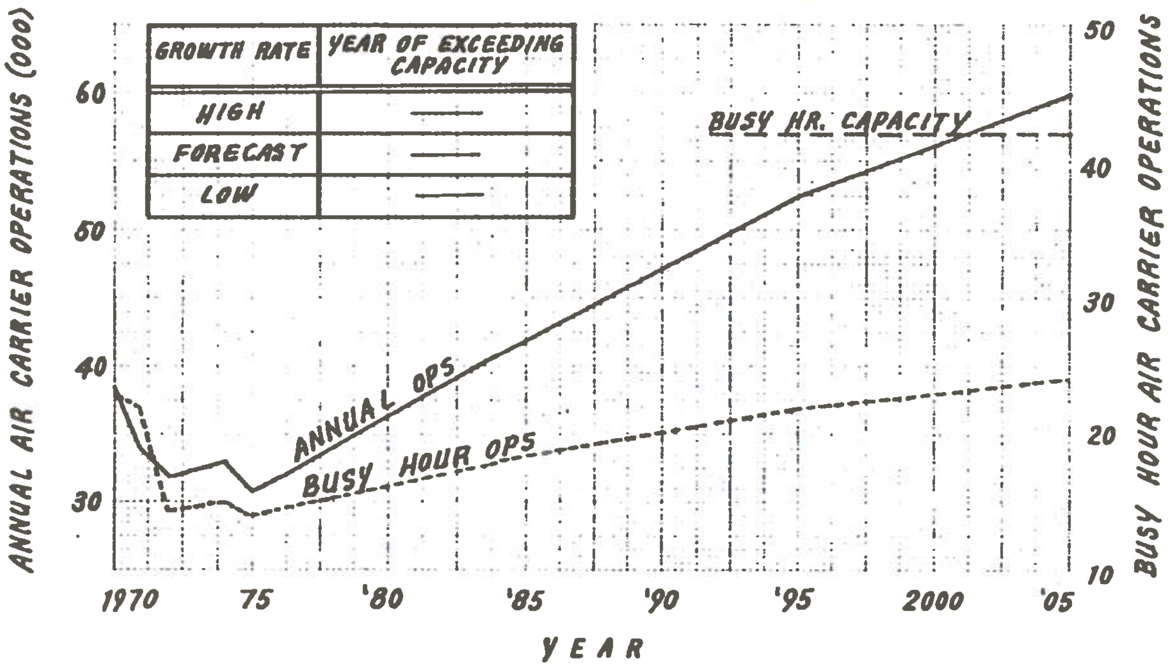


FIGURE 6-13.—CONTINUED (SHEET 26)

EL PASO —— INTERNATIONAL



NORFOLK —— NORFOLK REGIONAL

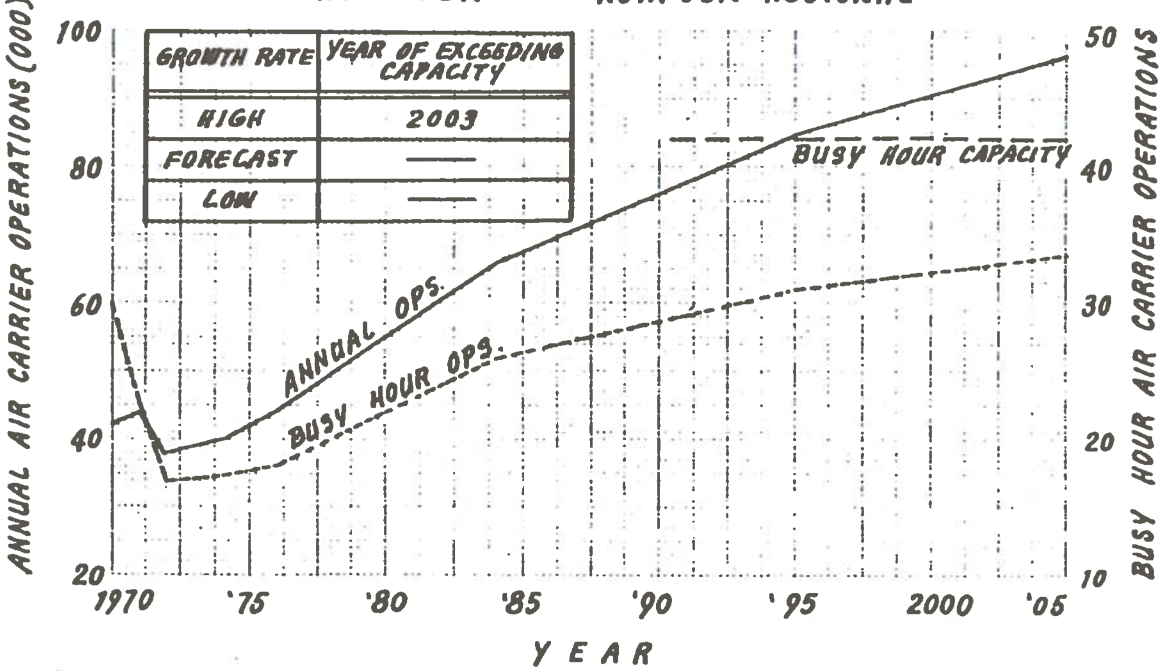
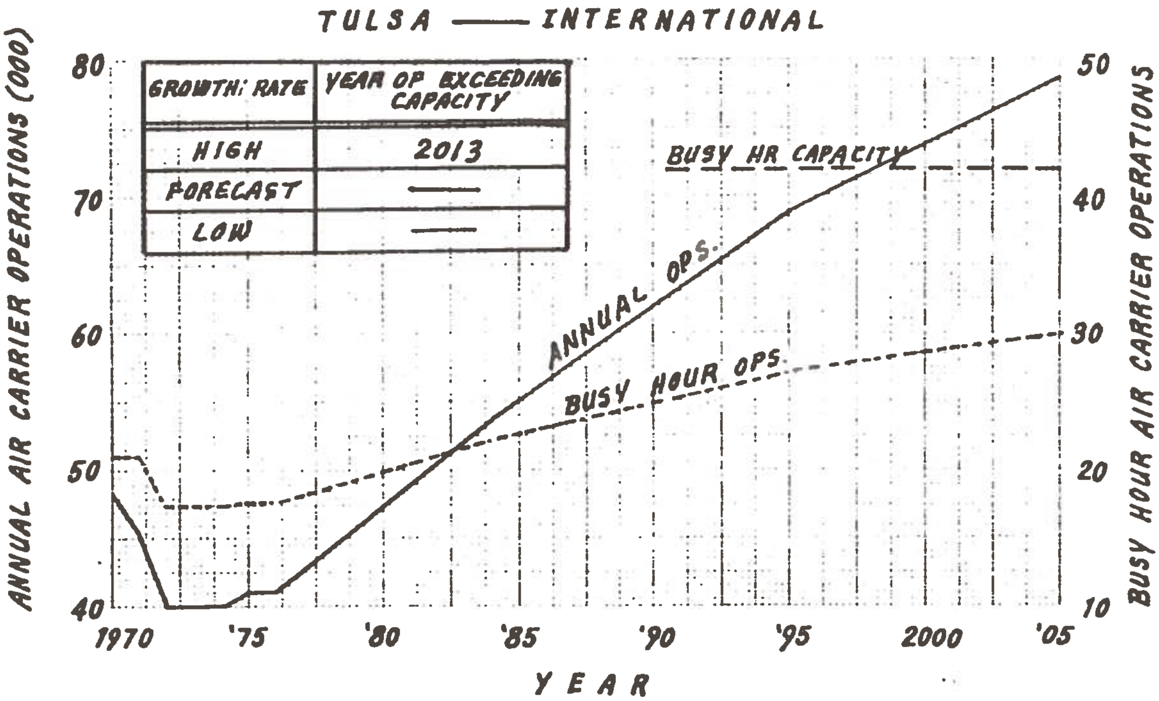


FIGURE 6-13.—CONTINUED (SHEET 27)



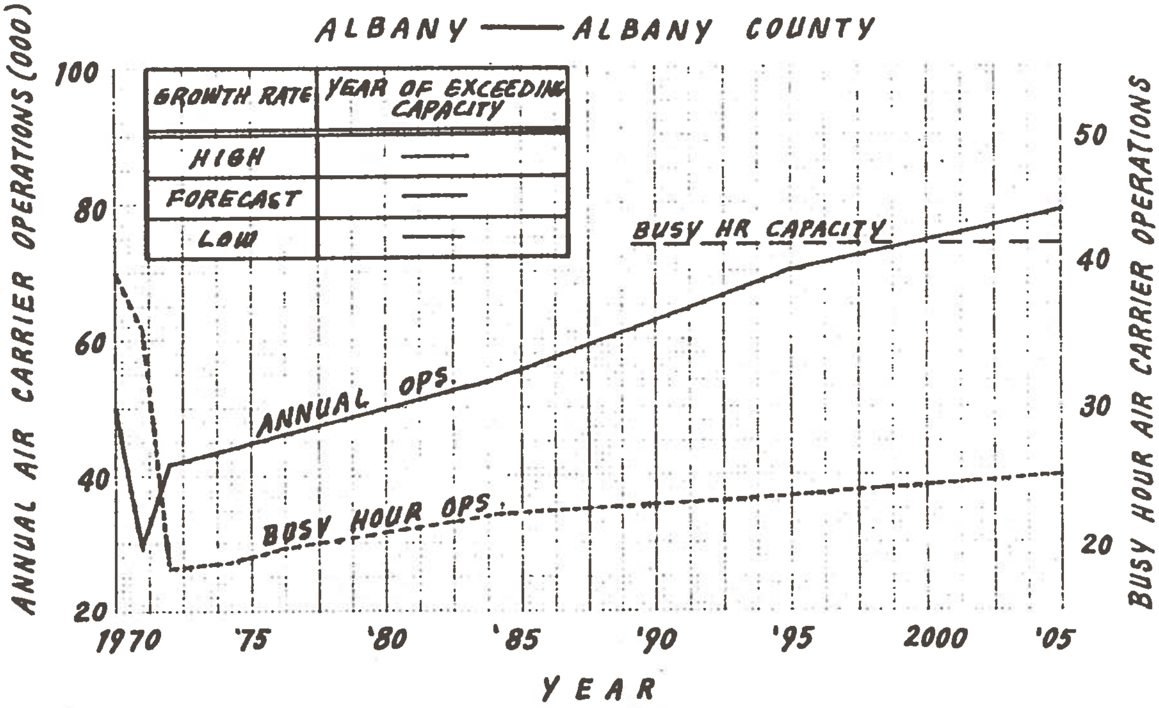
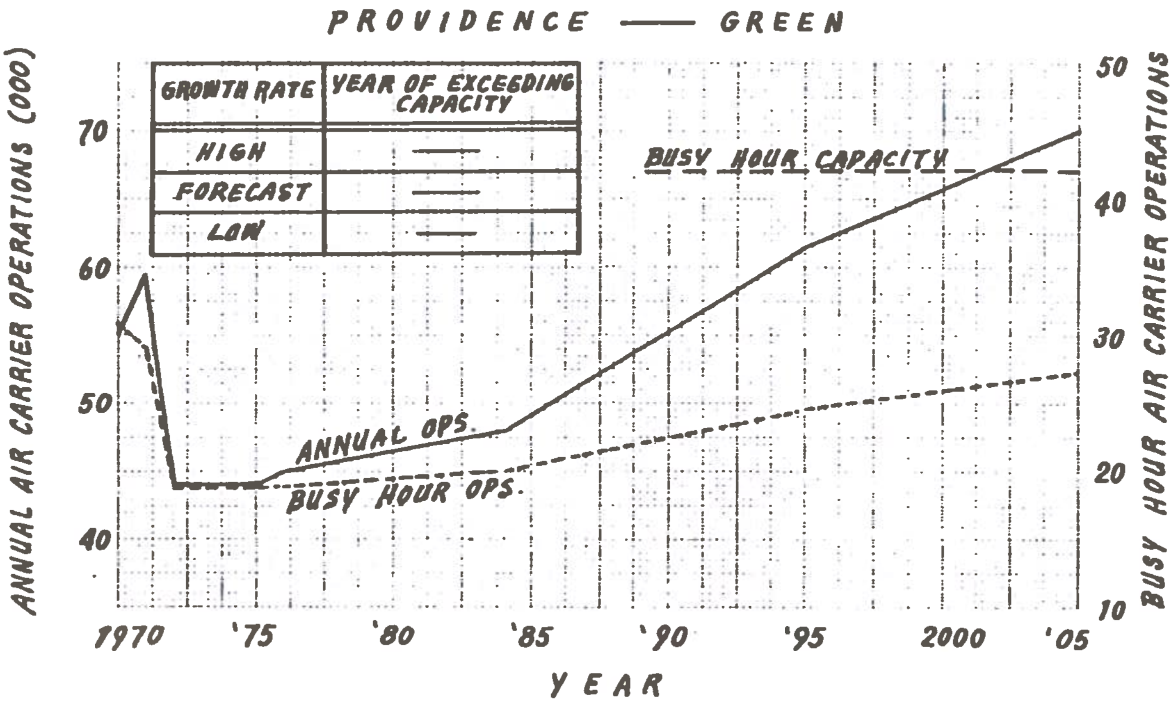


FIGURE 6-13.—CONTINUED **(SHEET 28)**



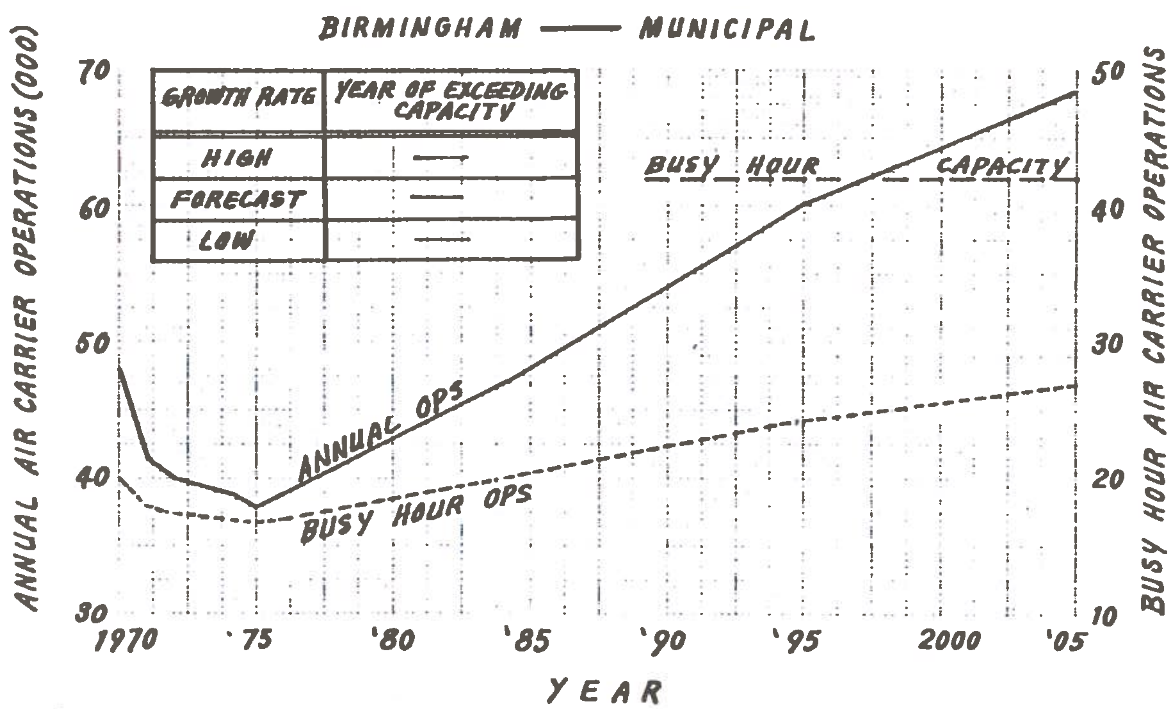
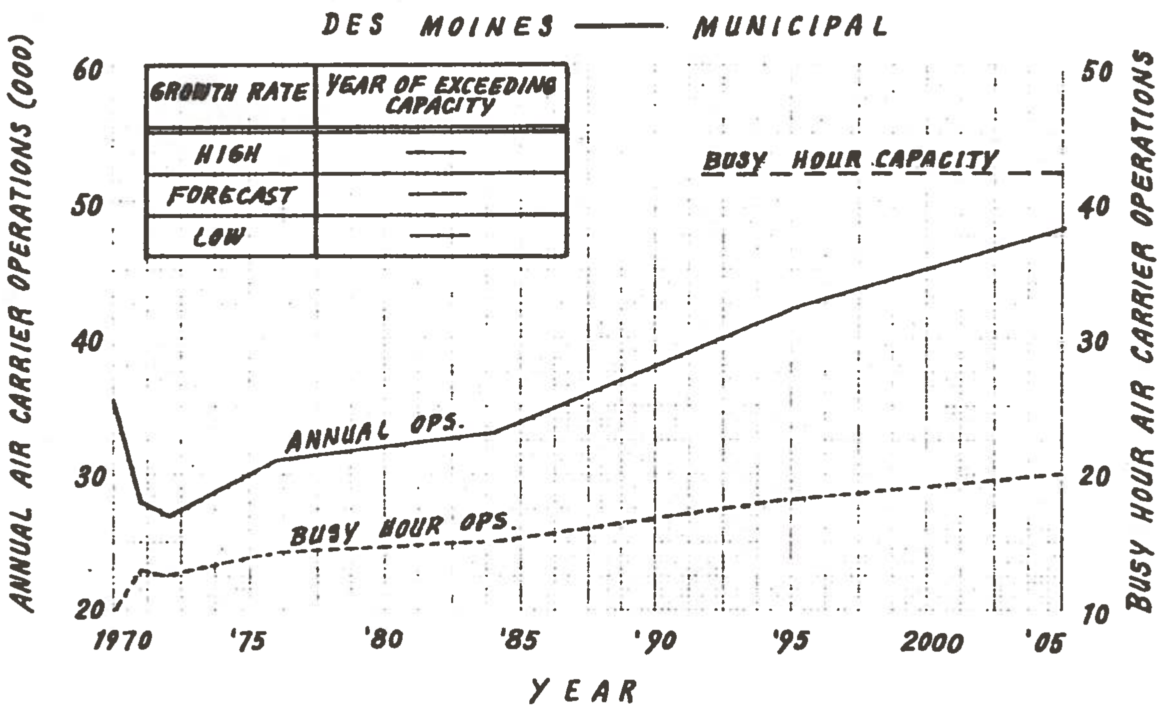


FIGURE 6-13.—CONTINUED (SHEET 29)



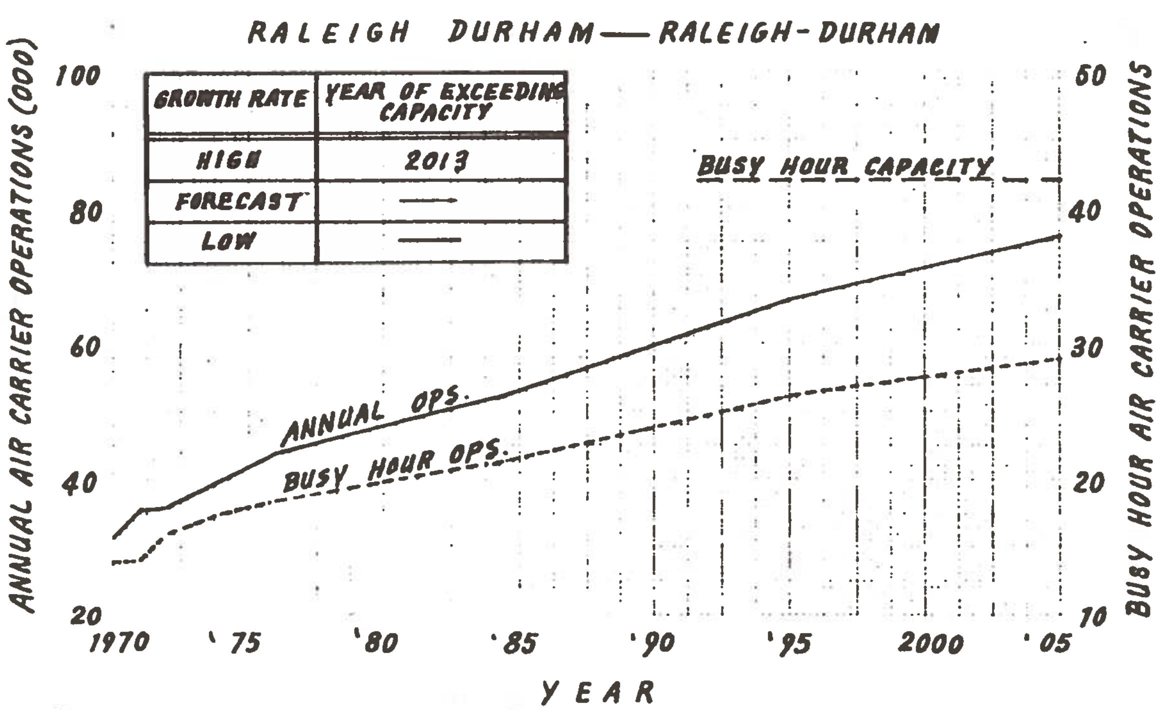
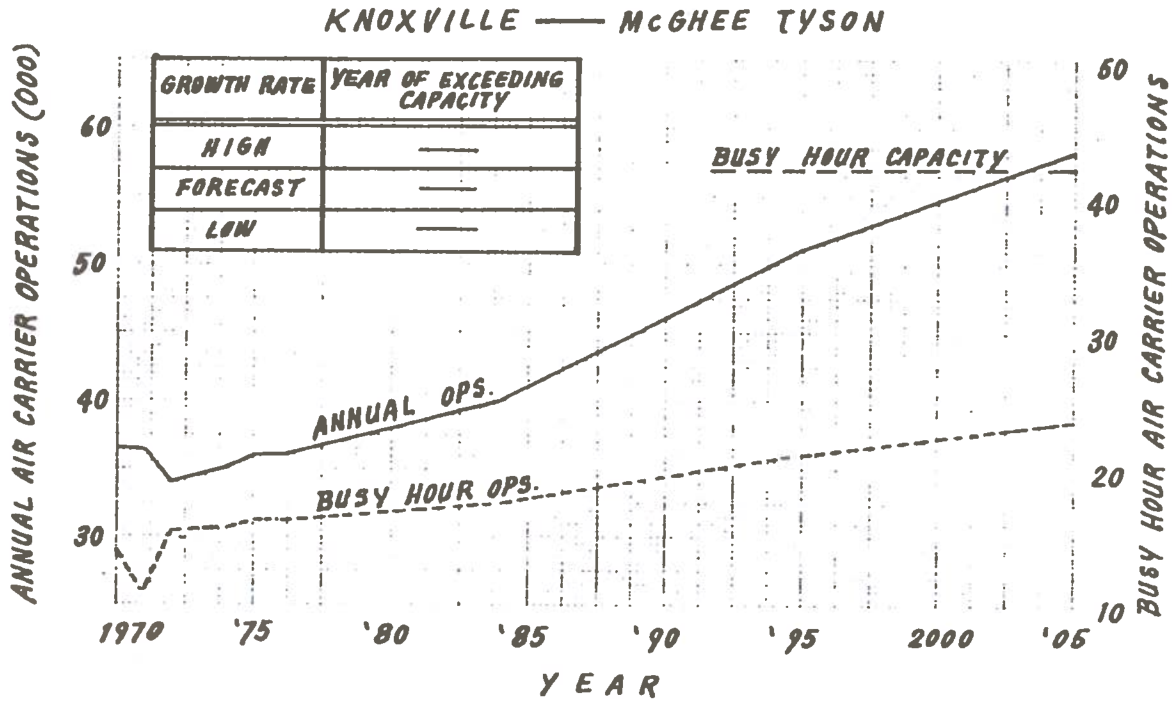


FIGURE 6-13.—CONTINUED **(SHEET 30)**



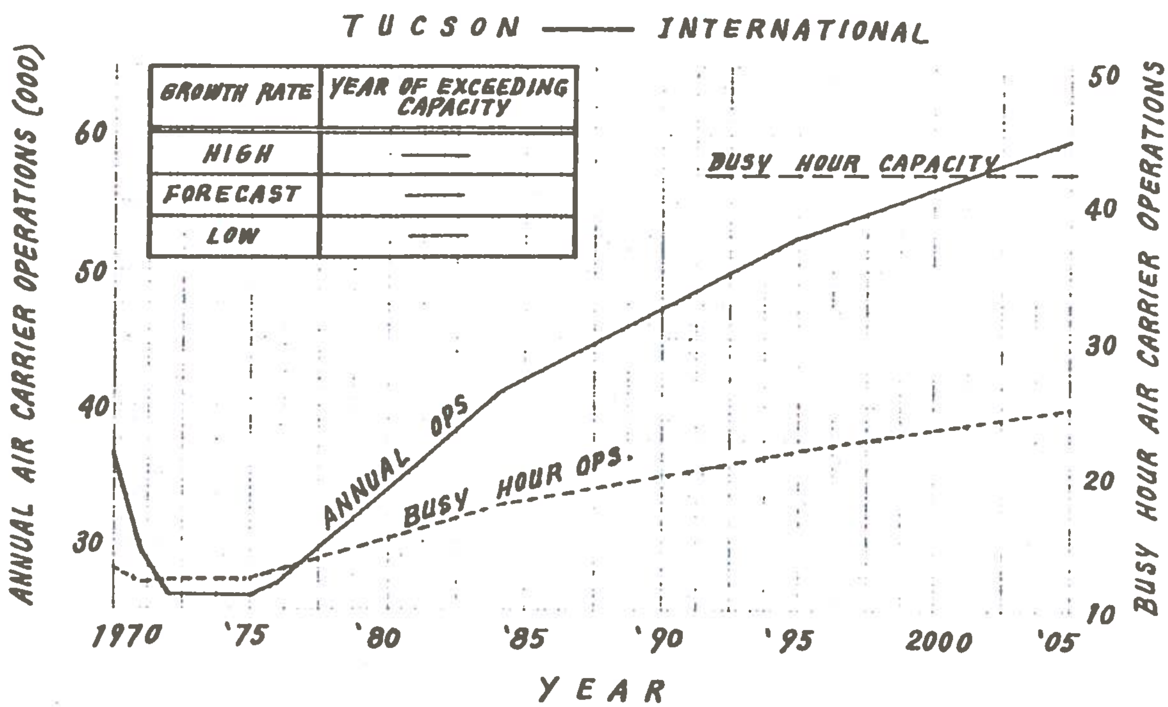


FIGURE 6-13.—CONCLUDED (SHEET 31)

TABLE 6-8.—INDEX TO FIGURE 6-13 AIRPORT TRAFFIC GROWTH CHARTS

SHEET	AIRPORTS
1	New York - Kennedy International New York - LaGuardia
2	Newark - Newark
3	Chicago - O'Hare Chicago - Midway
4	Los Angeles - International Atlanta - Wm B. Hartsfield International
5	Washington - Dulles Washington - National
6	Baltimore - Friendship International San Jose - Municipal
7	San Francisco - International Oakland - International
8	Dallas/Fort Worth Boston - Logan International
9	Miami - International Detroit - Metro Wayne
10	Pittsburgh - Greater Pittsburgh Philadelphia - International
11	Denver-Stapleton International Cleveland - Hopkins
12	St Louis - International Minneapolis-Minneapolis-St Paul International
13	Kansas City Houston - International
14	New Orleans - International Seattle - Seattle/Tacoma
15	Covington - Greater Cincinnati Las Vegas - McCarren International
16	Memphis - International Phoenix - Sky Harbor Municipal

TABLE 6-8.—CONCLUDED

SHEET	AIRPORTS
17	Tampa - International Buffalo/Niagara - Greater Buffalo/Niagara
18	Portland - International Indianapolis - Weir Cook
19	Salt Lake City - International Louisville - Standiford Field
20	San Diego - International Columbus - Port Columbus
21	Windsor Locks (Hartford) - Bradley International San Antonio - International
22	Milwaukee - General Mitchell Omaha - Eppley
23	Syracuse - Hancock Charlotte-Douglass Municipal
24	Rochester - Monroe County Jacksonville - International
25	Oklahoma City - Will Rogers Albuquerque - Sunport/Kirtland
26	Ogden - James M. Cox Nashville - Metropolitan
27	El Paso - International Norfolk - Norfolk Regional
28	Tulsa - International Albany - Albany County
29	Providence - Green Birmingham - Municipal
30	Des Moines - Municipal Raleigh Durham - Raleigh - Durham
31	Knoxville - McGhee Tyson Tucson - International

7.0 STRATEGIC TERMINAL DATA PROCESSING SIZING

The estimates for sizing the data processing requirements of a strategic terminal control system are based on a functional definition of the tasks to be performed. The major functions that are implied by the operational scenario have been expressed in algorithmic form and those definitions have been translated into a standard terminology of millions of instructions per second (MIPS) and millions of bits of rapid access storage.

First the components of instructions and words (bits) of rapid access memory for each unique event within the system are estimated. This estimate is based on the services that must be provided to each airplane under normal circumstances. The peak load that could exist within the terminal area is then estimated. By assuming that a rescheduling of all airplanes in the area would impose the worst case demand upon the data processing system and that all airplanes would have to be rescheduled within 5 minutes, it is possible to estimate the maximum rate in MIPS that the computer would have to provide.

There are several differences between the results obtained by this method of computer sizing and the data processing requirements for the mechanization of the strategic control algorithm as discussed in the other portions of this report. The major difference is in the design intent; this projection is an attempt to define a reasonably complete operational system independent of any specific computer or language. The simulation program discussed elsewhere was developed to test the performance of a strategic algorithm on a specific computer. The simulation was written in FORTRAN for "batch" operation and did not address a number of the elements of system load that would exist in an operational real-time system.

The second significant difference is in the evaluation of the load placed on the host computer by the simulation model. Ideally, this load could be expressed in terms of MIPS and used as a basis for validating the functional model of the data processing requirements discussed in this chapter. Because of the differences in design technique between the simulation and the more global design, such a direct comparison is not available. An attempt was made, however, to isolate the components of the simulation algorithm that would be carried forward in a future operational system.

An investigation of the algorithm, as mechanized on the CDC 6600, reflects an instruction storage count (in words) of:

$$M_{6600} = 10{,}875 + 278N_{types} + 86N_{A/C}$$

where

N_{types} = number of different airplane types for which performance information must be stored

$N_{A/C}$ = number of airplanes accommodated by the system at any one time

The actual number of instructions executed per airplane handled cannot be readily determined but can be estimated from the form of the algorithm logic and the required iteration loops at approximately 80,000 instructions.

The comparable value for the functional system sizing, which projects a more complex geometry, is 54,132 instructions per airplane (see sample below).

The above comparison does suggest that the projected data processing load per airplane is at least in the same scale as the simulation model data processing load. The forcing function for the MIP rate is the interval allowed for a complete reschedule of the airspace.

The total data processing requirement for strategic terminal control is developed in table 7-1, which identifies the projected demand and assumed strategic path structures for 1995. The peak demands shown are then translated into data processing requirements and displayed in table 7-2.

7.1 EN ROUTE STRATEGIC AIR TRAFFIC CONTROL DATA PROCESSING REQUIREMENTS

The system design concept for the strategic control of airplanes after they have departed a strategic control terminal area and prior to their entry into another strategic terminal area has not been defined. Consequently, the data processing requirements cannot, at this time, be established with any degree of confidence.

Two methods of computer sizing were attempted for the en route control of strategic airplanes. The first reasoned by analogy that the en route system must be similar to some number of strategic terminal areas and thus could be handled by a computer system that would be some multiple of the terminal system in size. The second attempt involved construction of a "strawman" en route strategic system design to allow definition of the functions that must be performed as an airplane executed a flight between strategic terminals. Neither of these attempts was deemed of sufficient credibility to report the results since both were constructed without an operational scenario and an effective system design concept.

As a result of these investigations, some insight was gained into the types of problems that are encountered in design of an integrated national system. These are expressed below in qualitative terms to act as a suggestion of areas that will require additional analysis as the design concept of the en route strategic system is developed.

This section gives a brief discussion of some of the relevant factors in designing an en route strategic control system.

For assessing computing requirements, the principal design decisions for the en route strategic control system are to specify the following:

1) Geographic segmentation of the country into regions of responsibility and the placement of control centers within these regions

TABLE 7-1.–STRATEGIC CONTROL DATA PROCESSING REQUIREMENTS BY CANDIDATE TERMINAL AREAS

CANDIDATE STRATEGIC CONTROL COMPUTER CENTER	MIPS APPLICATION	CORE BITS X 10^6	CORE WORDS X 10^3 (30 bits)
WASHINGTON	.0442	15.52	517
SAN FRANCISCO	.0546	15.62	521
NEW YORK	.0790	15.86	529
CHICAGO	.0623	15.00	500
MIAMI	.0422	14.81	494
LOS ANGELES	.0361	13.52	451
ATLANTA	.0361	13.52	451
BOSTON	.0238	13.40	447
DALLAS	.0329	13.49	450
PHILADELPHIA	.0209	13.37	446
PITTSBURGH	.0203	13.37	446
DENVER	.0238	13.40	447
SAN DIEGO	.0124	13.29	443
CLEVELAND	.0141	13.31	444
KANSAS	.0158	13.32	444
HOUSTON	.0173	13.34	444
NEW ORLEANS	.0158	13.33	444
	.5516	238.0	7,920

TABLE 7-2.—DEMAND ESTIMATES FOR DATA PROCESSING SIZING

STRATEGIC CONTROL CENTERS	1995 MEDIAN BUSY HOUR OPERATIONS		NUMBER OF ROUTES		NUMBER OF CONTROL POINTS
Washington D. C.					
Dulles	47		24		
National	72		24		
Friendship	44		24		
		163		72	360
San Francisco					
San Francisco	121		24		
Oakland	48		24		
San Jose	33		24		
		202		72	360
New York					
Kennedy	103		24		
Laguardia	97		24		
Newark	93		24		
		293		72	360
Chicago					
O'Hare	177		24		
Midway	53		24		
		230		48	240
Miami					
Miami	92		24		
Ft. Lauderdale (est)	74*		24		
		156		48	240
Los Angeles		133		24	120
Atlanta		132		24	120
Boston		88		24	120
Dallas/Ft. Worth		122		24	120
Philadelphia		77		24	120
Pittsburgh		75		24	120
Denver		88		24	120
San Diego		46		24	120
Clevcland		52		24	120
Kansas City		59		24	120
Houston		64		24	120
New Orleans		59		24	120

* Based upon 80% of Miami Operation Rate

2) Configuration of the computing facilities at the control centers

3) Communications procedures to be used in data exchanges

The geographic division of the continental U.S. into regions of responsibility is important because the shapes and number of these regions determine the number of transitions and the amount of interregion data transmission that must occur. At the one extreme, if the entire en route system were implemented on a single computer there would be minimal data exchange and no computing required to coordinate passage from one region to another. At the other extreme, if the U.S. were divided into 20 control regions, then the interregion communication for negotiation of conflict-free passage would be large, and the total amount of computing devoted to coordinating interregion passages would be considerable. In generating an en route plan for flying from Los Angeles to Boston, the Los Angeles computer would have to have on hand, or would have to obtain, data on flights scheduled through each region between the two cities. This would require a large quantity of data transmission and storage capacity, since the same information would be stored in the several computers along the proposed flightpath.

The impact of the method of physical delineation of the control regions on computing requirements is also significant. Another consideration that is affected by the geographic structure of the control system is overall reliability; it would most likely be less expensive to obtain a given reliability level with a dispersed network of computers than with one or two large control centers. In a network of 10 computers, the failure of a single machine would not be crippling to the overall system if the adjacent control regions could be dynamically reshaped to allow assumption of temporary responsibility for the failed computer's region. The total excess (standby) computing capacity to achieve a stated level of system reliability can be shown to be far less than with one or two large control centers, which would probably require complete backup systems.

The configuration philosophy of the individual computing facilities is important; if the nature of the scheduling software is such that it is possible to do a good deal of simultaneous or reentrant processing without excessive data base interference, then a multiprocessing computer with highly modular CPU resources would have quite different requirements than a large computer with a single CPU. Also, the use of such a multiprocessing concept would likely result in less costly resources to achieve a given level of reliability, since backup CPUs in regions A, B, and C could be brought up to absorb the load imposed by a computer failure in region D. On the other hand, a multiprocessing installation would likely have a higher level of system overhead, so that the above advantages are not obtained without cost.

Since each data exchange between computers requires some computational effort (if only to verify that the message is addressed properly), the communications procedures affect the total amount of processing that must be done at any control center. Also, the communication procedures affect the amount of buffer storage that must be allocated to telecommunications. These may represent very minor demands in a system concentrated in one or two computer centers, but in a widely fragmented system they could become a significant fraction of the available capacity.

7.2 TECHNOLOGY AND DEMAND FORECAST

Computer and communications systems are expected to develop in an evolutionary fashion through the planning horizon for the initial strategic control system (1985 standard product). Input and output devices will be reduced in cost and expanded in capability. Voice communications with both the airborne and the ground computer will be feasible and in common use. Details of the man-machine interface in strategic control will be discussed only as that interface contributes to the system requirements. For purposes of this study, an extension of existing sequential processing computers is specified for clarity of exposition. Where specific functions can be identified that could be done by associative or parallel processors, it is assumed that such a substitution will be made subject to cost benefit analysis.

Communications from ground to airplane are expected to be in digital form for computer-to-computer usage. Sufficient channels will be required to allow simultaneous communication with some significant fraction of the strategic airplanes in the terminal area (subject to further definition).

The demand forecast for a given strategic control terminal area is based on the load in a 1995 terminal area. This demand is used parametrically in the sizing algorithms to estimate the data processing requirements. The airplane operation saturation rate (D_{sat}) reflects the maximum load under saturated conditions for 180 minutes. This value influences both the processing and storage demand placed upon the system.

The number of unique airplane models (N_m) that can exist within the system is required to allow estimation of memory requirements for aerodynamic data storage.

7.3 STRATEGIC CONTROL COMPUTER ALGORITHM DESCRIPTION

This algorithm description is established to provide a baseline for the initial data processing sizing for strategic control and may not represent an optimum solution for use of either the airplane or the runway.

The computer program for scheduling and controlling strategic airplanes will consist of a series of scheduling tables, data tables, and the processing programs that are used to calculate the entries in the scheduling tables.

Inputs to the strategic control computer may be made by either the external world (operator, strategic control airplane) or the internal memory of the system (tickler file of airplane expected arrivals). The outputs will be directed to either an airplane (route-time profile) or to a human operator (request for help in resolving conflicts).

The basic algorithm for airplane control in the strategic control terminal area will have the following general characteristics:

1) Airplanes will be scheduled over a known number of predefined routes in space.

2) A single exchange of information (request/route-time profile response) when the airplane enters the area will be the only nonemergency communication.

3) Environmental data for strategic operations support will be available from other ATC modules.

4) Airplane tracking (surveillance) will be executed by other functional modules of the ATC system.

5) The basic scheduling horizon is set by the transit time to land from an entry fix plus an allowance for the probable limit time that airplanes would be held in a local stack awaiting a landing time:

Transit time:	Entry fix to threshold	= 30 min	= 1800 sec
	Holding time	= 60 min	= 3600 sec
	Total	= 90 min	= 5400 sec

The following assumptions are made to simplify the data processing sizing tasks:

1) Scheduling will not be iterative; i.e., each event will be entering into a fixed system at scheduling time.

2) The strategic control system will schedule one airplane at a time.

3) Aerodynamics curves will be stored for each unique model airplane in the system.

4) Velocity of airplane will be programmed by the strategic control system.

5) The airborne computer will, as minimum functions, be able to translate the route-time profile from the ground system into commands for the flight control system, direct the flight control system to follow the route-time profile, monitor the performance of the flight control system, and communicate with the flight crew through computer-driven displays and audio response mechanisms.

7.4 SUMMARY OF DATA PROCESSING REQUIREMENT

The number of instructions per airplane are summarized as follows with the source of the requirement.

7.4.1 Program Instructions

Program instructions are summarized in table 7-3.

TABLE 7-3.—PROGRAM INSTRUCTION COUNT SUMMARY

Function	Definition	Sample case value
Input request for RTP		500
Receive and validate request		200
Compute EEAT/LEAT	$1000\ (0.7 + N_{cp}/R)$	5,700
Duration of reservation at control fixes	$2500\ N_{cp}/R$	12,500
Fit demand to schedule		4,200
Test conflict		100
Assign aircraft to control fixes and optimize usage		25,000
Add reservations tables	$(5 \times 180/L_w) + 10$	300
Add to scheduling lists	$[N_0\ (1 + 44 \times L_w)/R + 10]\ N_{cp}/R$	111
Create route-time velocity profile		500
Transmit response		100
Exception processing		nil
Instruction per aircraft, projected New York strategic control center load		49,211 instructions

Note:

N_{cp} = number of control points in the system

L_w = word length (in bits) of the computer being used for sizing

N_0 = number of operations within the scheduling horizon of the strategic control system

R = number of strategic routes entering or leaving a terminal area

EEAT = estimated earliest arrival time reflects the earliest time that a given aircraft could arrive at a control point

LEAT = latest estimated arrival time reflects the latest time that a given aircraft could arrive at a control point

7.4.2 Memory

Memory demand has two major components. Space must be provided for all of the data required for processing at a given point in time. Space must also be allowed for the processing programs that will use the system data. This design assumes that all data and programs are allocated to the same type of rapid access storage.

The total estimate is 15.8×10^6 bits, of which 2.9×10^6 bits are for data storage and 12.9×10^6 bits for program storage.

7.4.3 Data Storage

The data storage requirements are summarized in table 7-4 (number of models = 50). This sample value is based upon the New York area, which is the largest traffic load.

TABLE 7-4.—DATA STORAGE REQUIREMENTS SUMMARY

Function	Definition	Sample value (bits)
Master schedule	$C_{ms} = (N_{cp})(T_n)$	1.94×10^6
Scheduling lists	$C_{sl} = (44)N_{cp}N_0/R$	6.446×10^4
Work areas	$C_{wa} = (LEAT\text{-}EEAT)N_{cp}/R$	1.5×10^3
Buffer areas	$C_{buff} = C_{msg}(D_{sat})$	2.956×10^5
Aircraft performance	$C_{pr} = L_{pr}(D_{sat})$	5.63×10^5
Aerodynamics curves	$C_{pc} = N_m(C_{curves})$	5.8×10^4
Wind/temperature data	$C_{wt} = 84N_{cp}$	3.02×10^4
Local turbulence	$C_{turb} = (\text{cells}) \times (C_{tr})$	0.088×10^4
	Total	2.9×10^6

Note:

C_{ms} = core required for master schedule array

C_{sl} = core required for scheduling lists

C_{wa} = core required for work areas

C_{buff} = core required for input/output buffer storage

C_{pr} = core required to store aircraft performance data

C_{pc} = core required for aerodynamics curves

C_{wt} = core required for wind and temperature data

C_{turb} = core required for local turbulence data

T_n = number of seconds in the scheduling window for strategic control

C_{msg} = core required for a completed route-time velocity profile

L_{pr} = length of an aircraft performance record in bits

D_{sat} = saturation demand upon a strategic control terminal area

N_m = number of unique aircraft type/models that will operate in the strategic mode

C_{curves} = core required to store the aerodynamic data for a single model of aircraft

C_{tr} = core required to store data required for a single turbulence call

7.4.4 Program Storage

In general, the number of instructions required to support high frequency functions such as airplane scheduling will be a small fraction of the total number of instructions needed in the system. Low-frequency service functions must be included for core estimating although they do not contribute to the processor demand (MIPS). In consideration of the type of application and the preliminary nature of the design, a ratio of 10 to 1 will be used for sizing the program core requirement. Thus, a strategic application will require:

(Number of Instructions per Airplane) (10 Instructions)

If the average instruction requires 24 bits, then the total core required will be: 24 (54,132 x 10) = 12.98 x 10^6 bits.

7.4.5 Overhead

Processing requirements are specified as an effective processing load. The application program of 49,211 instructions in the sample case is assumed to be written with the high-efficiency compilers that are projected for 1980. A derating estimate of 10% for compiler inefficiency is allocated to bring the actual demand for the sample case to (49,211) + (0.10) (49,211) = 54,132 instructions per airplane.

7.5 WORST-CASE DEMAND

The worst-case demand for this system should occur when all of the arrivals/departures for the planning horizon of 1-1/2 hours require rescheduling. For example, in the New York strategic center, a total of 440 airplanes must be rescheduled within 5 minutes. This produces a rate of 440/5x60 = 440/300 = 1.46 airplanes per second, or a processing load of (1.46)·(5.413x10^4) = 7.90 x 10^4 instructions per second or 0.0790 MIPS for 5 minutes (reschedule all airplanes in area).

7.6 RAPID ACCESS MEMORY REQUIREMENTS

The following section develops the details to support the rapid access memory requirements for data processing in a strategic control terminal area. The definitions are based on estimates of the space required by the major system functions.

7.6.1 Scheduling Lists

Each control fix in a strategic control terminal area will be represented by an internal table that will display:

- Airplane identification in the form of a pointer to additional data on that specific airplane
- Type of operation to be performed; i.e., arrival, departure, maintenance, etc.

- Time that operation will take place (to nearest second).

Memory required for one control fix is N_o x 44 bits, where N_o is the number of operations allowed within the scheduling horizon of 5400 seconds. The maximum core requirement can be estimated by:

- Treating merged routes as separate, but superimposed

- Allowing airplanes to remain in all lists from entry time until touchdown (clearing system).

Then if:

N_{cp} = total number of control fixes in system (although some control fixes will have data for merged paths and thus reduce the actual number of control fix tables, the conservative assumption is made here that space must be reserved for the maximum possible table space)

L_{cp} = total number of entries in control fix tables

R = total number of paths in system

The system inputs are evenly distributed over all paths and the number of operations per path during the scheduling horizon will be N_o/R, and the list size for each control fix will be N_o/R in length. Thus, there will be a maximum of:

$$L_{cp} = N_{cp}\, N_o/R$$

entries in the scheduling list. The core memory required will be:

$$C_{sl} = 44 \times N_{cp}\, N_o/R \text{ bits.}$$

7.6.2 Work Areas

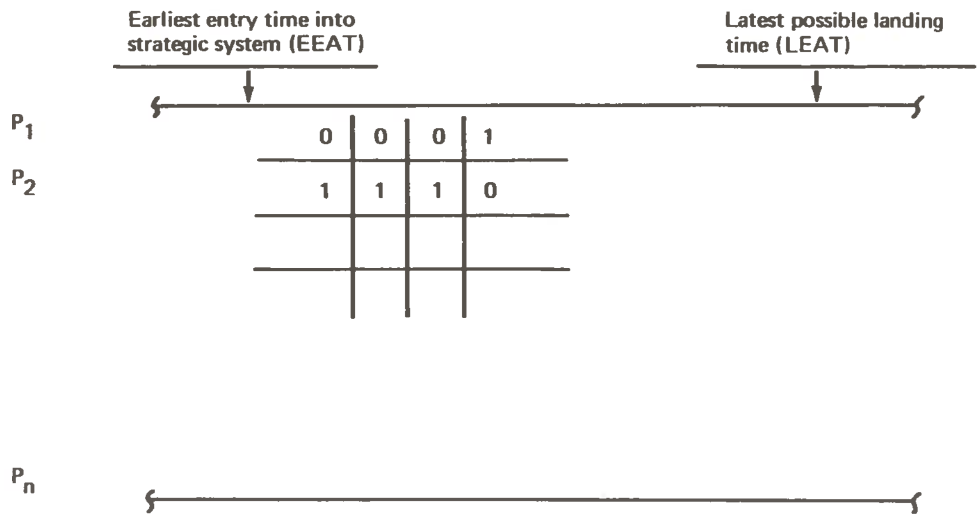
Each airplane being scheduled through the master schedule will require a work area (C_{wn}) set by the window size at the threshold and by the number of control fixes through which it will be scheduled. This work area will be a subset of the master schedule array such as shown in figure 7-1.

$$C_{wn} = \text{(LEAT-EEAT)} \times \text{(number of control fixes along the route)}$$

The maximum will occur for the airplane with the longest path time flying over the route with the largest number of control fixes.

$$\text{Max } C_{wn} = \max\text{(LEAT - EEAT)} \times \max\text{(control fixes/path)}$$

$$C_{wn} = \max\text{(LEAT - EEAT)} \times N_{cp}/R$$



Note: P_n is the n^{th} point that the aircraft will use.

FIGURE 7-1.—MASTER SCHEDULE ARRAY

This area will be extracted from the master schedule and used to build the detailed schedule for an individual airplane by examination of the events that have been previously scheduled at each control fix. The area (C_{wn}) will be available for reuse upon completion of each scheduling cycle.

7.6.3 Buffer Areas

The average requirement of rapid access memory will be a function of the communications volume per unit time, communications system speed, the degree of buffering available outside of the computer, the buffer assignment algorithm, and the average message size. For an initial sizing estimate, the following may be used as a point of departure:

- V_{avg} = average number of messages per minute
  = 2 x (total of arrivals and departures in 30 minutes)/30 minutes
- Average message size = 672 bits
- Buffer assignment = rotating assignment from free memory
- External buffering = no external buffering assumed
- Communications speed = 9600 bits/second (effective)

The maximum buffer size will occur when the strategic control system reschedules all of the airplanes within the system. Assuming that C_{msg} is 672 bits and D_{sat} is the total number of airplanes to reschedule, then the maximum value of C_{buff} is $(C_{msg}) \times (D_{sat})$.

7.6.4 Aircraft Performance Records

Each airplane in the strategic control terminal area will be represented by a performance record. The performance record will be linked to the scheduling lists and other reference lists by a set of pointers. The pointers will allow rapid access to airplane performance data by the scheduling and timing algorithms. Performance records will be created as an airplane enters the strategic control system and deleted memory when the airplane has completed the scheduled operation. The performance record will total 1280 bits.

The maximum requirement for performance records will occur when the system is in a saturated condition, i.e., when 5400 seconds worth of arrivals/departures are all active simultaneously. This implies that the last hour of departures has been allowed and that the system is required to schedule the next 30 minutes of arrivals/departures in addition to the past hours of demand. Given the above, the memory required for performance records will be:

$$C_{pr} = (L_{pr}) \times (D_{sat})$$

when

L_{pr} = length of a performance record in bits (1280 bits)

C_{pr} = memory required for performance records

D_{sat} = saturation demand on a strategic control terminal area (approximated by the total of 5400 seconds of demand)

7.6.5 Aerodynamic Performance Curves (Aero Curves)

Prototype aerodynamic performance data for all airplane models that will use the terminal area will be stored for rapid access. These records will be used by timing algorithms to determine the EEAT/LEAT for an airplane. Pointers to the aero curves will be retained in each airplane performance record for reference purposes along with the calculated delays that have been established by the final schedule.

The number of models of airplanes (N_m) and the number of bits required for a set of performance curves (C_{curves}) will determine the memory requirement as:

$$C_{pc} = (N_m) \times (C_{curves})$$

The initial estimate of C_{curves} is 1160 bits.

7.6.6 Wind/Temperature Data

Each route segment will have a unique wind/temperature (w/t) record stored for rapid access.

For simplicity in sizing, the wind/temperature data will be expressed as an average number of entries for the control fixes on a path. Given an average of five control fixes per path, and a total elevation change of 45,000 feet, then the average table will be 45/5 or 9 entries per control fix for a table size of 168 bits per average wind/temperature record at a control fix. If control fixes along merged routes are considered, then about one-half of the w/t tables on a path will be redundant and, as a consequence, be pointers to the data for that fix.

The total w/t table storage requirement will be:

$$C_{w/t} = \text{(tables with pointers)} + \text{(tables with data)}$$

$$C_{w/t} = 1/2\, N_{cp}\,(12 + 12) = 1/2\, N_{cp}\,(168)$$

$$C_{w/t} = 96\, N_{cp}$$

7.6.7 Local Turbulence Cell

Local weather disturbances will be held in rapid access storage for use in generation of the route-time and velocity profiles. The data will be used by the route-time assignment program to adjust velocity in the case of clear air turbulence or select an alternate route for storm cell avoidance.

For conservative design, an estimate of local turbulence storage requirement will be based on having 20 turbulent areas within the 175-mile radius of the strategic control terminal area. Each occurrence of local turbulence will be recorded in a local turbulence cell record size of 44 bits.

The maximum rapid access storage required to store local turbulence data will be:

$$C_{turb} = \text{(number of cells)} \times (C_{tr})$$

$$\text{Max } C_{turb} = (20 \times 44)$$

$$= 880 \text{ bits}$$

7.7 PROCESSING REQUIREMENTS

Processing requirements will be developed in terms of the number of instructions required to execute each functional module of the strategic control computer algorithm. The total instruction estimate will then be used with a peak demand per unit time to establish the MIPS rate that should be available to support the algorithm in the worst case.

7.7.1 Input Processing

Input to the system will generally be by digital data link and will consist of a request for a route-time/velocity profile for either an arrival or a departure. There may be occasional input from an ATC operator to change the status of a system element or from a service module that will maintain a tickler file of scheduled flights that will arrive/depart within the scheduling horizon of the strategic control system. Assuming that 98% of all input is from an airplane and using an estimate for other inputs, the probable number of instructions per route-time profile for input processing will be 500 instructions.

7.7.2 Receive and Validate Requests

Each request for service will be subject to extensive edit and validation. The airplane identification and model numbers will be verified with stored data, and positional data will be checked with prestored flight plans to ensure reasonableness of the request. The estimate to receive and validate requests is 200 instructions.

7.7.3 Compute Earliest Estimated Arrival Time and Latest Estimated Arrival Time (EEAT/LEAT)

For each request for service the earliest and latest arrival times must be computed for each control fix on the planned path. These values are then used to establish the possible window for scheduling the airplane at each control fix. The EEAT/LEAT calculation uses the following tables as input to determine the estimated arrival times:

- Performance records
- Aerodynamics data
- Wind/temperature data
- Local turbulence data

With the entry location/altitude known, the algorithm will compute the longest and shortest time that the airplane can take to fly over the fixed geometry to the next control fix. Simple rules for establishing velocity schedules between control fixes will be established that conform to the adjusted flight envelope of the airplane and meet passenger comfort criteria.

The aerodynamics data will be retrieved and modified by data on the wind/temperature and the local turbulence. The result will be an adjusted flight envelope for the airplane make and model. Adjustment for gross landing weight will be applied to set the low-speed boundary of the flight envelope.

- To retrieve tables and adjust—1200 instructions
- To compute lower boundary at known landing weight—500 instructions.

Once the adjusted flight envelope has been developed the algorithm will compute the EEAT and LEAT values for each path segment.

- To compute EEAT—500 instructions per segment
- To compute LEAT—500 instructions per segment

Thus, the total instruction requirement will be

$$\text{Total} = 1700 + (1000)\,(N_{segments})$$

Since the average number of segments will always be one less than the number of control fixes, $N_{segment} = (N_{cp}/R)-1$. Then the requirement may be restated as $(1000)(0.7 + N_{cp}/R)$.

7.7.4 Compute Duration of Use of Each Control Fix

The scheduling system must take the distribution of expected arrival time into consideration to avoid scheduling two airplanes into a potential conflict situation.

The scheduling problem then reduces to finding an interval at each control fix within EEAT and LEAT that does not conflict with a prior reservation of that control point.

- To compute using airplane and schedule data—1000 instructions/control fix
- To compute using airplane performance data—1500 instructions/control fix

When N_{cp}/R is the average number of control fixes in a path, the total estimated instruction requirement is $2500\ N_{cp}/R$.

7.7.5 Fit Demand to Master Schedule

The earliest and latest estimated arrival times computed are used to select the columns of the master schedule that will be used for schedule analysis. The control fixes related to the specific path that the airplane will use for arrival/departure will be used to identify the control fixes or rows of the master schedule that will be used for schedule analysis. Using the above selection criteria a subset of the master schedule will be created in a work area.

To identify, select, and construct the subset of the master schedule will require 200 instructions assuming LEAT-EEAT is equal to 300 seconds and the number of control fixes is five. The value of D_0' for each control fix (fig. 7-2) is then used as a scheduling mask to attempt allocations of each control fix.

Allocation is done by searching for an area in the subset of the master schedule that will allow insertion of an interval D_0'. In the sample, the interval D_0' can be inserted between T_1 and T_2. Allocation of the operation time will be determined by the assignment algorithm according to the system objective functions.

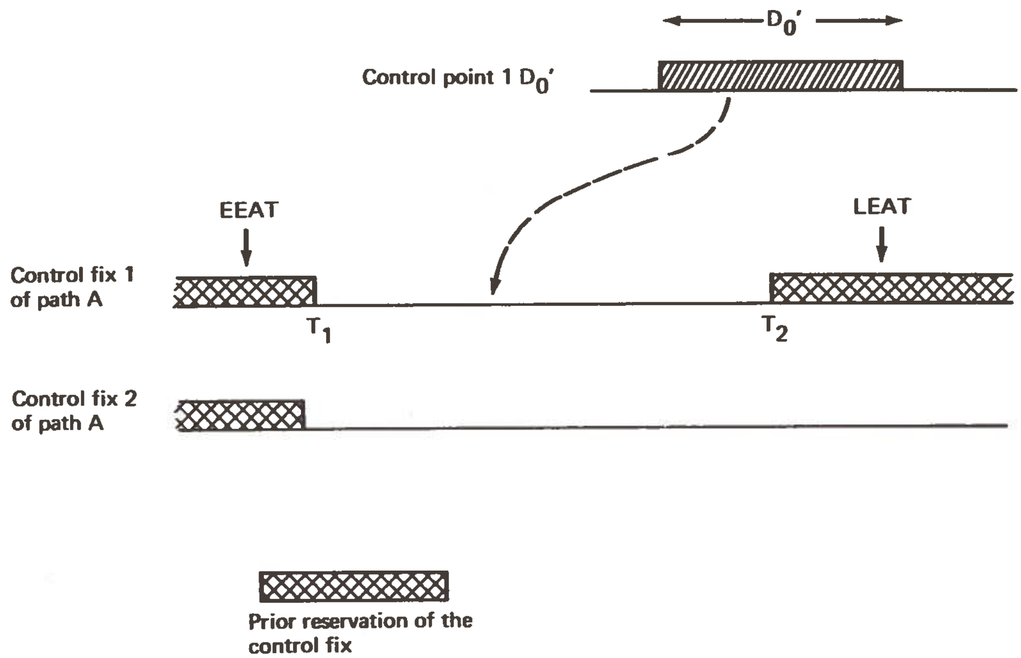


FIGURE 7-2.—SCHEDULING MASK

Allocation will be done on a control fix basis until all control fixes have been attempted. If a control fix cannot be scheduled, the conflict will be noted and control will be passed to a conflict resolution algorithm.

To test five control fixes for insertion of D_{01}', D_{02}, . . . within a 300-second scheduling window requires (150 + 150) (2) (5) + selection logic + 200 instructions for a total of 4200.

7.7.6 Test for Conflict

The results of the allocation module will be analyzed. If conflict-free scheduling can be done, processing will continue for assignment of arrival times. If there are conflicts the system will attempt recovery by entering a conflict resolution algorithm. To test for conflict and tag requires 100 instructions.

7.7.7 Assign Airplane to Control Fixes

Each relevant control fix is assumed to have one or more intervals I_0 that will satisfy D_0', the airplane demand (fig. 7-3).

The assignment of the interval, I_{0_n}, and the positioning of the demand, D_0', to be earliest, latest, or otherwise assigned is controlled by the system objective function. This function, not yet defined, is the set of rules that ensure optimization of some part of the total system (i.e., least delay in operation, best use of runways, fewest changes in airplane

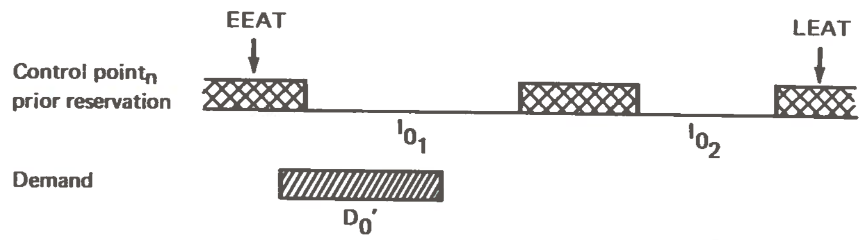


FIGURE 7-3.–INTERVAL ASSIGNMENT

velocity . . .). This may involve application of linear programming or dynamic programming techniques. To assign operation intervals for control fixes requires (5) (5000) or 25,000 instructions.

7.7.8 Add Reservations to Master Schedule

The event start time and duration for each relevant control fix is entered in the master schedule. This consists of changing the status of the selected cells from zero to one. For a typical operation duration of 180 seconds, the total instruction requirement may be expressed as the product of the number of instructions and the number of control fixes (rounded high) plus the control logic requirement or

$$\text{Total} = \left(\frac{180}{L_w}\uparrow\right) \times 5 + 10$$

where

$\uparrow$ = round high

L_w = word length of computer expressed in bits

7.7.9 Add Reservations to Scheduling Lists

The assignments made above, now referenced by the estimated operation time T, must now be entered in the correct chronological order in the master schedules. In the worst case each control fix along the route will have N_o/R entries. Each table must be searched to find the correct insertion point; all later entries must be moved down in the list and the new value entered.

Search		Move table		Move data			Control fixes
$[N_o/2R$	+	$N_o/2R$	x	$(44/L_w)\uparrow$	$+ 10]$	x	(N_{cp}/R)

or

$$[(N_o/R)(1 + 44/L_w) + 10]\,(N_{cp}/R).$$

7.7.10 Create Route-Time Velocity Profile

The information in the scheduling list is combined with the input request data, checked and validated, and the format adjusted for transmission to the airplane. To validate and reformulate a route-time profile is estimated to be 500 instructions.

7.7.11 Transmit Response

The route-time profile is transmitted over an automated digital data link. The establishment of communication control and checking for valid communications are done at this point. The estimate assumes a 1% retry rate. To transmit response to airplanes is estimated to be 100 instructions.

7.7.12 Conflict Resolution Algorithm

This algorithm is specified for documentation purposes only at this time. In concept the adjustment of conflicting schedules could be allowed or the overlap in usage of the control fix could be overridden by an objective function that may involve air traffic control operator decisions.

7.7.13 Build Buffer Stack

In the event that an airplane can be scheduled through the first few segments of the path but has a conflict at a later point, this algorithm will generate a limited plan that will bring the airplane into a close-in stack and hold it there for later entry at the nearest control fix. Management of the reservations for all buffer stacks will be included. There will be at least three buffer stacks on each system path (R) with 10 altitudes per stack area. To build partial route-time profiles (assuming an average of 2.5 control fixes per incomplete route-time profile) is estimated to be 2000 instructions. However, this function is expected to occur for fewer than one airplane out of 1000 and can thus be ignored for data processing sizing considerations.

7.7.14 Exit System for Operator Servicing

In the event that all else fails the system operator will be informed that an "impossible to schedule" state has occurred. The system operator will then execute one or more conflict resolution techniques and return control to the strategic system. Provisions should be included to allow learning to take place so that future conflicts of a similar nature can be resolved by the system without operator intervention. This function should not reflect any appreciable load on the data processing system.

8.0 BENEFITS OF STRATEGIC CONTROL

The benefits of strategic control versus the benefits of manual radar vectoring and basic metering and spacing control as presently being implemented are compared in this section for various evaluation criteria. A flow diagram of the study is shown in figure 8-1. This illustrates that the following criteria are selected for comparison:

- Capacity criteria
  - Runway operations rate
  - Total delay
- Airspace criteria
  - Airplane economics
  - Number of conflicts
  - Control workload
  - Terminal area flow rates
- Communications loading

The criteria were selected by the contracting office (ref. 8-1).

Figure 8-2 illustrates in general the method used to obtain quantitative results. The Los Angeles terminal area is used as a model for the fixed inputs. The control concepts to be compared provide differences in the inputs. The quantification methods are the simulation of task 4 (this study), results from previous studies, and results from ATC models available at Boeing.

The details of the study follow. First, a summary of the results is given, followed by a detailed discussion of the results and methods of obtaining them, describing assumptions about the important conceptual differences. The final section includes a brief description of the models and derivations used in obtaining these results.

8.1 SUMMARY OF RESULTS

The benefits available are in terms of increased ATC system capacity (or reduced delay for a given level of operations), reduced ATC operating costs, reduced flight costs, and increased safety. The particular advantages that provide the basis for benefits are:

- *Reduced Controller Workload.* The strategic control concept provides safe separation between airplanes automatically, with the controller normally only

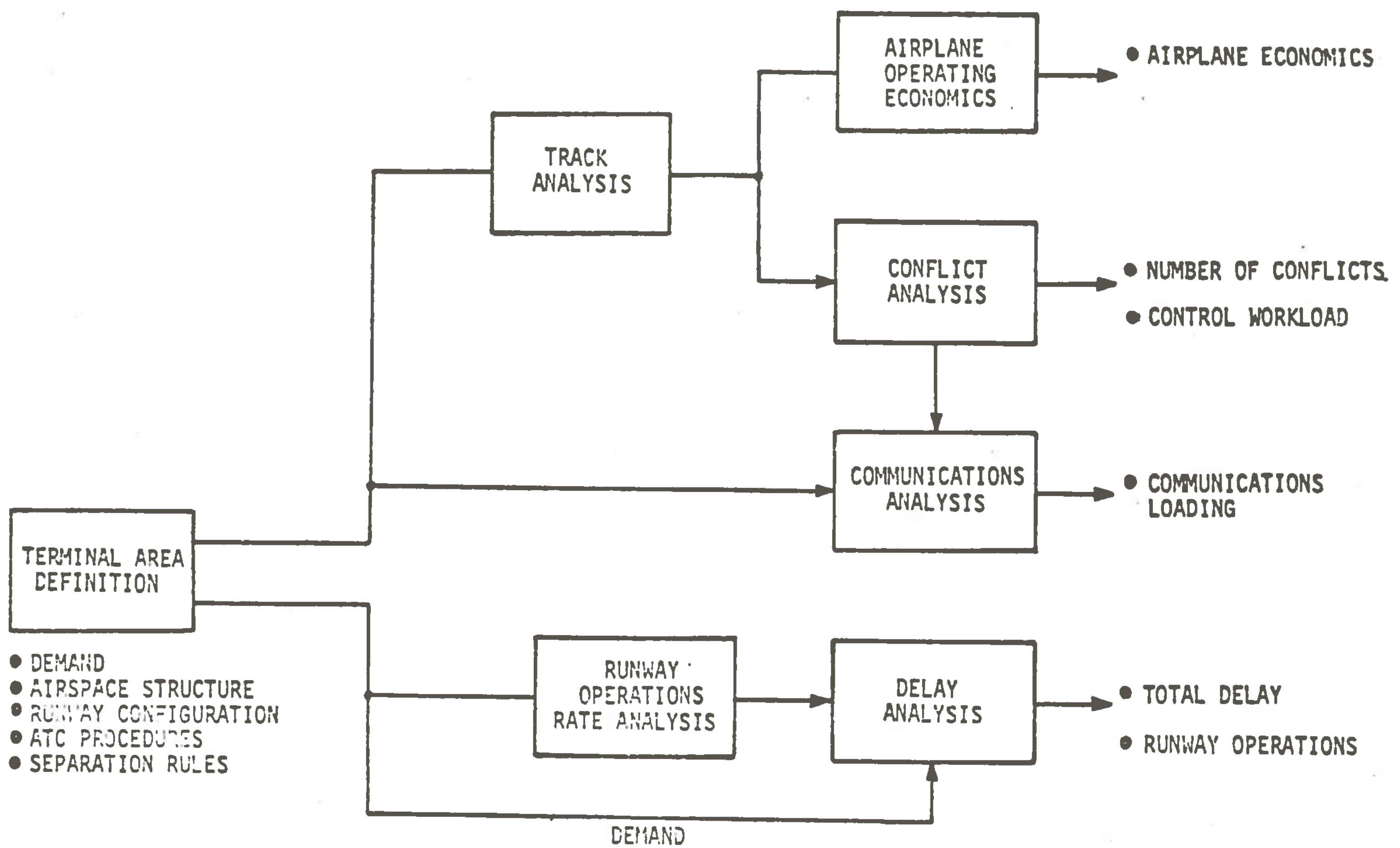


FIGURE 8-1.—BENEFITS OF STRATEGIC CONTROL

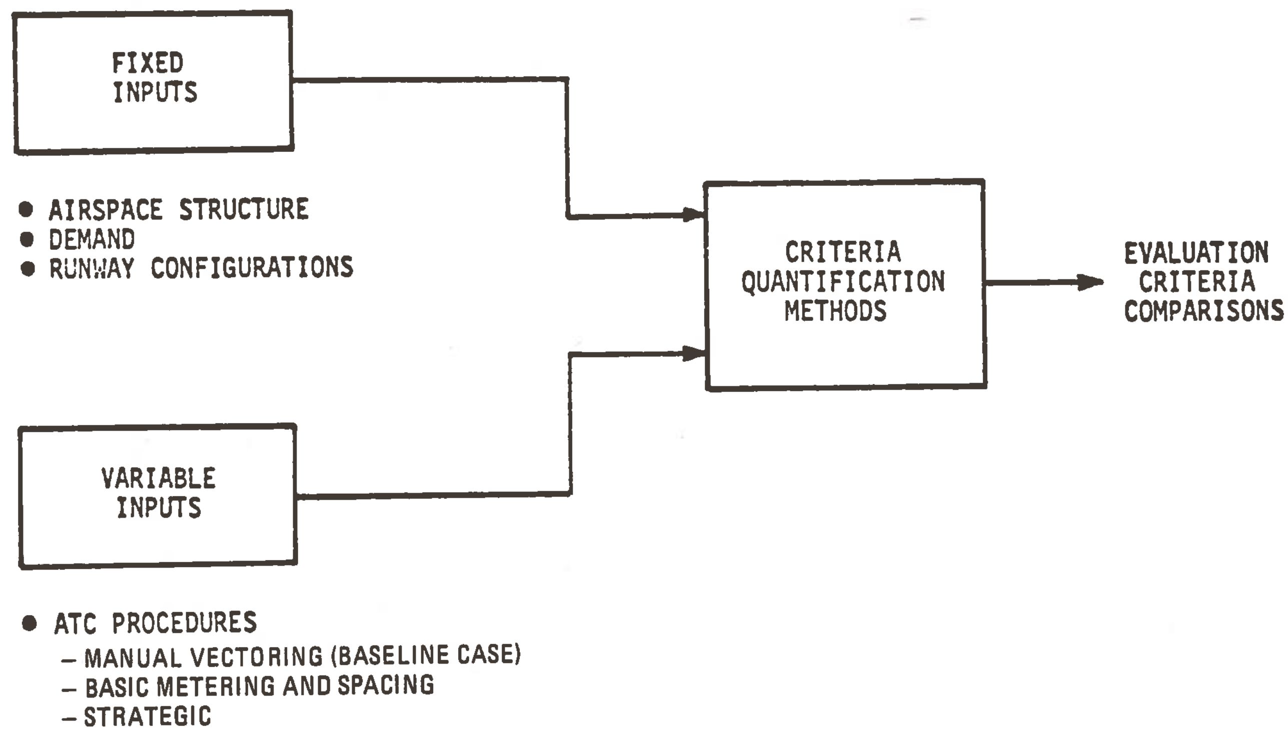


FIGURE 8-2.—BENEFIT STUDY METHODOLOGY

monitoring the traffic flow. Thus, the part of controller workload that provides this ATC function is removed as the limiting factor on the flow rate, and the work force 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 communication 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 in control of along-path position versus time results from having the guidance/control entirely within the airplane and allows reduced safe separations between airplanes.

- *Minimum Airspace Requirements.* Spacing control is exercised along track so that only the safety buffer around the track needs to be protected as large volumes of airspace are not required for path stretching. This maximizes airspace capacity, increasing the freedom of flight and eliminating a potential bottleneck to airfield operations.

- *More Flexibility in Use of Available Airspace.* Since tracks are not tied to navaid locations or predefined waypoints, the number and location of tracks can be changed to fit the existing traffic situation.

- *Reduced Flight Time.* With all control exerised along track, flightpath does not require (to provide for shortening) that the nominal track length be greater than minimum. Thus the nominal flight time is reduced.

- *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 system is interrupted, each airplane under strategic control already has an assigned conflict-free flightpath, and can continue to destination in safety.

- *Independent Navigation and Surveillance.* In an ATC system such as today's where the surveillance and navigation environments are separate systems, strategic control provides separately redundant protection against either ground or airborne blunders (large errors caused by unpredictable events). This protection is not available in manual vectoring or metering and spacing since all information for path control is provided by only the ground surveillance system.

Quantitative results for the Los Angeles terminal area have been obtained for all of the selected evaluation criteria. Some of the most important of these are summarized in table 8-1. Three system concepts are compared. The manual vectoring concept is based on the present ATC procedures that are used in the United States as applied to the Los Angeles area environment including airport configurations and track structure.

TABLE 8-1.—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

The metering and spacing (M&S) concept used in this study is based on the present understanding by the study team of the initial basic M&S applications being investigated. A brief outline of this understanding is as follows.

Metering and spacing is a method for sequencing, scheduling, and spacing control of the terminal area operating to and from an airfield. In this discussion the application to arrival control and to runway scheduling of both arrivals and departures is assumed. M&S is the control method for the upgraded third-generation ATC system that has ARTS III and NAS Stage A as the data processing equipment.

With the M&S operational program (as usually described) being only in ARTS III, sequencing, scheduling, and spacing control must be done between the initial approach fixes (IAFs) and the runway. NAS Stage A would meter airplanes to the individual fixes, but this is the extent of en route involvement.

Sequencing can be done by controlling the time each airplane passes or departs an IAF. The IAF is normally 35 to 40 nautical miles from the runway. By itself, speed control along a common path inside the IAF cannot provide the needed spacing control. Therefore, spacing control will require varying the flightpath length (this at times will involve holding at the IAF).

Control to achieve the needed path length variation can be accomplished by vectoring (time to turn) instructions, definition of the desired path in two or three dimensions, or definition of the desired path and time schedule (four-dimensional path).

A significant factor affecting M&S performance is the method for communicating instructions to the airplane. The principal choices are:

1) Voice communication from controller to pilot

2) Data link ARTS III computer to pilot after controller approval

3) Data link ARTS III computer to pilot with controller monitoring

4) Data link ARTS III computer to airplane flight control system

It is understood that basic M&S will use voice to communicate vectoring instructions to the pilot (refs. 8-2 and 8-3). Advanced M&S will employ data link from ARTS III to the pilot with controller monitoring to transmit control instructions for flight using two-/three-dimensional area navigation. With advanced M&S, the longitudinal separation is planned for 2 nautical miles (ref. 8-3). In this analysis a reduction to 2-1/2 nautical miles was associated with basic M&S.

In basic metering and spacing, all sequencing, scheduling, and spacing is done in the terminal area. Heading, speed, and altitude commands are displayed to the controller. The controller communicates base commands to the pilot.

The strategic concept used for this comparison is that given in the functional description of the algorithm designed during the study (sec. 4.0) and as applied in the algorithm evaluation model (sec. 5.0).

The percentage improvements over manual vectoring indicated in table 8-1 are given for a peak 1972 traffic level at Los Angeles International Airport. Similar improvements are obtained at the higher projected levels. Table 8-2 details the traffic levels used in this study.

TABLE 8-2.—TRAFFIC LEVELS AT LOS ANGELES INTERNATIONAL AIRPORT

Demand year	Number of busy-hour arrivals	Number of busy-hour operations	Busy-day operations
1972	66	92	1244
Low 1995	124	172	2330
Med 1995, Low 2020	175	237	3220
High 1995, Med 2020	241	324	4400
High 2020	341	478	6500

Note: Scheduled air carrier

Details of results including assumptions and methods are contained in the appropriate succeeding sections. Some highlights of the study are shown in figures 8-3, 8-4, and 8-5. Figure 8-3 compares the runway operations rates obtainable under the three concepts. This shows the significant advantage attained by strategic control especially in the arrivals-only case and the mixed (dual-runway) case.

Figure 8-4 translates these advantages into delay savings using the schedule at Los Angeles International Airport (LAX) as input. It shows that the strategic concept satisfies the DOT-TSC busy-hour delay criterion at twice present-day demand levels—without changes to the airport configuration.

The histogram (fig. 8-5) illustrates on a relative scale the reduced workload possible using strategic control. Three important workload criteria are totaled on this chart: conflicts, duration, and number of conflict airplanes.

Finally, a comparison of the number of communication links required for approach control (busy hour) is shown in table 8-3. This assumes voice communications with a 90% load factor. If it is assumed that one control position is used on each link, this also indicates the required number of positions. It is seen that the use of strategic control can reduce this requirement by more than half.

TABLE 8-3.—COMMUNICATION LINK REQUIREMENTS

Demand year	Number of approach control communication links required*		
	Manual vectoring	Basic metering and spacing	Strategic
1972	2	2	1
Low 1995	4	4	2
Medium 1995, Low 2020	6	5	3
High 1995, Medium 2020	8	6	4
High 2020	11	9	5

*Assuming 90% loading

8.2 CAPACITY ANALYSIS

An essential measure of the ATC system efficiency is the rate at which airplanes can be delivered into and out of the terminal area. The capacity of the air transportation system is critically limited in most operational situations at the runway. The speed and efficiency with which operations can be sequenced and scheduled to maximize runway utilization (minimizing operational delay) is a primary measure of the efficacy of postulated ATC systems.

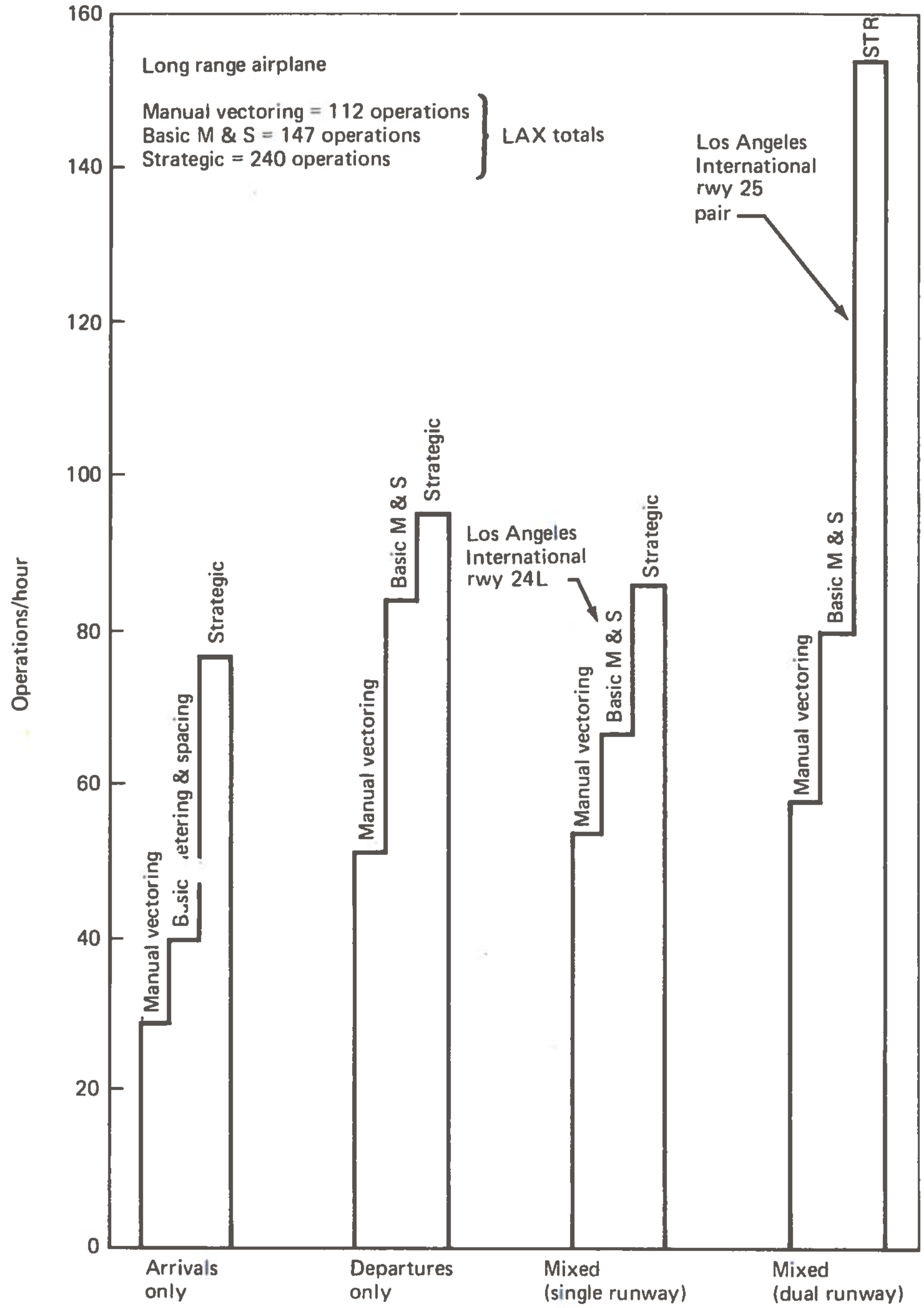


FIGURE 8-3.—OPERATIONS RATE SUMMARY

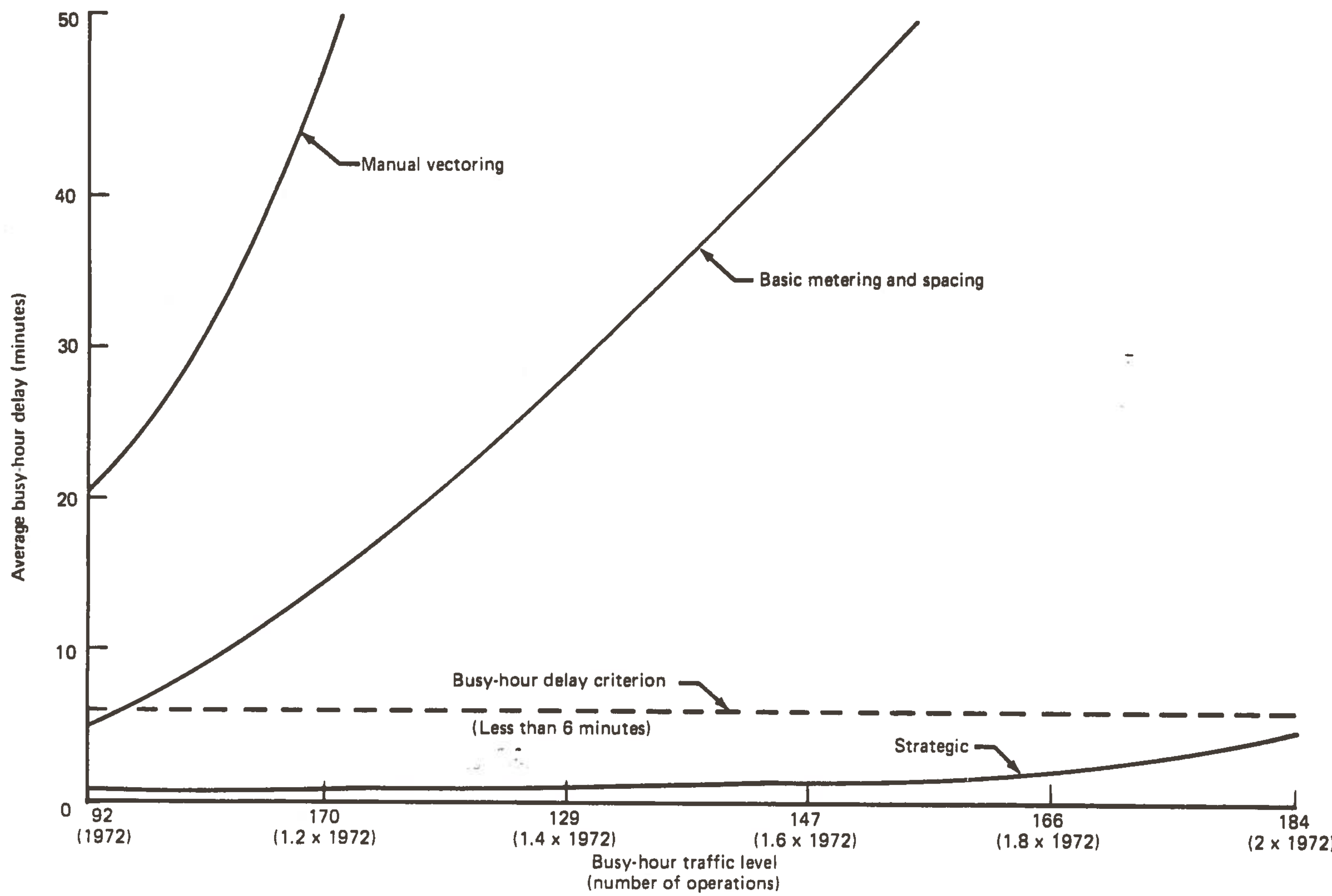


FIGURE 8-4.—BUSY-HOUR DELAY COMPARISON

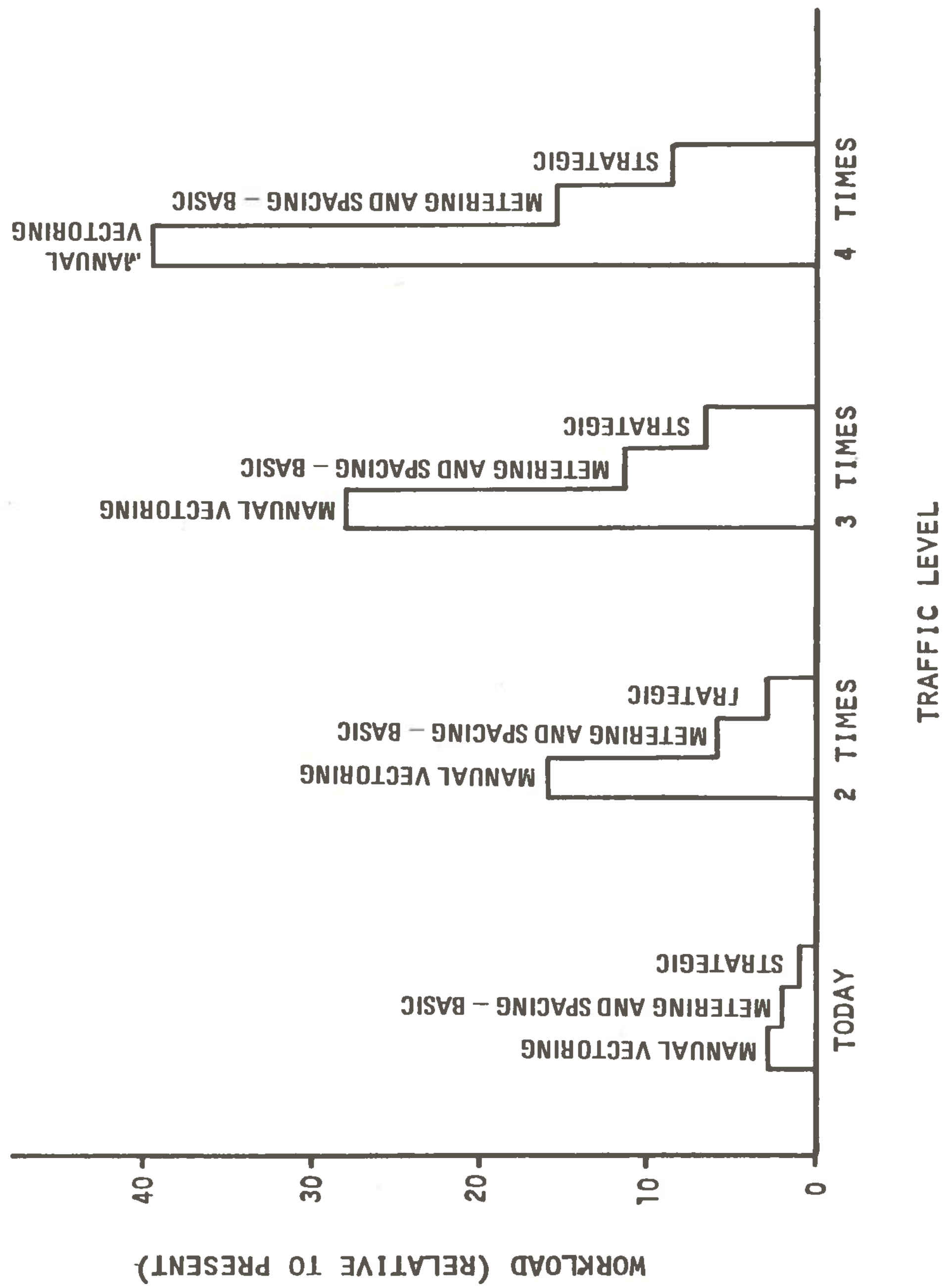


FIGURE 8-5.—RELATIVE WORKLOAD

Figure 8-6 shows the primary inputs and outputs of the capacity analysis and the relationship between the runway analysis and the delay analysis. The delay analysis takes the interoperation times determined in the runway analysis and the forecast demand levels to determine delay statistics. These delay factors are compared with the delay criteria to determine acceptable and unacceptable data sets that have been input.

8.2.1 Runway Capacity

Various definitions of runway capacity have been used in measuring ATC system performance. In this section we are concerned with two measures: runway operations rates and runway interoperation times. Runway operations rates are the number of operations that can be processed per unit time, subject to safety criteria and assuming airplanes are always waiting to be processed. Runway operations rates are determined for arrivals only, departures only, and mixed operations assuming alternating arrivals and departures. The second measure of capacity is interoperation time derived for four operational sequences: an arrival following an arrival, an arrival following a departure, a departure following a departure, and a departure following an arrival. For each operational sequence a mean or average interoperation time is determined subject to safety criteria.

Interoperation times and runway rates are determined for three airplane populations representing a medium range, a long range, and a short range collection of airplanes. These three airplane collections are evaluated assuming three different ATC environments: one representative of today's ATC system (performance, procedures, and separation criteria), one representative of a metering and spacing terminal area ATC system, and an ATC environment representing a strategic control ATC concept. The Los Angeles International Airport (LAX) configuration data is used. Capacity data is developed for both a single runway and a dual-lane or close-spaced parallel runway pair. In all, 18 data sets are derived (three aircraft populations x three ATC concepts x two runway configurations).

The results of the runway analysis are shown in tables 8-4 and 8-5. Table 8-4 gives the mean interoperation times for arrival/arrival, arrival/departure, departure/departure, and departure/arrival spacings. The values in the table are given in seconds. Nine data sets are presented representing three ATC systems and three airplane populations. For the arrival/departure entries two values are given. The first number is the mean interoperation time on a single runway followed by the time on a dual-lane (or close-spaced parallel) runway. Table 8-5 shows runway operations rates for the same nine data sets. Operations rates are given for arrivals only, departures only, mixed arrivals and departures on a single runway, and mixed operations on a dual-lane runway. The mixed operations rates are based on alternating arrivals and departures.

The three ATC systems are characterized by performance parameters and separation criteria. Three parameters are used in describing ATC performance. The outer marker delivery error for arrival control performance is assumed to be 18 seconds (one sigma) for today's ATC system, 8 seconds for metering and spacing, and 2 seconds for strategic control. The values of the outer marker delivery error for the metering and spacing and the strategic ATC systems are based on analyses conducted on the Boeing fourth-generation ATC system study. The 8-second metering and spacing number is representative of the results of the terminal area simulation model (ref. 8-4). The 2-second strategic control

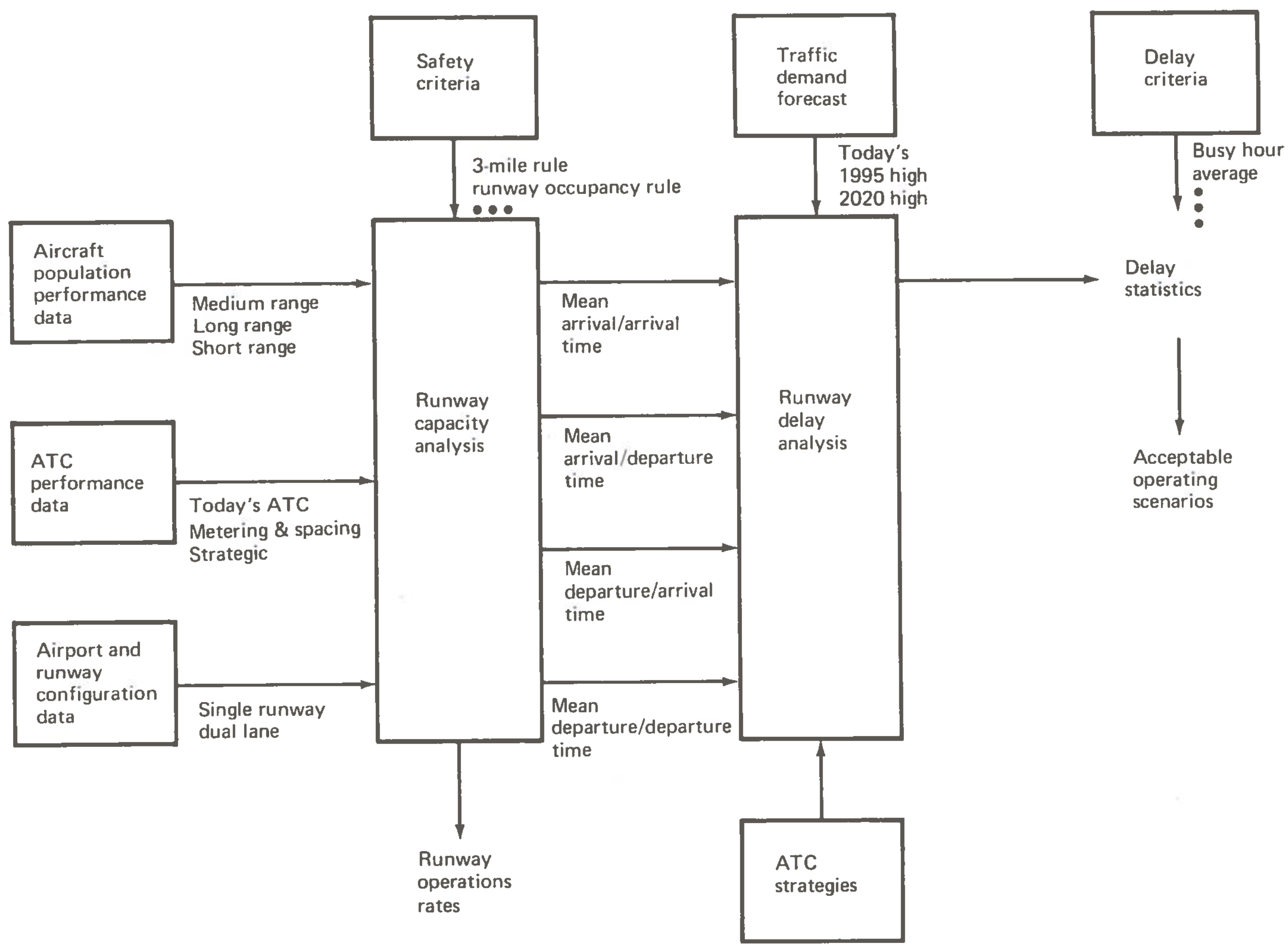


FIGURE 8-6.—CAPACITY ANALYSIS INPUTS AND OUTPUTS

TABLE 8-4.—MEAN INTEROPERATION TIMES SUMMARY

ATC system	Operation	Preceding operation	ATC rule	Mean interoperation time—seconds		
				Medium range	Long range	Short range
Manual vectoring	Arrival	Arrival	3 miles	140	124	151
	Arrival	Departure	2 miles	87/34	63/23	76/40
	Departure	Departure	1 minute	70	70	70
	Departure	Arrival	1 minute	70	70	70
Basic metering and spacing	Arrival	Arrival	2.5 miles	104	90	116
	Arrival	Departure	Runway occupancy	80/27	64/24	66/30
	Departure	Departure	6000 foot	48	43	43
	Departure	Arrival	6000 foot	48	43	43
Strategic	Arrival	Arrival	Runway occupancy	60	47	43
	Arrival	Departure	Runway occupancy	61/8	46/6	41/5
	Departure	Departure	6000 foot	43	38	38
	Departure	Arrival	6000 foot	43	38	38

TABLE 8-5.—RUNWAY OPERATIONS RATE SUMMARY

ATC system	Operating mode	Runway operations rate (operations/hour)		
		Medium range	Long range	Short range
Manual vectoring	Arrivals only	26	29	24
	Departures only	51	51	51
	Mixed-single runway	46	54	48
	Mixed-dual runway	52	58	48
Basic metering and spacing	Arrivals only	35	40	31
	Departures only	75	84	84
	Mixed-single runway	56	67	62
	Mixed-dual runway	70	80	62
Strategic	Arrivals only	60	77	84
	Departures only	84	95	95
	Mixed-single runway	69	86	91
	Mixed-dual runway	120	154	167

arrival error is based on the airborne navigation guidance and control performance data derived in the fourth-generation study (ref. 8-5). The departure control performance is characterized by the mean and standard deviation of the response time distribution. Values assumed are 10 seconds and 2 seconds (one sigma) for today's ATC system, 5 seconds and 1 second (one sigma) for M&S, and negligible time for the strategic system.

Corresponding changes in ATC rules allowing closer spacings but requiring increased probability of conformance are assumed. The rules for each operational sequence and ATC system are given in table 8-4. Conformance with the in-air separation criteria are assumed at the 95% level and with the runway occupancy criteria at the 99% level. The critical arrival/arrival spacing is assumed to drop from 3 nautical miles in-air spacing with today's ATC system, to 2.5 nautical miles for the metering and spacing system, to the no-joint runway occupancy criteria for the strategic control system. The controller workload inherent in the tactical metering and spacing of arrivals should preclude a substantial decrease in in-air separation (with corresponding increase in arrival throughput rate). The controller workload limitation would not constrain the strategic system.

Three airplane populations are assumed corresponding to a medium-range, a long-range, and a short-range fleet. The medium-range fleet is typified by today's commercial fleet. A medium approach velocity (115 knots average) and 6 ft/sec^2 runway deceleration rate are assumed. The long-range fleet is characterized by higher approach velocities (135 knots average) and improved performance (deceleration of 12 ft/sec^2). The short-range fleet combined a low approach speed (average 105 knots) and a high deceleration rate (12 ft/sec^2) to allow rapid runway exit.

Other parameters required for the derivation of interoperation times are detailed in section 8.5.1. These include time to brake and turn off the runway for arrivals and time to the 6000-foot point (longitudinal distance measured from the brake release point) for departures. Values used in this analysis were:

Parameter	Medium range	Long range	Short range
Arrival time on runway	53 sec	40 sec	36 sec
Departure time to 6000 ft	43 sec	38 sec	38 sec

The values quoted in table 8-5 are the mean or average interoperation times for the particular ATC system, airplane fleet, and operational sequence. In some cases, particularly for dual-runway operations, the sum of the arrival/departure and departure/arrival times is less than the arrival/arrival spacing. In these cases the true constraint on the mixed operations capacity is the arrival/arrival separation criteria. The runway operations rates cited in table 8-5 are assumed in such cases to be twice the arrivals-only operations rate. One departure is inserted between arrival/arrival pairs.

Figure 8-7 shows a plot of the derived runway operations rates for the nine data sets. Composite values of the associated interoperation times (averaged over the four operational sequences and three airplane fleet assumptions) are listed in table 8-6.

Figure 8-7 assumes equal numbers of the three airplane types and the arrival/departure sequence.

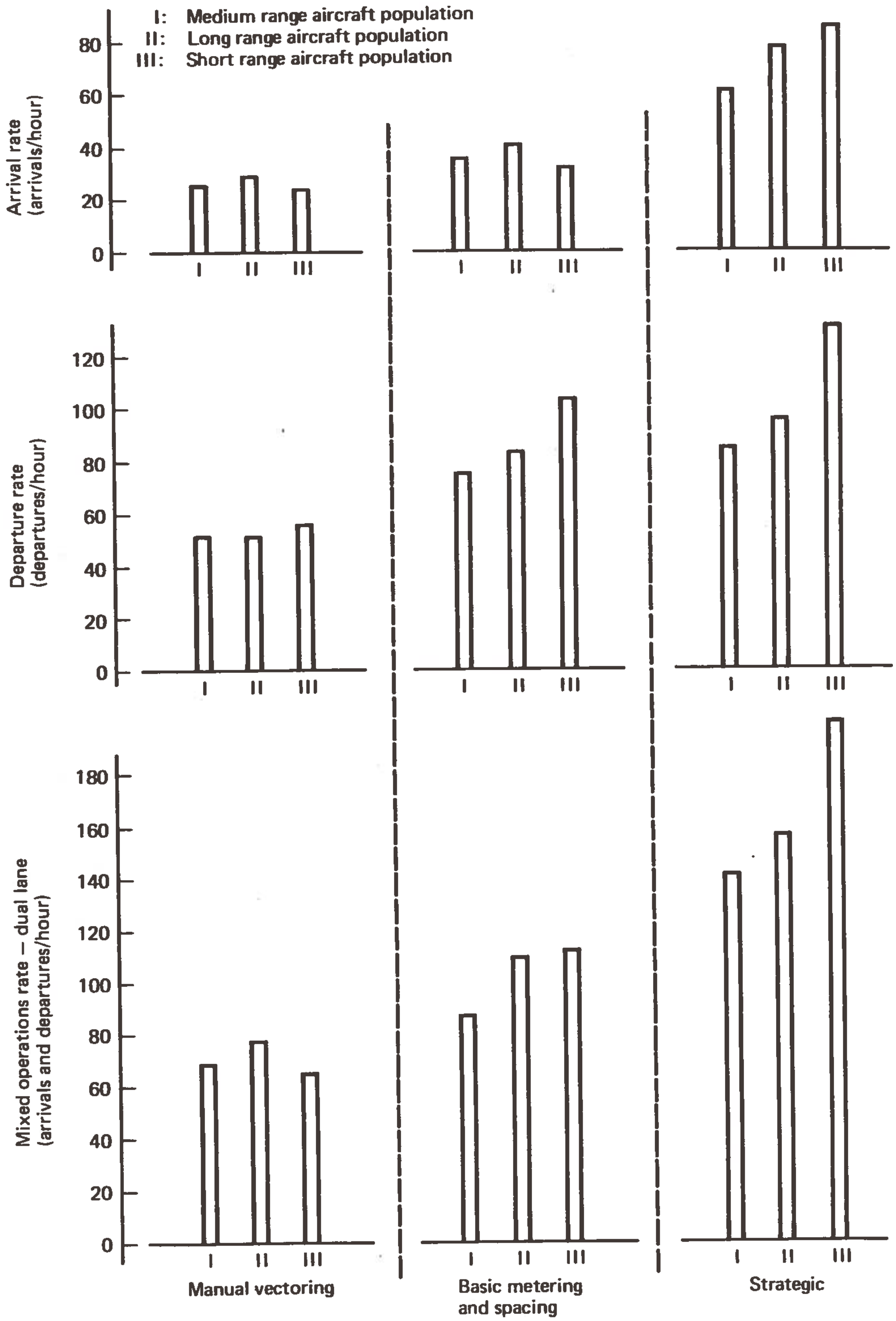


FIGURE 8-7.—RUNWAY OPERATIONS RATES

TABLE 8-6.—AIRPLANE INTEROPERATION TIMES

Operational concept	Runway type	
	Single	Dual
Manual vectoring	88 sec	78 sec
Basic metering and spacing	65 sec	55 sec
Strategic	45 sec	35 sec

8.2.2 Delay Analysis

Results of running a simulation model (AIRSIM; described in sec. 8.5.2) developed by Boeing show that significant reductions in delay can be obtained by using the strategic control concept at Los Angeles International Airport. The delay reduction calculated is only that obtainable by the increased operations rates reported in the previous section. Gains resulting from other factors inherent in strategic control (rescheduling, path length reductions, etc.) are not included in this analysis.

The model used calculates the delay as that time that the operation (arrival or departure) must wait due to use of the airport by other operations. It is equal to the time of actual operation minus the time at which the operation was ready. The delay will be zero if a runway is available for use at the time the operation is ready. In actual practice today, delay is often measured as holding delay (delays inherent in speed control, vectoring, etc., are not counted). The model includes all these as delays and so produces higher averages than some statistics obtainable. However, delay measured by the model does agree with the delay as defined in reference 8-6. "Time difference between actual time from landing approach fix and wheels on to the minimum such time interval."

This part of the study combines the operations rates with the demand and ATC operation to determine the delay.

8.2.2.1 Demand

The demand inputs to this work are two: The Los Angeles International Airport (LAX) schedules and the mix of airplanes. The basis for both of these inputs is supplied by reference 8-6, which describes the operational environment for 1995.

The airplane types from this reference were categorized as long, medium, and short range. Table 8-7 shows the assumed airplane ranges and approach velocities; also shown are the relative percentages of these types for the future U.S. domestic fleet and a mix derived from the present traffic statistics at LAX. The latter is derived using the ranges of the flights in a 1972 schedule of operations at LAX. The 1972 mix was used for the present-day traffic demand and the other mix was used for the future demand levels.

The demand levels are obtained by scaling up the 1972 LAX schedule to four additional levels in the ratio of the predicted future fleet size as shown in table 8-8. These demand levels are then run through the delay model operating to represent LAX under IFR conditions.

TABLE 8-7.—AIRPLANE MIX

Airplane type	Range (miles)	Landing speed (miles per hour)	Percentage	
			Future	*LAX-1972
Long range	2000	160	14.2	35.2
Medium range	200-2000	120-140	57.2	41.8
Short range	200	110-125	28.6	23.0

*Los Angeles International

TABLE 8-8.—PREDICTED FLEET SIZES

Year	Fleet size	Scale factor
1972	2700	1.0
Low 1995	5000	1.86
Medium 1995 Low 2020	7000	2.58
High 1995 Medium 2020	9500	3.52
High 2020	14000	5.20

8.2.2.2 ATC Operation

To establish the rules and procedures used in the model, operations at LAX were observed.

The layout of Los Angeles International consists of five parallel runways but, for practical purposes, LAX can be regarded as two pairs of parallel runways since runway 26 is restricted to light general aviation aircraft and is used only infrequently. The general operational concept is that aircraft arriving from or departing to the north operate with runways 24R and 24L and airplanes arriving from or departing in a southerly direction operate (under a separate controller) with 25R and 25L. However, as 25R/L is not stressed for airplanes over 350,000 pounds, this means that jets such as the Boeing 747 cannot use the 25 complex and it can be used by other wide-body airplanes only at light weight. Additionally, 24R is restricted under VFR weather to operation by light piston airplanes and cannot be used by jets due to sideline noise restrictions.

When the weather permits, all arriving airplanes are allowed to make visual approaches. As the weather deteriorates jets still use the three southern runways (24L, 25R, 25L) with sequencing and spacing coordinated by the air traffic controllers. With actual IFR weather, however, all four runways are used. Departures are conducted from 24L and 25R and simultaneous independent arrivals are allowed on 24R and 25L. Under such weather conditions the noise restrictions on 24R are overruled to satisfy the current spacing requirement of 5000 feet between runway centerlines for parallel independent IFR operations.

This IFR operation serves as the basis for the selection of the rules of operation for the model.

8.2.2.3 Interoperation Times

The interoperation times used are those of the dual-runway case in the preceding section (see table 8-5). These times are modified by two factors. In the case of a sequence of operation arrival/departure/arrival on one runway path the total times would be less than the required arrival/arrival spacing. This violation is accounted for in the delay model by adding time to the arrival/departure spacing. The times selected are also varied in the Monte Carlo simulation by assuming a normally distributed time with a 10% one sigma.

8.2.2.4 Results

The following delay criteria for the advanced (post-1990) ATC system (ref. 8-6, "General Design Characteristics") were used:

- Daily average–less than 3 minutes
- Busy-hour average–less than 6 minutes
- 90% delay–less than 15 minutes (daily)
- 99.9% delay–less than 30 minutes (daily)

Results for these criteria for all cases are given in table 8-9.

The criteria specified apply to the advanced Air Traffic Management system, which is meant to improve the ATC in many areas including those of capacity and delay. The need for improvement is shown by considering that only the strategic concept spacings can satisfy the criteria chosen for the low 1995 demand.

In all of the LAX demand cases the busy-hour average delay of less than 6 minutes was the most difficult criterion to achieve. If this was met the other criteria were also met. As can be seen, by the time traffic reaches the medium 1995 demand level, none of the spacings are sufficient. Therefore, at this level an additional Los Angeles airport (or equivalent at LAX) is indicated.

A comparison of the three concepts for demand levels varying from LAX 1972 to twice that is given in table 8-10. These data are run for the future mix in all cases. It can be seen that only the strategic concept satisfies all criteria. The strategic concept would permit a 100% increase in traffic. Today's system fails all criteria at about a 10% demand level increase. The metering and spacing concept fails all criteria at about a 30% increase in

TABLE 8-9.—DELAY RESULTS

Demand level	Spacing	Delay results (minutes)*			
		Daily average	Busy-hour average	90% less than	99.9% less than
1972	Manual vectoring	3.77	18.02	11.38	25.98
	Basic metering-spacing	1.34	4.02	3.64	13.59
	Strategic	0.13	0.36	0.70	2.89
Low 1995	Manual vectoring	169.52	366	>200	>200
	Basic metering-spacing	61.77	163	140.3	174.4
	Strategic	1.13	3.22	3.54	11.03
Med 1995 Low 2020	Manual vectoring	–	–	–	–
	Basic metering-spacing	–	–	–	–
	Strategic	6.00	27.6	16.1	35.9
High 1995 Med 2020	Manual vectoring	–	–	–	–
	Basic metering-spacing	–	–	–	–
	Strategic	–	–	–	–
High 2020	Manual vectoring	–	–	–	–
	Basic metering-spacing	–	–	–	–
	Strategic	–	–	–	–

*Delay is under IFR operation and is defined as that time greater than the minimum operation time assuming no other traffic

traffic. Figure 8-4 shows that for the busy-hour criterion (less than 6 minutes delay) the failure of the other concepts occurs at a much lower level.

8.3 AIRSPACE ANALYSIS

In this section an analysis of the airspace is performed to compare the concepts in the following four evaluation criteria:

- Number of conflicts
- Control workload
- Airplane economics
- Terminal area flow rates

The method chosen to quantify these criteria is an airspace simulation model developed by Boeing and described in section 8.5.3. The use of the model to generate results is shown in figure 8-8. The inputs to the model are the demand and the airspace structure. The airspace structure is the input that is varied to describe the three concepts being compared.

TABLE 8-10.—DELAY RESULTS (1972 INCREMENTS)

Demand level	Spacing	Delay results (minutes)*			
		Daily average	Busy-hour average	90% less than	99.9% less than
1972	Manual vectoring Basic metering-spacing Strategic	4.16 1.49 0.15	20.50 4.50 0.41	13.12 4.12 0.74	27.65 14.14 2.78
1.13 x 1972	Manual vectoring Basic metering-spacing Strategic	7.84 2.53 0.25	35.86 10.22 0.64	23.59 6.87 0.98	44.92 36.89 4.67
1.30 x 1972	Manual vectoring Basic metering-spacing Strategic	33.93 4.25 0.39	95.0 21.8 1.04	84.50 13.42 1.30	111.20 29.62 6.25
1.69 x 1972	Manual vectoring Basic metering-spacing Strategic	129.46 15.48 0.68	286.4 52.3 1.78	>200 39.56 4.12	>200 63.42 9.20
1.86 x 1972	Manual vectoring Basic metering-spacing Strategic	169.52 61.77 1.13	366.0 163.0 3.22	>200 140.3 3.54	>200 174.4 11.03
2.00 x 1972	Manual vectoring Basic metering-spacing Strategic	179.47 72.69 1.54	389.0 195.7 5.13	>200 164.6 5.09	>200 >200 13.44

*Delay is under IFR operations and is defined as that time greater than the minimum operation time assuming no other traffic.

8.3.1 Airspace Structure

This section provides the background used to obtain the results. Assumptions used as input to the model about the airspace and its operation are described. The present structure, the assumed metering and spacing structure, and the strategic concept structure used in the algorithm evaluation model are described.

The input required for the structure description is the following:

- Airport locations (latitude, longitude)
- Runway locations (latitude, longitude)
- TMA entry points (latitude, longitude)

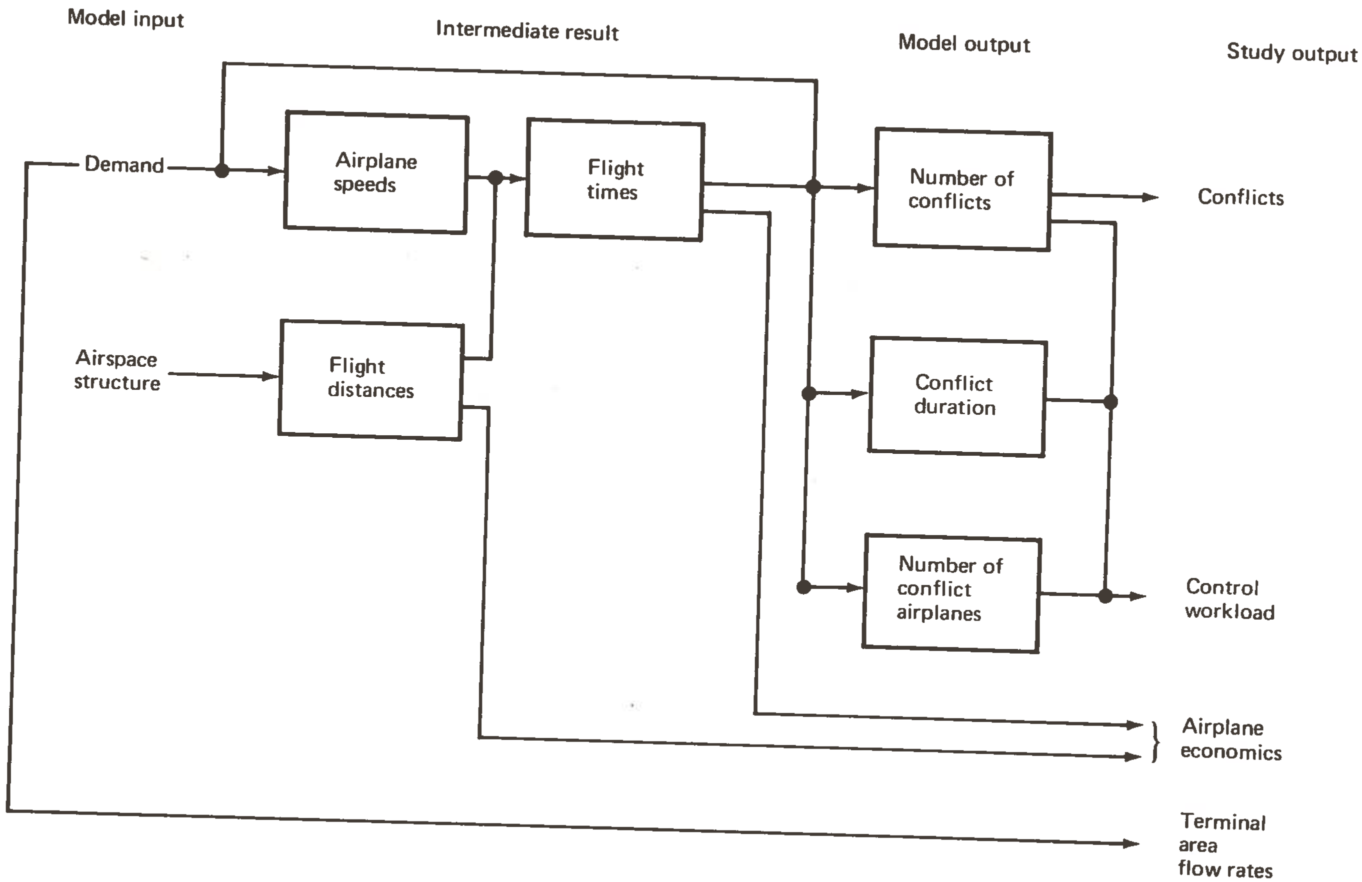


FIGURE 8-8.—GENERATION OF STUDY OUTPUTS

- TMA exit points (latitude, longitude)
- Waypoint locations (latitude, longitude)
- Track description including altitude constraints

Presently, spacing and sequencing of Los Angeles traffic is achieved by speed control and vectoring. The system works well at present traffic levels because of the long path lengths available for speed control and because sector coordination allows flexibility in the use of airspace for vectoring. Figure 8-9 is drawn to represent the present nominal LAX arrival and departure paths (west flow). These nominal paths are relatively direct from the airplane operator's viewpoint, but are frequently not followed because of ATC vectoring. The area of the TCA (terminal control area) is shaded in figure 8-9 indicating the amount of airspace protected for the manual vectoring operation.

This layout is used to specify the present day airspace structure. The model contains 19 airports, 17 entry and/or exit points, and 51 waypoints connecting the entry/exit points to the two LAX runways. Fifteen arrival tracks and 11 departure tracks are defined. The demand is allocated to these tracks dependent on the city of origination or destination. A radius of 150 nautical miles from LAX is used to contain this structure. Present day altitude restrictions are imposed along the tracks.

Figure 8-10 shows the assumed application of the basic metering and spacing concept to LAX. With this system airspace is reserved within the terminal area for adjustment in the sequencing and base leg areas by means of path altering. The figure shows nominal paths bracketed by the airspace needed for adjustments of ±2 minutes in sequencing areas and 1 minute in base leg areas at reasonable jet airplane speeds. In implementing this structure in the model the present day entry points are maintained. All flights are assumed to fly VOR-oriented paths to the four fixes shown feeding the spacing adjustment areas.

Figure 8-11 represents the strategic concept geometry. In this structure each entry point of the present structure is fed along VOR radials to one of the three fixes shown (IAF1, IAF2, IAF4).

These structures are maintained in all of the following work described. Although the model handles both arrivals and departures, only the arrival routes are analyzed because of the lack of detailed design of the metering and spacing and strategic departure tracks.

8.3.2 Economic Analysis

The initial output of the model is a measurement of the distance, time, and number of flights flown on each track input to the model. The distances are calculated in nautical miles taking into account the Los Angeles area geography. Altitude changes are included. The flying times are determined using the assigned flight profiles and airplane types to specify speeds. The differences in the three concepts are determined by the track structures required to accommodate the different separation methods.

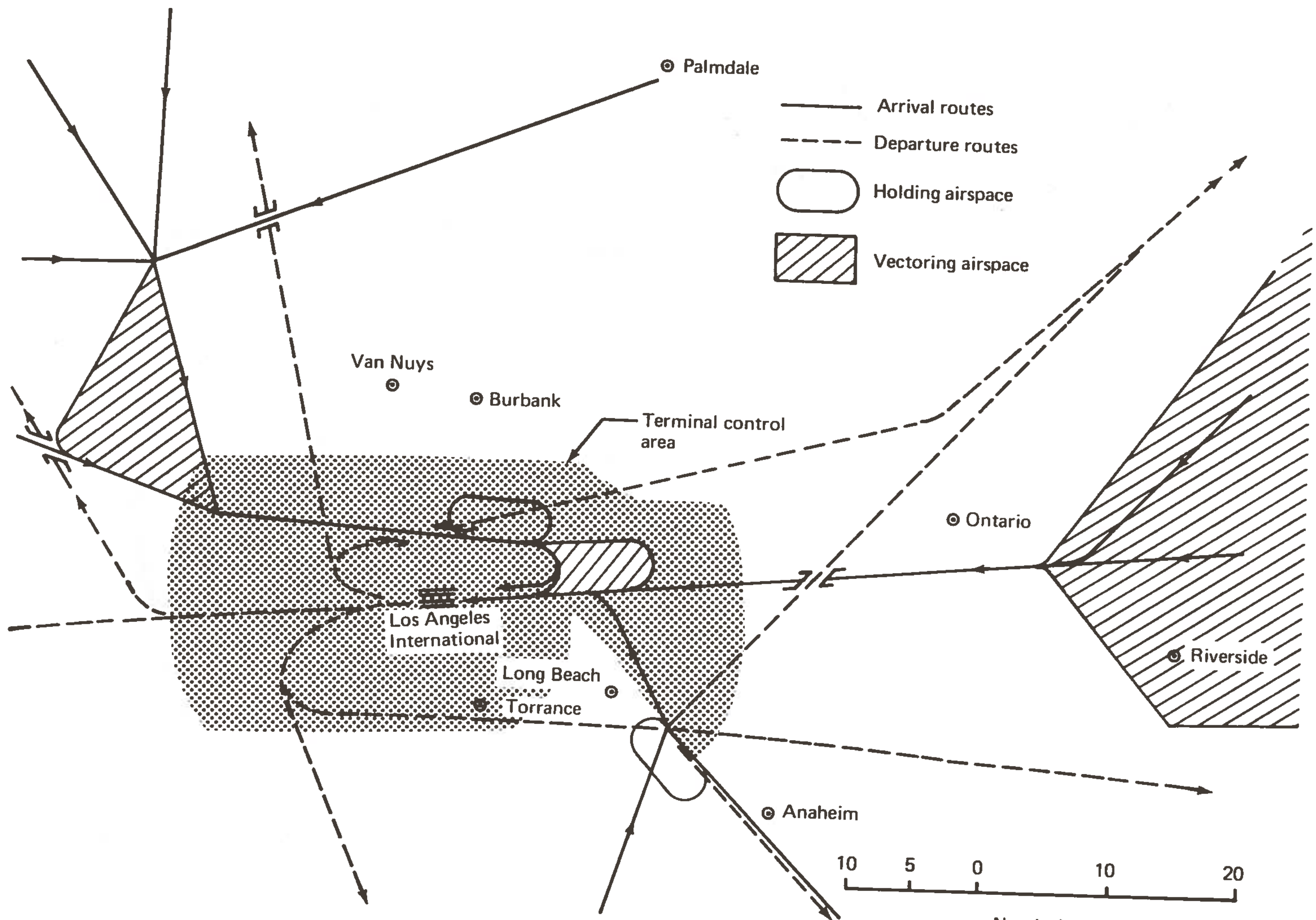


FIGURE 8-9.—PRESENT PROCEDURES LOS ANGELES INTERNATIONAL ROUTING—WEST FLOW

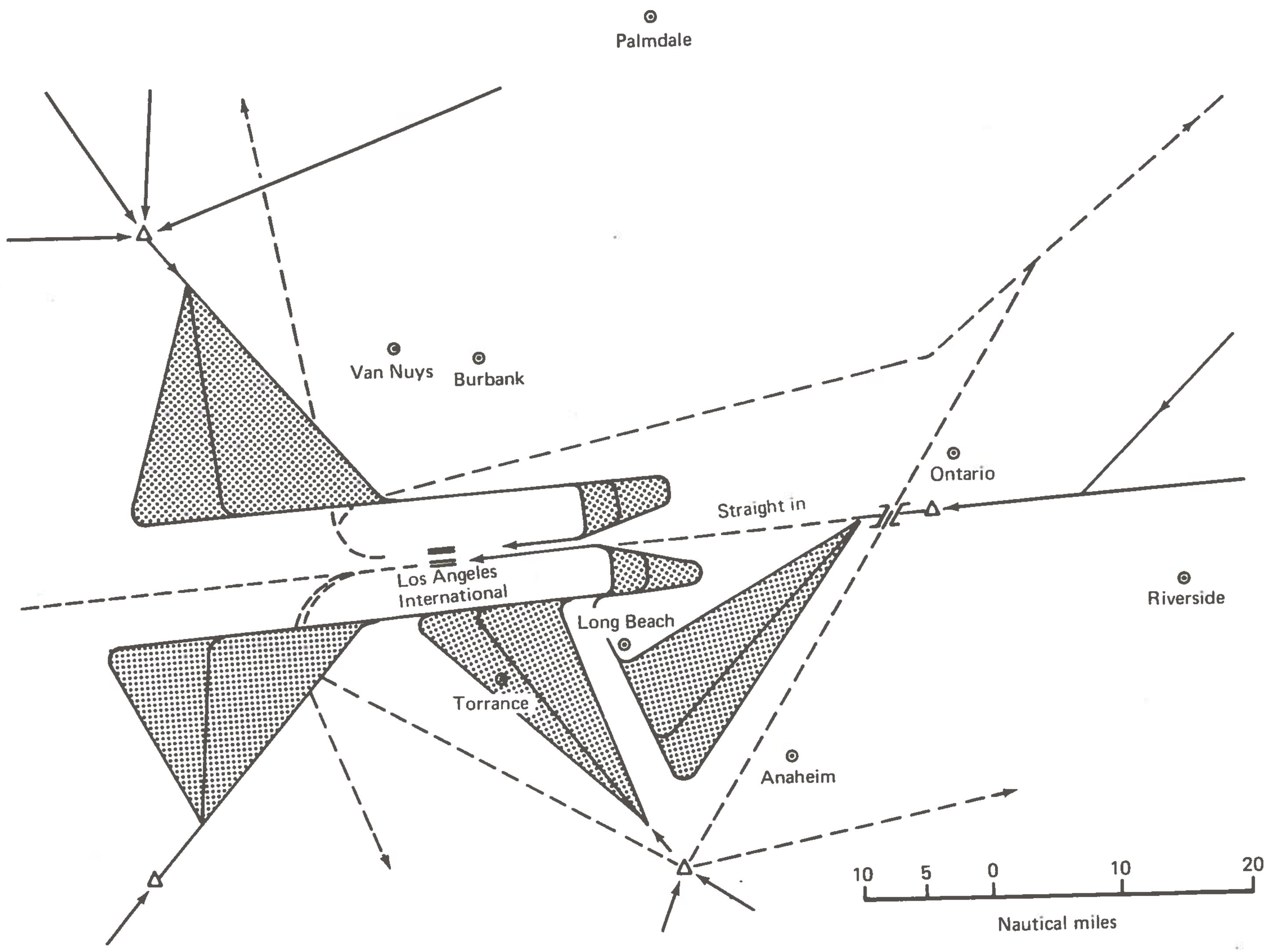


FIGURE 8-10.–METERING AND SPACING FOR LOS ANGELES INTERNATIONAL

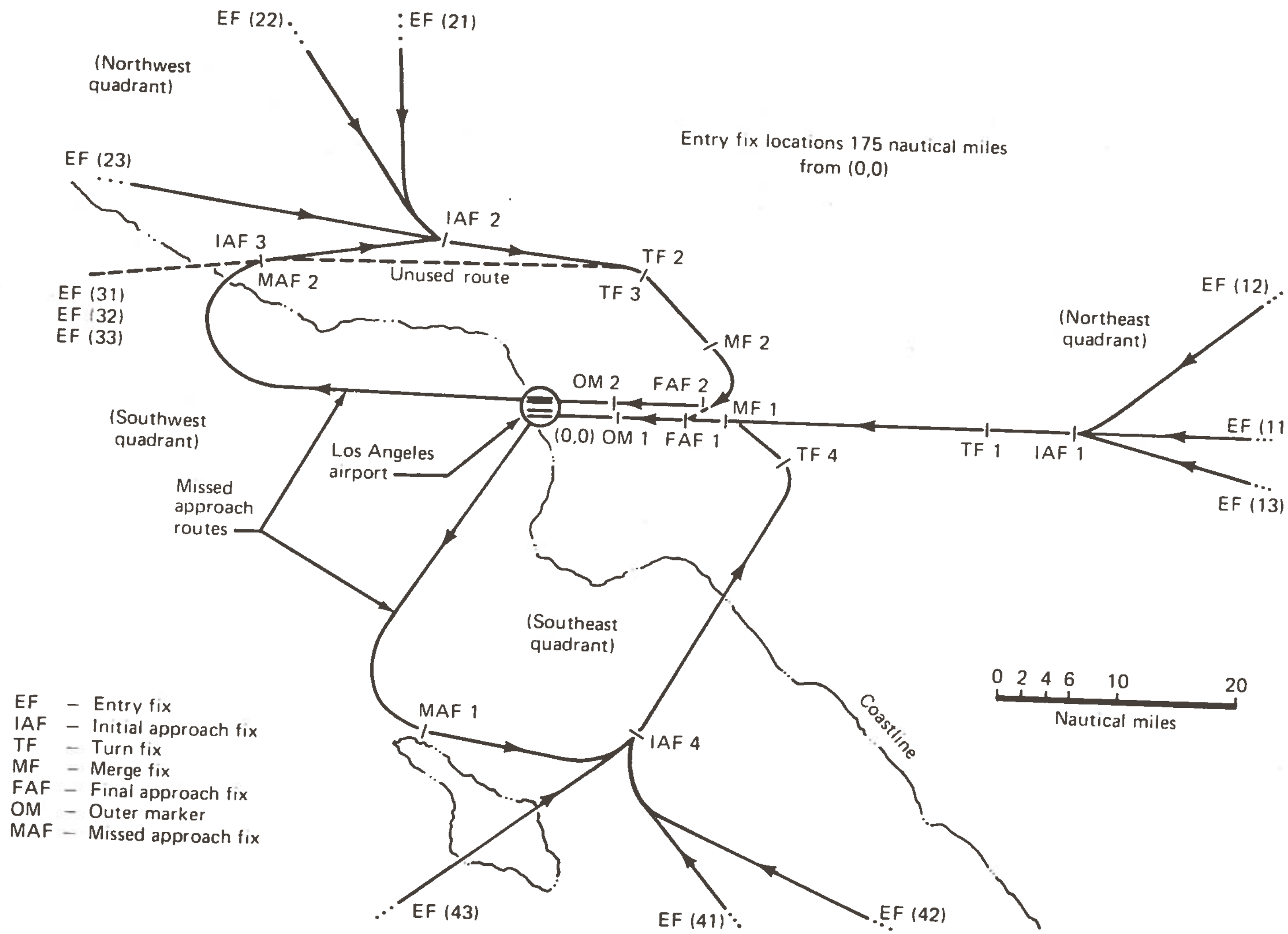


FIGURE 8-11.—LOS ANGELES STRATEGIC ARRIVAL GEOMETRY

In the present manual vectoring system separation is accomplished by holding stacks, by controlling speed along the present VOR-oriented tracks, and by vectoring airplanes away from other airplanes. The present nominal track structure along the VORs at a radius of 150 nautical miles from LAX has an average track length of 164 nautical miles; average flight time is 47 minutes. These figures are weighted averages based on percent of flights flown on each track. The average flight would be longer than this depending on the amount of vectoring required by reason of the other traffic.

To describe the basic metering and spacing concept it is assumed that each track has a path-stretching segment contained within that permits adjustment in arrival times for separation purposes. Airplanes fly the VOR radials from the terminal area entry points to the path-stretching segment. The nominal track is flown within the path-stretching segment. This track structure measures 186 nautical miles and 49 minutes (weighted).

The strategic concept feeds separated traffic to the three initial fixes shown in figure 8-11. The airplanes fly VOR radials to these points. This results in an average track length of 167 nautical miles and 44 minutes flying time.

The results show that the nominal track length for a metering and spacing system would be 19 nautical miles and 5 minutes greater than the strategic track length. This savings would be applied to every approach. By extrapolation to future traffic schedules the busy-day economic savings shown in table 8-11 are obtained.

TABLE 8-11.—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

8.3.3 Conflicts

A conflict is defined as a violation of the specified separation standards. All of the concepts compared are designed to prevent the occurrence of these violations by detecting situations that might lead to a conflict. In the present system the controller monitors the flightpaths and projects them to detect potential conflict situations (conflict prediction). He has available several means of resolving these potential conflicts including holding when the traffic situation becomes too heavy. It was assumed that under the metering and spacing concept the capability will be developed to avoid the heavy traffic problem by metering airplanes into the terminal area at a rate consistent with the separation requirements.

Path-stretching maneuvers resolve potential conflicts inside the terminal area. These systems may be called tactical in that potential conflicts are detected and acted upon in real time based on information obtained during the actual situation being resolved.

The strategic concept avoids potential conflict situations and the necessity for conflict predictions entirely by assigning conflict-free paths to all airplanes immediately upon entry into the system.

In summary, in all the concepts actual conflicts occur only when the operation of the system does not conform to the theoretical concept. Because of this in comparing the systems it is more meaningful to compare potential conflicts. As discussed above, resolving these potential conflicts is the major function of the present ATC system and of the metering and spacing concept. The strategic concept admits to no potential conflicts.

Therefore, the number of conflicts occurring in theoretical systems based on each of the three concepts would be zero. A comparison of potential conflicts would be meaningful in the manual vectoring and the basic metering and spacing (M&S) concepts but would show no potential conflicts in the strategic system.

The model used in this analysis to quantify this criterion measures conflicts but does not resolve them. It counts the conflicts that would occur if no action were taken. In this sense the results obtained do show the amount of intervention required using the manual vectoring system and the basic metering and spacing concept. Following the previous discussion the results for the strategic concept only indicate the level of complexity involved in determining the conflict-free tracks.

The number of conflicts obtained for each traffic level and for the three concepts are shown in table 8-12 and figure 8-12. These were obtained by using the track structures described and keeping all other inputs including the demand the same. As the traffic level was increased no holding strategies were implemented. However, the traffic was separated at each entry fix so that conflicts did not occur at these points. The results shown are for a full day's traffic. The conflict levels selected for comparison are consistent with today's terminal area separations and with the single runway occupancy separations discussed in section 8.2.1 (88 seconds today, 65 seconds for metering and spacing, and 45 seconds for strategic control).

TABLE 8-12.—CONFLICT RESULTS

Traffic level	Number of potential conflicts (daily)		
	Manual vectoring	Basic metering and spacing	Strategic
1972	228	150	91
2X	1508	569	288
3X	3035	1142	556
4X	3979	1435	680

Note:

For the tactical concepts (manual vectoring and basic metering spacing) results indicate the number of interventions required. For the strategic concept the results indicate the level of complexity required in assigning conflict free tracks.

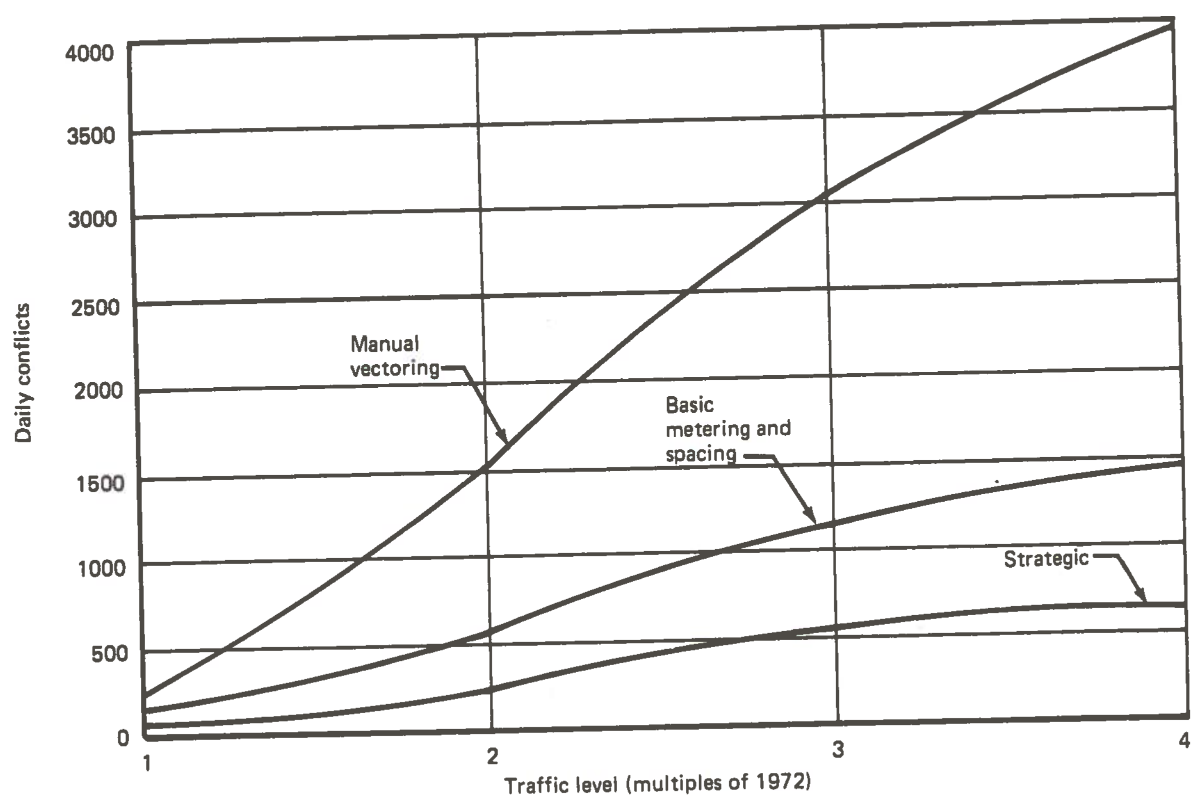


FIGURE 8-12.—CONFLICTS VS TRAFFIC

8.3.4 Control Workload

There is no generally acceptable definition of control workload in absolute terms. Presently, controllers can handle 10 to 15 airplanes at the same time. This limit is caused by the communications loading, airspace complexity, conflict situations, and other factors. For purposes of this study the conflict situation is used to develop a relative workload measure of the three concepts.

The measures of workload produced by the model used in the preceding section that are applicable in this context are the number of conflicts, their duration, and the number of airplanes involved. It can be seen that all of these factors influence the work involved in resolution. In order to obtain one total measure of workload the separate results of the model are compared in table 8-13 to one another using the 1972 manual vectoring concept as a base value (100%). Percentage improvements over this value are shown for the other concepts and demand years. In the total column the percentage improvement of the separate results is added together and divided by three. The results of this exercise are shown in table 8-13. This shows that strategic control has one third the workload of the manual vectoring except for 1972 traffic and 20% of the workload for high demand loads.

TABLE 8-13.—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

8.3.5 Terminal Area Flow Rates

Flow rates in the terminal area are basically a function of the required separation standards, the track structure, and the controller workload. The results discussed in the preceding sections indicate that for some safety levels and airport numbers metering and spacing flow rates can be about 30% higher and strategic flow rates can be 100% higher.

8.4 COMMUNICATIONS ANALYSIS

The strategic control concept minimizes communications loading in the terminal area by assigning tracks to the airplanes that require no further instructions issued to avoid potential conflicts. The control job then becomes one of monitoring the airplanes to determine that the actual tracks are within safe tolerances of the assigned tracks. The concept is designed so that deviations requiring action on the part of ATC are infrequent, thereby reducing communications.

The basis for comparison of the various concepts is the type and frequency of approach control communications today. Information in reference 8-7 is used to obtain these data. Selected types of these messages are assumed to be eliminated or their frequency reduced by the metering and spacing concept and the strategic concept. Table 8-14 summarizes the results of this exercise. The messages selected for comparison (approximately 75% of the total) are shown. These messages are those that are most likely to be affected by the concept changes.

TABLE 8-14.—MESSAGE STRUCTURE COMPARISON

Message types (ref. 8-3)		Approach control statistics			
		Contact length (sec)	Messages per flight: Manual vectoring	Messages per flight: Basic M&S	Messages per flight: Strategic
ATC instructions	Vectoring	5.3	3.13	2	1 (at EF)
	Holding	5.2		1	
	Altitude control	6.7	1.94		
	Speed control	5.2	0.77		
	Clearance	7.9	1.63	1 (at IAF)	
Comm. support	Report in	3.4	1.01		
	Beacon control	4.1	0.52		
	Hand-off	6.3	1.07		
ATC support	Position report	5.2	2.19	ATCRBS	2.19
	Altitude report	3.7	3.32	ATCRBS	
	Vector/speed report	7.8	0.94	ARTS III	
Advisory	Traffic	10.9	0.61		
	Airplane status	3.5			
	Weather	11.9	1.08		
	Airport status	7.0			

IAF = initial approach fix
EF = entry fix

Under the heading "ATC instructions" the vectoring messages are reduced to two for the metering and spacing concept. This assumes two terminal area points at which time-to-turn instructions are issued to the airplanes. It is further assumed that the M&S type system eliminates the need for clearance control type messages, but that altitude and speed control messages are unchanged. The strategic concept includes no vectors and one message is required to supply the airplane with its entire terminal area track.

For the ATC support type messages, no change is assumed for the metering and spacing concept. The strategic concept includes altitude and speed within the position report messages that are assumed to maintain the same frequency as today.

Having specified the frequency and contact length for each concept, next the total communications loading is determined as a function of concept and demand year. The busy-hour number of arrivals multiplies the contact length and messages per airplane to obtain the total busy-hour load for each message. These results are presented in tables 8-15 and 8-16. Finally, the total loading for each concept by demand year is shown in table 8-17.

If we assume a 90% load factor for each communications channel, the number of channels (or controllers) required for communications alone is shown in table 8-18. The strategic concept is able to reduce this requirement to one half of today's requirement.

It is recognized that arrival control today uses more than two channels and that strategic control (and metering and spacing at some time) will use a digital data link. However, it is felt this analysis does make the point that strategic control significantly reduces the communications load, especially as it reflects on controller workload.

8.5 DERIVATIONS

This section contains the descriptions and/or derivations of the various models and equations used in the preceding results.

8.5.1 Interoperation Times

The development of the interoperation times for takeoffs and arrivals and corresponding runway operations rates are based on a composite of empirical data, analyses, and computer model results. Simple analytic models have been developed to specify the mean values of interoperation time statistics for arrival/arrival, arrival/departure, departure/departure, and departure/arrival pairs.

The principal factors considered in the development of interoperation times are shown in figure 8-13. The landing factors include the distribution of approach speeds, the final approach length, the outer marker delivery accuracy, and the time on the runway. The takeoff factors include the response time distributions for departure control and pilot, the distribution of takeoff weights, and the time to liftoff and 6000 feet (longitudinal distance from brake release point) as a function of gross takeoff weights. Separation criteria between successive operations and criteria violation frequency are also required.

The determination of interoperation times requires careful definition of the beginning the end of each operation. For a landing following a landing we define the interoperation time interval as beginning when the leading airplane exits the runway and ending when the following airplane exits the runway. For a landing following a departure we define the

TABLE 8-15.–COMMUNICATIONS LOADING–LOW TRAFFIC LEVELS

Message types	Communications loading (min./busy-hour)								
	1972			Low 1995			Low 2020, Med 1995		
	Manual vectoring	Basic M&S	Str.	Manual vectoring	Basic M&S	Str.	Manual vectoring	Basic M&S	Str.
Vectoring	18.2	11.7		33.7	21.7		47.0	30.2	
Altitude control	14.3	14.3		26.6	26.6		36.9	36.9	
Speed control	4.4	4.4		8.2	8.2		11.4	11.4	
Clearance	14.2		11.0	26.5		20.4	36.5		28.4
Position report	12.5	12.5	12.5	23.3	23.3	23.3	32.3	32.3	32.3
Altitude report	13.5	13.5		25.1	25.1		34.9	34.9	
Vector/speed report	8.1	8.1		15.1	15.1		20.9	20.9	
Other messages	28.4	28.4	28.4	52.8	52.8	52.8	73.2	73.2	73.2

TABLE 8-16.–COMMUNICATIONS LOADING–HIGH TRAFFIC LEVELS

Message types	Communications loading (min/busy-hour)					
	High 1995, Med 2020			High 2020		
	Manual vectoring	Basic M&S	Str.	Manual vectoring	Basic M&S	Str.
Vectoring	64.1	41.2		94.6	60.9	
Altitude control	50.3	50.3		74.3	74.3	
Speed control	15.5	15.5		22.9	22.9	
Clearance	50.0		38.7	73.9		57.2
Position report	44.0	44.0	44.0	65.0	65.0	65.0
Altitude report	47.5	47.5		70.2	70.2	
Vector/speed report	28.5	28.5		42.1	42.1	
Other messages	100.0	100.0	100.0	147.7	147.7	147.7

TABLE 8-17.–TOTAL COMMUNICATIONS LOADING

Demand year	Number of busy-hour arrivals	Total communications loading (hours per busy-hour)		
		Manual vectoring	Metering & spacing (basic)	Strategic
1972	66	1.89	1.55	0.87
Low 1995	124	3.52	2.88	1.62
Med 1995, Low 2020	175	4.88	4.00	2.25
High 1995, Med 2020	241	6.65	5.46	3.06
High 2020	341	9.84	8.09	4.53

TABLE 8-18.—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.

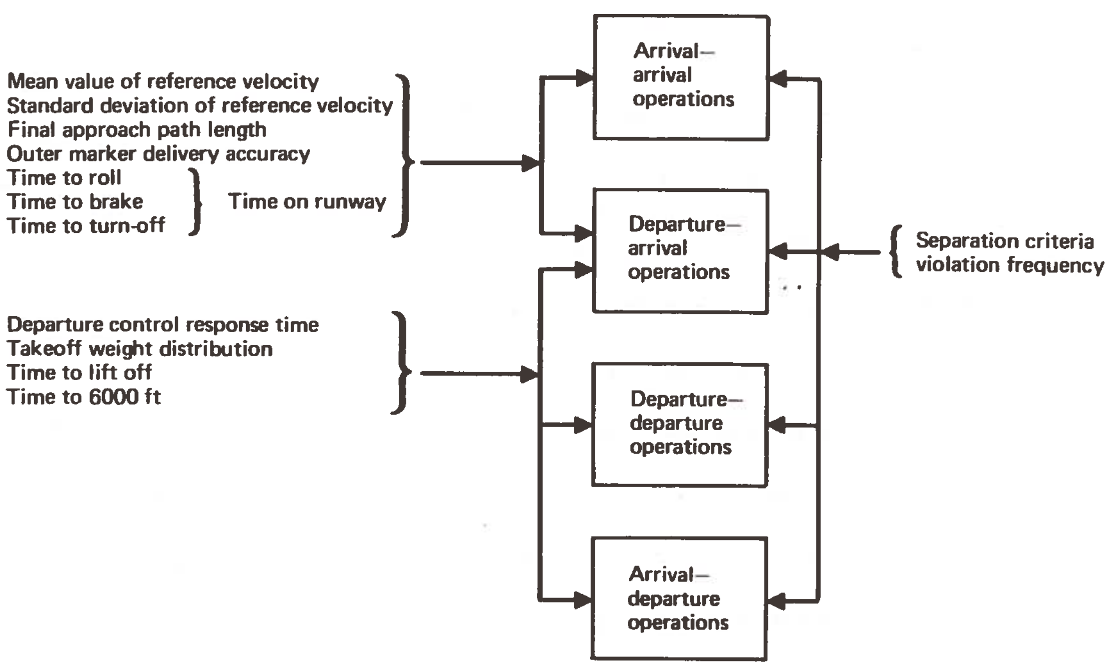


FIGURE 8-13.—PRINCIPAL FACTORS IN DEVELOPING INTEROPERATION TIMES

interoperation time interval as beginning when the departing airplane reaches a constraint release point (60 seconds, or 6000 feet and airborne, etc.) and ending when the following arrival turns off the runway. This definition is modified for a dual-runway operation where the interval ends when the following arrival touches down. For a departure following a departure the interoperation time is measured from the leading departure constraint release point to the following departure constraint release point. The interoperation time interval for a departure following an arrival is defined from the arrival runway exit to the subsequent departure reaching the constraint release point. Again for dual runways the interval is defined as beginning at the leading arrival touchdown point.

If we were to take one of these operational pairs, say arrival/arrival, and measure the time intervals for a landing stream of airplanes, we could assemble a distribution of interoperation times. The mean (or average) value of this distribution is what we have estimated in section 8.2.1.

The derivation of the interoperation times is based on the following specified formulas. The specific safety criteria and performance values used in derivations are those of section 8.2.1. The derivation assumes normal distributions for VREF, outer marker delivery accuracy, takeoff weights, and departure control response times. The special case of the dual-lane runway operations is also discussed in the following.

8.5.1.1 Arrival/Arrival Spacing Factors

Let

TNOM = nominal time separation required to satisfy safety criteria

DS = in-air distance separation

MV = mean approach velocity

SV = standard deviation of approach velocity distribution

TRW = time on runway (threshold to turnoff)

α = required safety level

T_1 = random variable representing time of first airplane at threshold

T_2 = random variable representing time of second airplane at threshold

δ = random variable representing interoperation time interval at threshold

ϵ = guard time (increasing nominal time separation to satisfy safety criteria)

μ_{T_1} = mean value of distribution for T_1

μ_{T_2} = mean value of distribution for T_2

σ_{T_1} = standard deviation of distribution for T_1

σ_{T_2} = standard deviation of distribution for T_2

σ_{T_X} = standard deviation of transition time from outer marker to threshold

σ_{TOM} = standard deviation of outer marker delivery error distribution

DOM = distance from outer marker to threshold

Φ = cumulative normal distribution function

then

TNOM = DS/MV for distance separation criteria

= TRW for runway occupancy criteria

We require probability

$$\{T_2 - T_1 = \delta \geqslant TNOM\} = \alpha$$

where

μ_{T_2} $= \mu_{T_1} + TNOM + \epsilon$

α $= \text{Prob}\{\delta \geqslant TNOM\}$

$= 1 - \text{Prob}\{\delta < TNOM\}$

$= 1 - \Phi([TNOM - \{TNOM + \epsilon\}]/\sigma)$

$= 1 - \Phi(-\epsilon/\sigma)$

$= \Phi\ (\epsilon/\sigma)$

then if

α = 0.95, $\epsilon = 1.64\ \sigma$

α = 0.99, $\epsilon = 2.33\ \sigma$

α = 0.999, $\epsilon = 309\ \sigma$

where

$$\sigma = \sqrt{\sigma_{T_1}^2 + \sigma_{T_2}^2}$$

$$\sigma_{T_1} = \sigma_{T_2} = \sqrt{\sigma_{TOM}^2 + \sigma_{T_X}^2}$$

$$\sigma_{T_X} \approx DOM \cdot SV/MV^2$$

We then define

$$\mu_{A/A} = TNOM + \epsilon = \text{mean value of the arrival/arrival spacing}$$

8.5.1.2 Departure/Departure and Arrival/Departure Spacing Factors

Let

$f_1(W) = \alpha_1 W + \beta_1$ be a linear approximation of the time to liftoff as a function of gross takeoff weight

$f_2(W) = \alpha_2 W + \beta_2$ the linear approximation of time to 35-foot altitude as a function of gross takeoff weight

$f_3(W) = \alpha_3 W + \beta_3$ the linear approximation of time to 6000 feet down runway from brake release as a function of gross takeoff weight

μ_{TLO} = mean value of time, brake release to liftoff

σ_{TLO} = standard deviation of time, brake release to liftoff

μ_{TDC} = mean value of departure clearance response time

μ_{T35} = mean value of time, brake release to 35 feet

σ_{T35} = standard deviation of time, brake release to 35 feet

μ_{T6000} = mean value of time, brake release to 6000 feet

σ_{T6000} = standard deviation of time, brake release to 6000 feet

μ_{TCR} = mean value of constraint release time

μ_W = mean value of takeoff weight distribution

σ_W = standard deviation of takeoff weight distribution then

$$\mu_{TLO} \approx \alpha_1 \mu W + \beta_1$$

$$\mu_{T35} \approx \alpha_2 \mu W + \beta_2$$

$$\mu_{T6000} \approx \alpha_3 \mu W + \beta_3$$

$$\sigma_{TLO} \approx \alpha_1 \sigma_W$$

$$\sigma_{T35} \approx \alpha_2 \sigma_W$$

$$\sigma_{T6000} \approx \alpha_3 \sigma_W$$

μ_{TCR} = μTLO, μT35, μT6000, or 60 seconds, depending on ATC separation criteria.

We then define

μD/D = μTDC + μTCR = mean value of the departure/departure spacing

and

μA/D = μTDC + μTCR = mean value of the arrival/departure spacing

8.5.1.3 Departure/Arrival Spacing Factors

Let

TNOM = nominal time for arrival from constraint point to runway exit

DS = arrival following departure required separation

MV = mean approach velocity

SV = standard deviation of approach velocity distribution

TRW = time on runway (threshold to turnoff)

α = required safety level

T_1 = random variable representing time of departure brake release

T_2 = random variable representing time arrival reaches constraint distance

ϵ = guard time (increasing nominal time separation to satisfy safety criteria)

μT_1 = mean value of distribution for T_1

μT_2 = mean value of distribution for T_2

σ_{TDC} = standard deviation of departure control response time

σ_{TOM} = standard deviation of outer marker delivery error distribution

σ_{TO} = standard deviation of departure time, brake release to constraint release

TDEP = mean departure time, brake release to constraint release

DOM = distance from outer marker to threshold

Φ = cumulative normal distribution function

then

$$TNOM = DS/MV + TRW \text{ for a single runway}$$

or

$$TNOM = DS/MV \text{ for a dual lane runway}$$

Now let

$$P_r\{T_2 \geqslant T_1\} = \alpha$$

where

$$\mu T_2 = \mu T_1 + \epsilon$$

$$\begin{aligned} \alpha &= P_r\{T_2 - T_1 \geqslant 0\} \\ &= 1 - P_r\{T_2 - T_1 < 0\} \\ &= 1 - \Phi\left(\frac{0-\epsilon}{\sigma}\right) \\ &= \Phi(\epsilon/\sigma) \end{aligned}$$

$$\sigma = \sqrt{\sigma_{TDC}^2 + \sigma_{TOM}^2 + \sigma_{TX}^2} \quad \text{(in-air value)}$$

or

$$\sigma = \sqrt{\sigma_{TDC}^2 + \sigma_{TOM}^2 + \sigma_{TO}^2} \quad \text{(runway occupancy rule)}$$

and

$$\sigma_{TX} \approx (DOM\text{-}DS) \quad SV/MV^2$$

$$\sigma_{TO} = \sigma_{TLO} \text{ or } \sigma_{T35} \text{ or } \sigma_{T6000} \qquad \text{(from departure/departure analysis)}$$

then if

$$\alpha = 0.95, \quad \epsilon = 1.64\,\sigma$$

$$\alpha = 0.99, \quad \epsilon = 2.33\,\sigma$$

$$\alpha = 0.999, \quad \epsilon = 3.09\,\sigma$$

We then define

$$\mu_{D/A} = TNOM + \epsilon - TDEP = \text{mean value of the departure/arrival spacing}$$

8.5.2 Terminal Area Delay Model (AIRSIM)

The terminal area delay model program (AIRSIM) is a fast time simulation of airplanes landing at or taking off from an airport with two runways, both of which can handle takeoffs and landings under various airport Air Traffic Control (ATC) operational rules. The model has been used to assess the amount of delay to airplanes using the runways under different ATC rules, managerial procedures, and traffic loads. It has also contributed to the determination of the required quality of service provided by an individual airport as well as the factors affecting the scheduling of flights in that airport. In addition, the model has been used to investigate the scheduling procedures that would improve the airport capacity so as to permit continuous operation with minimum terminal delays at demand levels close to the theoretical capacity.

The model accepts and is sensitive to the following parameters:

1) *Hourly Schedules.* These are derived from present quick-reference edition (QRE) tapes that contain flight schedules or can be user determined. The input requires the number of arrivals and departures for each of the 24 hours. The numbers are broken down into scheduled air carriers and other airplanes.

2) *Within-Hour Schedules.* For each of the 24 hours a distribution of the expected number of arrivals and departures is specified. Various procedures can be used including random, normal, uniform, or a completely determined schedule.

3) *Airplane Type Input.* A matrix of four priorities for each type is specified. Five types and four priorities are required. The entries in the (5 x 4) matrix contain a percent of the total number of airplanes.

4) *Interoperation Time.* The mean value and the standard deviation of the time between successive operations is used. A matrix containing interoperation times for each type and arrivals and departures within each type is formed. Altogether, 100 values are supplied (10 x 10).

5) *Schedule-Keeping Capability.* These inputs modify the schedule time of each airplane by adding a number obtained by randomly sampling a gaussian distribution. Mean and standard deviation values for each priority distribution are specified.

6) *Air Traffic Control Rules.* The model contains the necessary logic to process airplanes by one of the following rules:

   a) First in, first out

   b) Arrivals first, then departures

   c) Arrivals first, until the departure queue exceeds a specified number, then first in, first out

   d) First in, first out until a specified queue length is exceeded, then process airplane in the biggest queue

   e) Process airplane by priority within each type; arrivals are taken first.

   f) Process arrivals in one runway and departures in the other

   g) Departures except priority 1 departures and priority 1 arrivals in one runway, and arrivals except priority 1 arrivals and priority 1 departures in the other.

Program operation to the above inputs can be easily described with reference to figure 8-14.

First, an airplane arrival/departure schedule is generated according to the input scheduling rules. These scheduled times are then modified by a number resulting from randomly sampling a schedule deviation distribution. The new times represent the airplane actual departure or arrival ready times. The airplanes are then ordered according to their ready times. Using the prescribed ATC rule, a runway is assigned to the next airplane waiting to use the runways. At this time an interoperation time is obtained based on the types of airplanes waiting to use the runway and the previous airplanes in that runway. For each airplane, the actual processing time is determined based on the interoperation time and the waiting time of the airplane before it is allowed to use the runway. The difference between the processing time and the ready time is the delay. Delays are stored in tables along with the type, priority, and arrival and departure hours. At the end of the simulation or at intermediate times, if necessary, the desired delay statistics can be selectively output. The terminal utilization is obtained by adding up all the interoperation times for that hour

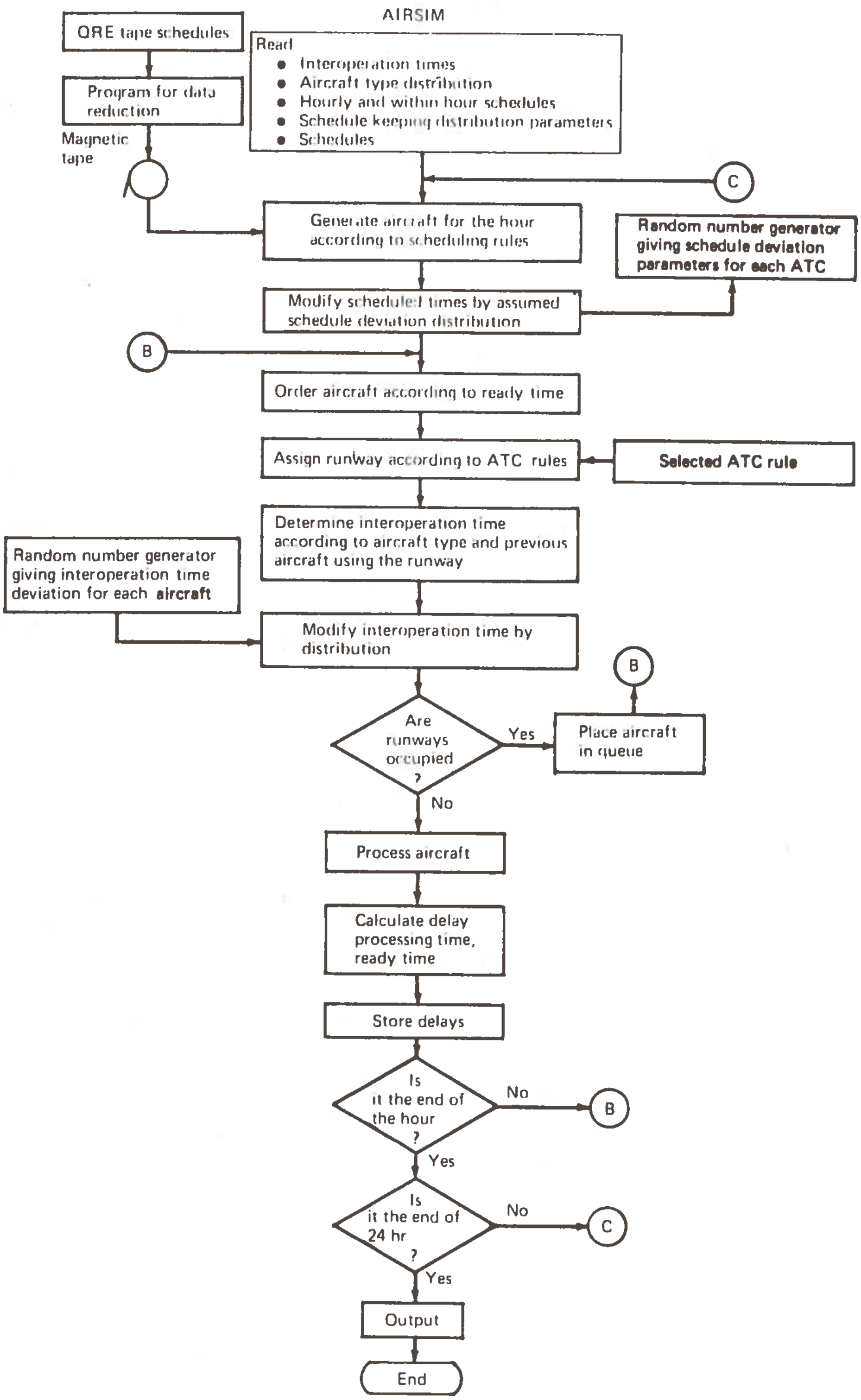


FIGURE 8-14.—AIRSIM FLOW DIAGRAM

or day and dividing by the number of operations in the runways. For a two-runway operation the utilization is divided by two. Average delays are subsequently calculated and stored in tables for final output.

The outputs of the model provide delay statistics in the form of frequency tables. The number of entries, the average delay, and the number of entries with zero delays followed by frequency classes are included in each table. Each class contains the number of entries whose delay is the number of minutes indicated; for example, class 0 contains all airplanes with delay greater or equal to zero and less than one minute. Depending on the necessary information, either hourly or daily tables are available.

In addition to the delay tables, daily as well as hourly tables summarizing delay information are provided. These tables present information on average delays, percent of delays in each operation type, terminal utilizations, and maximum queue lengths.

The model considers times to the nearest hundredth of a minute. This accuracy is kept in calculating average delays and all other parameters, except in the frequency classes.

8.5.3 Terminal Airspace Model

The model was designed primarily to investigate the problems arising in an airways network due to airplane flow. The model supports the present ATC system environment and considers primarily scheduled air carriers using the major flight routes. The model is suitable for investigating the following:

- The overall traffic flow
- Conflict situations for various flight accuracy and traffic levels
- The most used routes and waypoints
- Hourly distribution of conflicts in the system for different traffic loads
- Total controller workload at various network sectors
- The effects of various airplane scheduling schemes on the overall traffic flow
- Alternative route structure and their benefits on the overall traffic flow
- The flow of airplanes within a specified volume of air (to aid in altitude assignment procedures)
- The determination of optimal route structures so as to increase the total network capacity
- The placement of new airports or VOR sites so as to avoid congested areas

The selected airspace evaluation criteria are the airplane conflicts that arise because of actual or potential violations of separation rules, the control workload that is caused by these conflicts, airplane economic considerations, and the total terminal area flow rates. The generation of these criteria by the model is shown in figure 8-15.

The operation of the model in obtaining these outputs can be described by considering the series of actions occurring in a regularly scheduled air carrier flight. To begin, each commercial flight originates from an airport at a time that is dependent on the airport operational rules, traffic, etc., then it proceeds along a predetermined flight path at speeds and altitudes that are determined by the airplane characteristics and route length. During its flight, it may be delayed due to weather, traffic or simply by changing altitude to avoid conflicts. When it reaches its destination, it may be held in a holding pattern depending on the conditions of the traffic until it is cleared to land. This general flight process has been idealized and summarized in the model.

First, an origin and destination point (airport or TMA entry or departure point) are input to the program. This information generates a number of flights through the network. The departing flights are modified according to the delay statistics of the airport. These flights now have their actual departing times. The appropriate route is then chosen. At this time, all geographical locations for waypoints in the route are obtained from magnetic tape storage already in the program. The program then calculates the distances and elapsed times between successive waypoints in the route. By adding these times successively to the previous time, starting from the origin airport, the arrival times at each waypoint are obtained.

Flight altitudes are subsequently assigned by sampling from a uniform distribution having as upper and lower limits the allowed flight altitude levels for the route. Arrival times at waypoints are then modified if necessary to account for bad weather conditions or evasive action taken to avoid conflicts. These arrival times, along with the waypoint name, origin, and destination of the flight number and flight altitude, are stored for future usage. The program is then recycled and a new route is introduced. When all routes of interest have been considered, the program checks each waypoint and determines the potential conflict situations. All the above information can be selectively output.

Potential conflict situations are determined based on two factors: altitude and time separation. A conflict situation is said to exist if two or more airplanes flying at the same altitude will enter the same point separated in time by less than the conflict variable. For example, two airplanes flying at 33,000 feet will conflict with each other if they are scheduled to arrive at the same point 4 minutes apart, considering a conflict definition variable of 5 minutes.

The following are possible outputs from the program:

1) For each route, the distance in nautical miles between intermediate waypoints as well as the total flight time

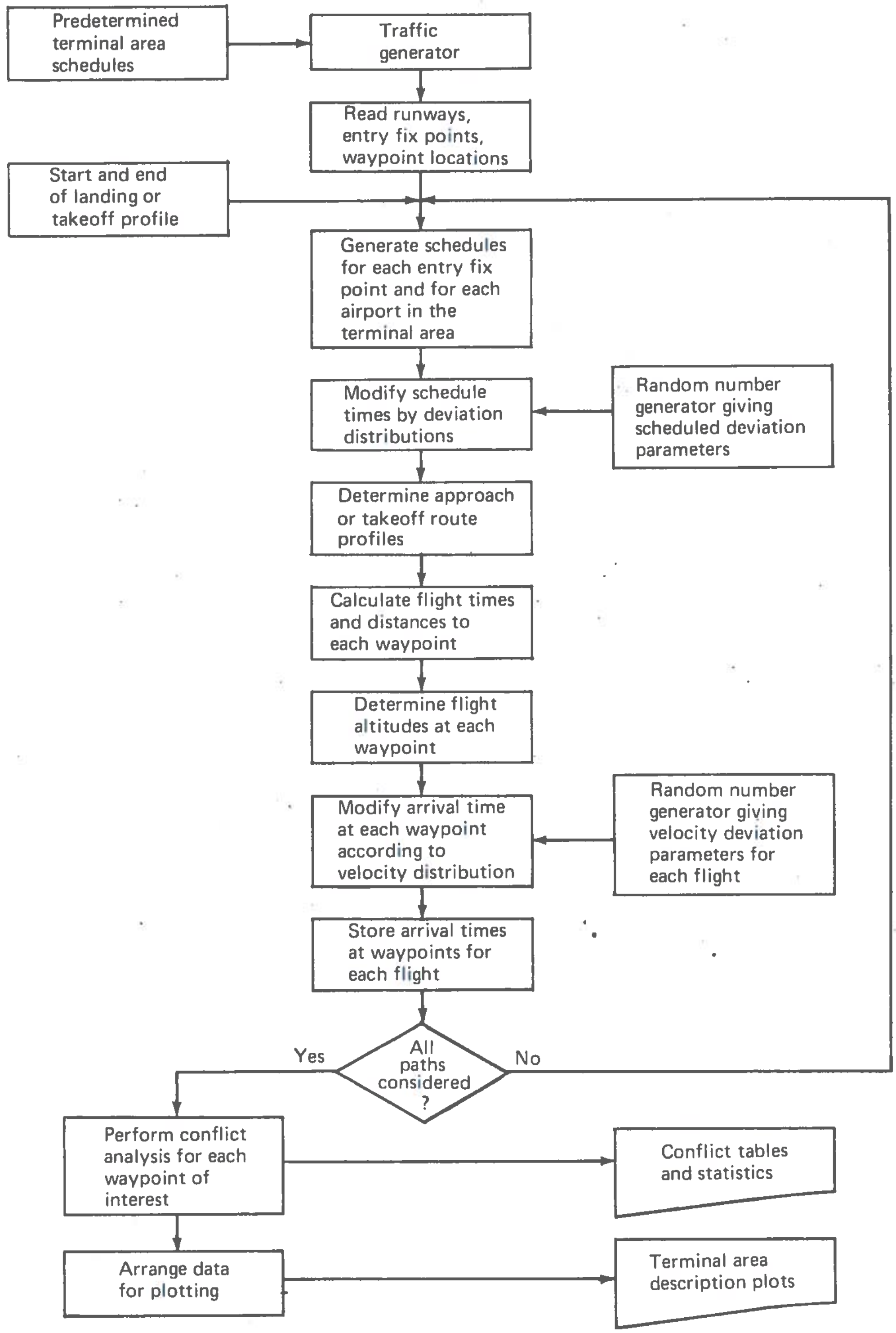


FIGURE 8-15.—TERMINAL AREA FLOW MODEL

2) A conflict situation table, which gives the number of conflicts, the conflict duration, and number of airplanes involved—24 hours of the day

3) List of flights through a waypoint

4) Histogram of the number of flights through a waypoint for the entire 24 hours

Any of the above tables or charts can be selectively output by arranging check parameters in the model.

8.6 ECONOMIC SAVINGS OF STRATEGIC CONTROL

This analysis investigates the economic benefits of the potential improvements in airplane operations due to the use of strategic control in the LAX terminal area. The dollar cost benefits accruing to the airlines, the airport operator, and the community interests are related to airplane direct operating costs where possible. The results are presented in terms of cost savings due to the value of additional operations, delay reductions, flightpath length reductions, and control workload reduction.

8.6.1 Additional Operations

The increase in airport/runway utilization obtainable using strategic control has the desirable feature of getting greater utility out of what has become a very expensive and environmentally difficult transportation hub. One alternative to an increase in existing runway utilization is the construction of new runways or new airports. A new airport or a new runway at an existing airport requires an airport master plan. The airport master plan draws widespread interest from private citizens, community organizations, airport users, area-wide planning agencies, conservation groups, ground transportation officials, and aviation and airport concessionnaire interests. These groups must be consulted during the development of the plan, or it will likely be unsuccessful when presented to the public. Many of these interested parties will insist that all available means be explored to increase the capacity of the existing airport and runways without constructing additional facilities. The dollar value to both the community and the airlines of delaying or avoiding the construction of additional facilities has not been estimated. It is possible that this option is not available and that growth restrictions are the alternative.

Strategic control will allow an increase in operations rate of the runways. At LAX this is obtained as a result of improving the outer marker delivery accuracy from 18 seconds (one sigma) for a manual vectoring ATC system or 8 seconds for the basic ARTS III metering and spacing type system to the 2-second accuracy possible with strategic control. The resulting operations rates for the dual-runway setup at LAX are 112, 147, and 240 operations, respectively (see sec. 8.2.1).

The value of the additional 93 operations (strategic above basic ARTS III M&S) has been estimated. These additional 93 airplanes represent additional revenue for the airport operator. If 46 of these operations are landings and the proportional fleet mix (ref. 8-8) is represented, the following simplified approach may be taken:

3 long-haul airplanes	800,000 pounds
14 medium-haul airplanes	500,000 pounds
29 short-haul airplanes	200,000 pounds

Using a landing fee of $.60/1000 pounds as representative, the following additional revenue is realized:

Long-haul additional revenue	$1440
Medium-haul additional revenue	4200
Short-haul additional revenue	3480
Each day's busy-hour additional revenue	$9120

Annual revenue, assuming a 300-day year, is estimated to be $2,736,000 at Los Angeles International Airport for the busy hour. Revenue for all hours during a 13-hour day is estimated at over $27,000,000 per year.

8.6.2 Reduction in Delay Time

In the National Aviation System Policy Summary (ref. 8-9), it is stated that some 30% to 60% of the delay occurring at the five busiest terminals is attributable to airport capacity limitations. The remaining delay, according to this source, is generally considered attributable to inadequate airspace due to proximity of other airports, noise abatement procedures, controller workload saturation, and the inability of the system to predict and react promptly to transient adverse weather, wind shifts, etc.

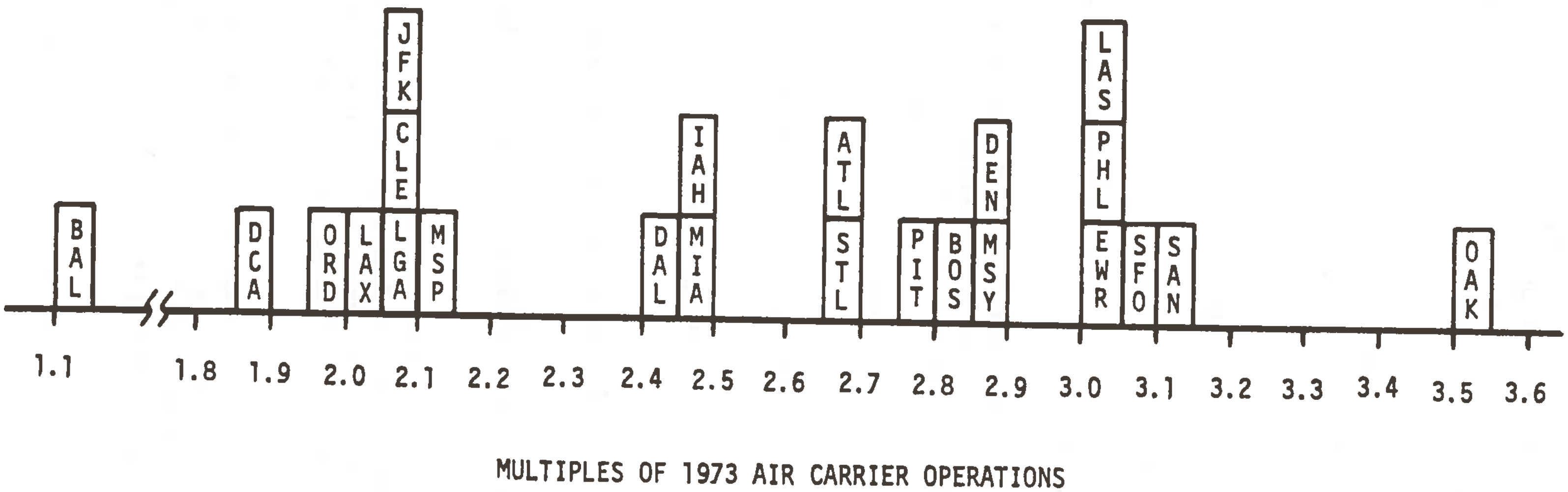
Solutions to delay might properly be listed as:

1) Build new airports. New airports are expensive and very difficult to implement for many political and social reasons. Most airports in the United States are run by local governments with commissioners appointed by elected officials. With leadtimes of from 10 to 15 years from planning to operation, and with almost complete blockage of attempts at construction of new facilities, it seems unlikely that construction of new airports will solve the delay problems.

2) Introduce new multiple independent and close parallel runways and landing aids, use higher quality flight control equipment, provide ground/air/ground data link, and provide better surveillance for traffic flow organization and conflict monitoring.

3) Impose quota restrictions on flights into the major terminals to avoid complete system breakdown that is the inevitable result of airport saturation.

The delay experienced at each airport will be, in part, a function of the growth experienced in air carrier operations over the years between now and 1995. The growth rates at some airports show a projected tripling of air carrier operations, as shown on the histogram, figure 8-16.



Legend:

BAL: Baltimore
DCA: Washington National
ORD: Chicago O'Hare
LAX: Los Angeles International
JFK: Kennedy

CLE: Cleveland
LGA: LaGuardia
MSP: Minneapolis–St. Paul
DAL: Dallas Love
IAH: Houston
MIA: Miami

ATL: Atlanta
STL: St. Louis
PIT: Pittsburgh
BOS: Boston
DEN: Denver
MSY: New Orleans

LAS: Las Vegas
PHL: Philadelphia
EWR: Newark
SFO: San Francisco
SAN: San Diego
OAK: Oakland

FIGURE 8-16.—HISTOGRAM OF PREDICTED AIR CARRIER GROWTH AT SELECTED AIRPORTS

The results of the delay analysis of Los Angeles airplane traffic discussed in section 8.2.2 indicate that the projected LAX growth will lead to unacceptable delays for both the present-day manual vectoring system and for the planned basic ARTS III metering and spacing system during the time period specified for this study.

An estimate at the dollar cost of this delay at LAX has been made. Direct operating costs (DOC) per block-hour were developed using today's costs and today's airplanes as the data base for the estimates. Costs and performance data used were developed from CAB data (ref. 8-10), a portion of which is shown in table 8-19. These direct operating costs per block-hour are shown in table 8-20.

Fleet average cost per block-hour was determined to be $1435.

The airport operations data, airplane mix data, and operations per airplane used were taken from the demand data supplied by TSC (ref. 8-8). This reference also identified those airplanes of the fleet mix that will be equipped with four-dimensional RNAV equipment, which may be sufficient to support strategic control.

Using $1435/block-hour, the cost per airplane per minute of delay would be $23.91. The per-minute cost of delay for the 1995 estimated 5,840,000 approaches at the strategic airports would be $139.6 million and the cost per day for one minute of delay is $382.560.

The DOT-TSC delay criteria (ref. 8-8) for the advanced (post-1990) ATC system would have the following economic implications:

- Average delay—less than 3 minutes—less than $71.73 per average airplane in direct operating costs

- Busy-hour average delay—less than 6 minutes—less than $143.50 per airplane in delay cost

- 90% of the traffic—delays of less than 15 minutes—less than $358.75 of DOC because of delay

- 99.9% of the traffic—delays less than 30 minutes—less than $717.50 DOC loss 99.9% of the time

An estimate of the ATC delay resulting from the typical Los Angeles air carrier schedule has been made using the Boeing terminal area delay model. Details of this work are contained in section 8.2.2. The model was exercised for traffic levels of 1972 (average busy hour = 92 operations) to twice that level. The 1995 traffic estimate is approximately 1.9 times 1972 traffic.

The model results, with delay costs shown, are illustrated in figure 8-17. These assume IFR operations with reduced separations for the strategic and M&S cases resulting from the improved operations rates discussed previously. Note that the model shows average busy-hour IFR delay costs of about $500 per airplane in 1972.

TABLE 8-19.—AIRCRAFT OPERATING COST AND PERFORMANCE REPORT

LINE No.	EXPENSES, PERFORMANCE and CHARACTERISTICS	DOMESTIC OP.—DOMESTIC TRUNKS PASSENGER CABIN CONFIG. T.FAN,4-ENG., WIDE-BODIED B-747 12 MONTHS ENDED DEC. 31, 1971	1970	DOMESTIC OP.—DOMESTIC TRUNKS PASSENGER CABIN CONFIG. T.FAN,4-ENG., REG-BODIED B-707-100B 12 MONTHS ENDED DEC. 31, 1971	1970	DOMESTIC OP.—DOMESTIC TRUNKS PASSENGER CABIN CONFIG. T.FAN,4-ENG., REG-BODIED B-707-300B 12 MONTHS ENDED DEC. 31, 1971	1970	DOMESTIC OP.—DOMESTIC TRUNKS PASSENGER CABIN CONFIG. T.FAN,4-ENG., REG-BODIED B-707-300C 12 MONTHS ENDED DEC. 31, 1971	1970	LINE No.
	AIRCRAFT OPERATING EXPENSES	(2)	(8)							
	PER BLOCK HOUR (ALL SERVICES) (IN DOLLARS)									
	FLYING OPERATIONS (LESS RENTALS)									
1	CREW	272.83	248.43	191.54	193.15	211.72	198.84	[illegible]	196.26	1
2	FUEL AND OIL	378.24	351.29	192.26	190.28	214.2[illegible]	217.14	225.23	209.04	2
3	INSURANCE	[illegible]3.99	74.76	5.24	6.59	3.31	10.75	11.71	9.17	3
4	OTHER	1.07	2.16	0.33	0.60	[illegible]	0.41	[illegible]	0.50	4
5	TOTAL FLYING OPERATIONS (LESS RENTALS)	716.12	676.65	389.37	390.62	43[illegible].14	427.14	[illegible]	414.96	5
	MAINTENANCE—FLIGHT EQUIPMENT									
6	DIRECT MAINTENANCE—AIRFRAME AND OTHER	127.15	144.19	49.97	48.78	47.[illegible]	43.08	57.[illegible]	[illegible]	6
7	DIRECT MAINTENANCE—ENGINE	166.3[illegible]	122.67	35.35	40.41	[illegible]	34.17	[illegible]	[illegible]	7
8	MAINTENANCE BURDEN	[illegible]	142.71	100.56	101.03	[illegible]8.79	94.49	[illegible]	74.87	8
9	TOTAL MAINTENANCE—FLIGHT EQUIPMENT	[illegible].38	409.57	185.90	190.22	18[illegible]	171.74	[illegible]	188.44	9
	DEPRECIATION AND RENTALS—FLIGHT EQUIPMENT									
10	DEPRECIATION—AIRFRAME AND OTHER	[illegible]37.57	182.57	103.52	110.94	[illegible]	54.64	[illegible]	139.01	10
11	DEPRECIATION—ENGINE	53.93	37.81	18.65	19.96	[illegible]	11.63	[illegible]	24.44	11
12	OBSOLESCENCE AND DETERIORATION—EXPENDABLE PARTS	[illegible]	5.76	1.24	1.36	[illegible]	1.73	[illegible]	3.65	12
13	RENTALS	[illegible]	517.29	16.40	16.21	[illegible]	110.57	[illegible]	18.06	13
14	TOTAL DEPRECIATION AND RENTALS—FLIGHT EQUIPMENT	546.[illegible]	743.43	140.01	148.47	178.91	178.98	[illegible].31	185.17	14
15	TOTAL AIRCRAFT OPERATING EXPENSES	1686.29	1829.64	715.29	729.31	798.[illegible]	777.86	815.[illegible]	788.56	15
16	PER AIRBORNE HOUR (ALL REVENUE SERVICES) (IN DOLLARS)	[illegible]1.52	2109.52	747.90	827.70	886.55	887.56	[illegible]	899.26	16
17	PER AIRCRAFT MILE (ALL REVENUE SERVICES) (IN DOLLARS)	3.73	4.21	1.59	1.72	1.85	1.83	[illegible]	1.86	17
18	PER REVENUE TON-MILE (SCHEDULED REVENUE SERVICE) (IN CENTS)	[illegible]	27.848	25.319	25.743	22.311	23.084	[illegible]	25.800	18
19	PER AVAILABLE TON-MILE (SCHEDULED REVENUE SERVICE) (IN CENTS)	7.[illegible]	7.851	9.503	9.310	8.974	8.998	[illegible]	9.357	19
20	PER REVENUE PASSENGER-MILE (SCHEDULED REVENUE SERVICE) (IN CENTS)	2.5[illegible]	3.160	2.947	2.963	2.786	2.818	[illegible]	3.032	20
21	PER AVAILABLE SEAT-MILE (SCHEDULED REVENUE SERVICE) (IN CENTS)	[illegible].135	1.235	1.409	1.354	1.298	1.308	1.[illegible]	1.366	21
	PERFORMANCE and CHARACTERISTICS									
	UTILIZATION									
22	AVERAGE AIRCRAFT ASSIGNED TO SERVICE (CARRIER'S ROUTES/EQUIPMENT)	[illegible]	62.8	93.2	96.1	23.8	21.2	[illegible]	50.9	22
23	TOTAL AIRBORNE HOURS (ALL REVENUE SERVICES)	[illegible]174.	39603.	299839.	310204.	82694.	73726.	[illegible]	145020.	23
24	REVENUE HOURS PER AIRCRAFT PER DAY (CARRIER'S ROUTES EQUIPMENT) (IN HOURS)	[illegible]	8.51	[illegible]	8.84	9.52	9.53	[illegible]	7.81	24
25	PERCENT TOTAL AIRBORNE TO REVENUE AIRBORNE HOURS	[illegible]	104.3	103.6	100.8	101.[illegible]	102.7	[illegible]	102.5	25
26	PERCENT BLOCK-TO-BLOCK TO AIRBORNE HOURS	[illegible]	110.5	113.9	112.6	[illegible]	111.1	[illegible]	111.3	26
27	PERCENT SCHEDULED TO TOTAL REVENUE AIRCRAFT MILES	[illegible]	99.9	99.6	99.9	99.3	99.3	[illegible]	85.2	27
28	AVERAGE STAGE LENGTH (ALL REVENUE SERVICES) (IN MILES)	1986.	2297.	1097.	114[illegible].	1436.	1436.	1014.	1238.	28
	AIRCRAFT CAPACITY									
29	AVERAGE AVAILABLE TONS PER AIRCRAFT MILE (ALL REVENUE SERVICES)	52.7	53.6	17.7	18.5	20.[illegible]	20.3	14.2	19.7	29
30	AVERAGE AVAILABLE SEATS PER AIRCRAFT MILE (ALL REVENUE SERVICES)	326.6	341.0	119.6	127.1	140.6	139.6	137.[illegible]	139.6	30
	SPEED									
31	AVERAGE AIRBORNE SPEED (ALL REVENUE SERVICES) (IN MPH)	5[illegible]7.	501.	473.	481.	485.	486.	476.	483.	31
32	AVERAGE BLOCK-TO-BLOCK SPEED (ALL REVENUE SERVICES) (IN MPH)	[illegible]63.	453.	427.	427.	444.	437.	[illegible]34.	434.	32
	PRODUCTIVITY									
33	AVERAGE AVAILABLE TON-MILES PER AIRBORNE HOUR (ALL REVENUE SERVICES)	26733.	26866.	8392.	8888.	9677.	9845.	[illegible]	9496.	33
34	AVERAGE AVAILABLE SEAT-MILES PER AIRBORNE HOUR (ALL REVENUE SERVICES)	166[illegible]23.	170789.	56601.	61115.	68331.	67766.	[illegible]5428.	67446.	34
	FUEL									
35	GALLONS OF FUEL CONSUMED PER BLOCK HOUR (ALL SERVICES)	3367.	3555.)(15)	1657.	1732.	178[illegible].	181[illegible].	1882.	1895.	35
36	COST OF FUEL PER GALLON (ALL SERVICES) (IN CENTS)	11.[illegible]41	9.94[illegible]	11.326	10.775	11.954	11.7[illegible]	11.[illegible]	10.87[illegible]	36
	TRAFFIC									
37	AVERAGE REVENUE TONS PER AIRCRAFT MILE (SCHEDULED REVENUE SERVICE)	15.3	15.1	6.7	6.7	8.2	7.9	[illegible]	7.2	37
38	AVERAGE REVENUE PASSENGERS PER AIRCRAFT MILE (SCHEDULED REVENUE SERVICE)	128.[illegible]	133.3	57.2	58.1	65.6	64.9	[illegible]	61.4	38
39	TON LOAD FACTOR (SCHEDULED REVENUE SERVICE) (PERCENT)	[illegible].2	28.2	37.5	36.2	40.2	39.0	[illegible]	36.3	39
40	SEAT LOAD FACTOR (SCHEDULED REVENUE SERVICE) (PERCENT)	[illegible].2	39.1	47.8	45.7	46.6	46.4	[illegible]	45.[illegible]	40
41	FIRST CLASS PASSENGER LOAD FACTOR (SCHEDULED REVENUE SERVICE) (PERCENT)	[illegible].1	35.1	28.6	31.8	29.9	33.9	[illegible]	32.2	41
42	COACH PASSENGER LOAD FACTOR (SCHEDULED REVENUE SERVICE) (PERCENT)	41.4	40.1	54.0	50.2	49.6	49.4	[illegible]	47.8	42
43	PERCENT COACH TO TOTAL REVENUE PASSENGER-MILES (SCHEDULED REVENUE SERVICE)	[illegible].9	82.1	85.4	82.9	90.1	86.0	[illegible]	87.3	43

For footnotes, glossary, and methods of calculating derived data, see appendix at end of this report.

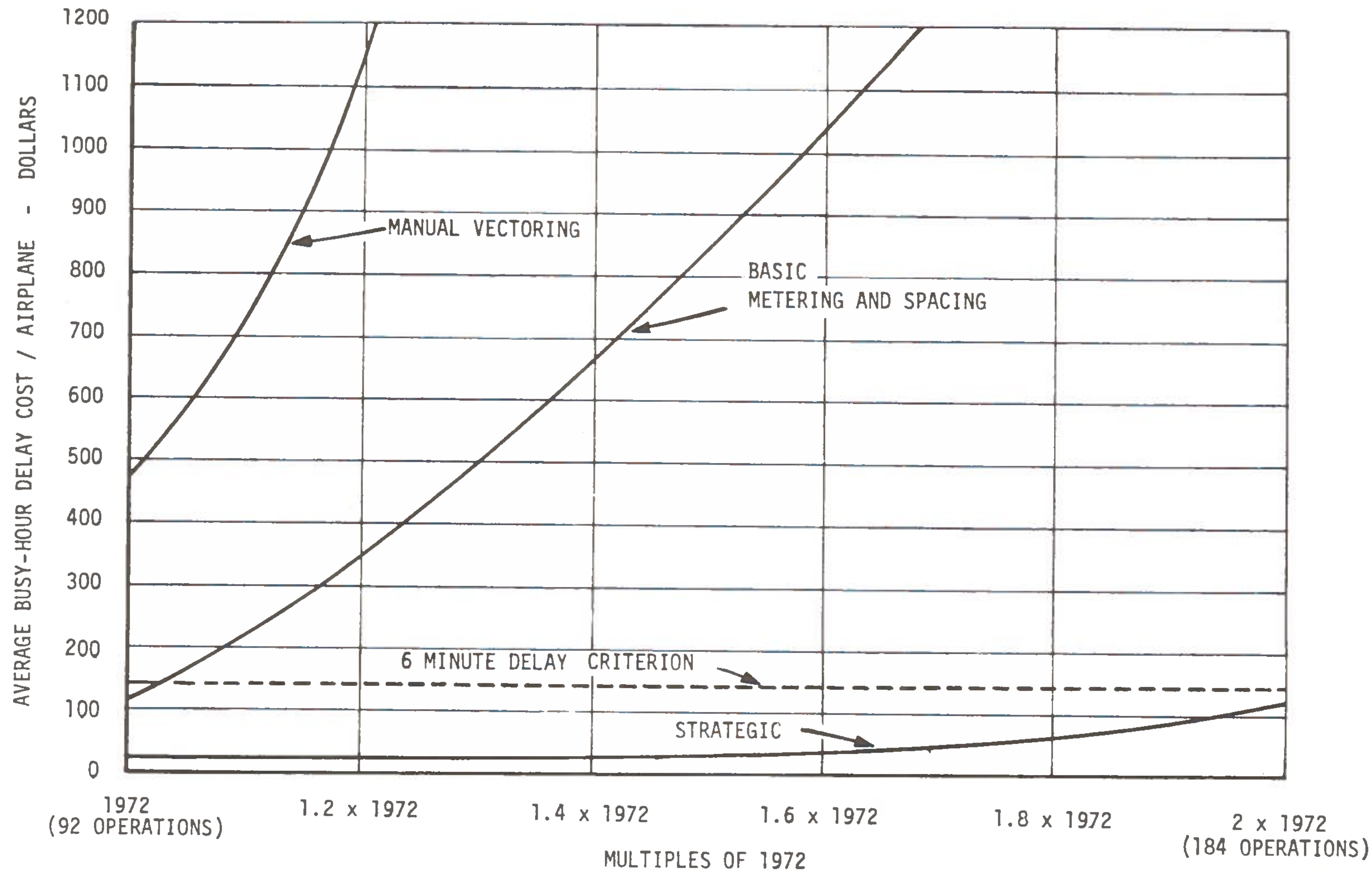


FIGURE 8-17.—BUSY-HOUR OPERATIONS/HOUR (INSTRUMENT CONDITIONS) DELAY COST COMPARISON

TABLE 8-20.—DIRECT OPERATING COSTS

Airplane size (passengers)	DOC/block-hour
600	$2800
400	2000
300	1600
250	1400
200	1200
120	1000
100	800
80	600

Metering and spacing IFR delay costs will reach $500/airplane when traffic volume during the busy-hour reaches 1.3 times the 1972 volume. At a growth rate of 1.036/year (doubling of busy-hour traffic by 1995) this level of busy-hour traffic will be reached by 1980. Those airports having an unconstrained predicted growth of 3 times by 1995 could reach the 1.3 x 1972 volume of traffic by 1978, or about the time basic metering and spacing is scheduled to be implemented.

The term "busy hour" implies a peak at a particular hour. Survey of traffic throughout the day shows that the busy hour continued throughout much of the airline day and had only a slight increase in operations compared to the adjacent hours, as indicated on the histogram, figure 8-18 (ref. 8-11).

To provide a measure of the relative delay cost savings of strategic control over the basic metering and spacing concept, several comparisons were made using the model results and the $1435/block-hour DOC. The results for 1972 (397,000 annual operations) show:

- Manual vectoring — Average delay/aircraft = 4.16 minutes; Annual cost of delay - $37.6 million
- Basic metering and spacing — Average delay/aircraft = 1.49 minutes; Annual cost = $13.5 million
- Strategic control — Average delay/aircraft = 0.15 minute; Annual cost - $1.4 million

These results indicate an annual savings of $36.2 million over the present manual vectoring system and $12.1 million over basic metering and spacing, if the system had been operational in 1972.

The 1995 traffic projection used is 1.86 times the 1972 level. For this traffic level the average delay for the strategic concept increased to 1.13 minutes. This translates into a total cost of $19.7 million for 778,000 operations. This figure is a $17.9 million savings over the

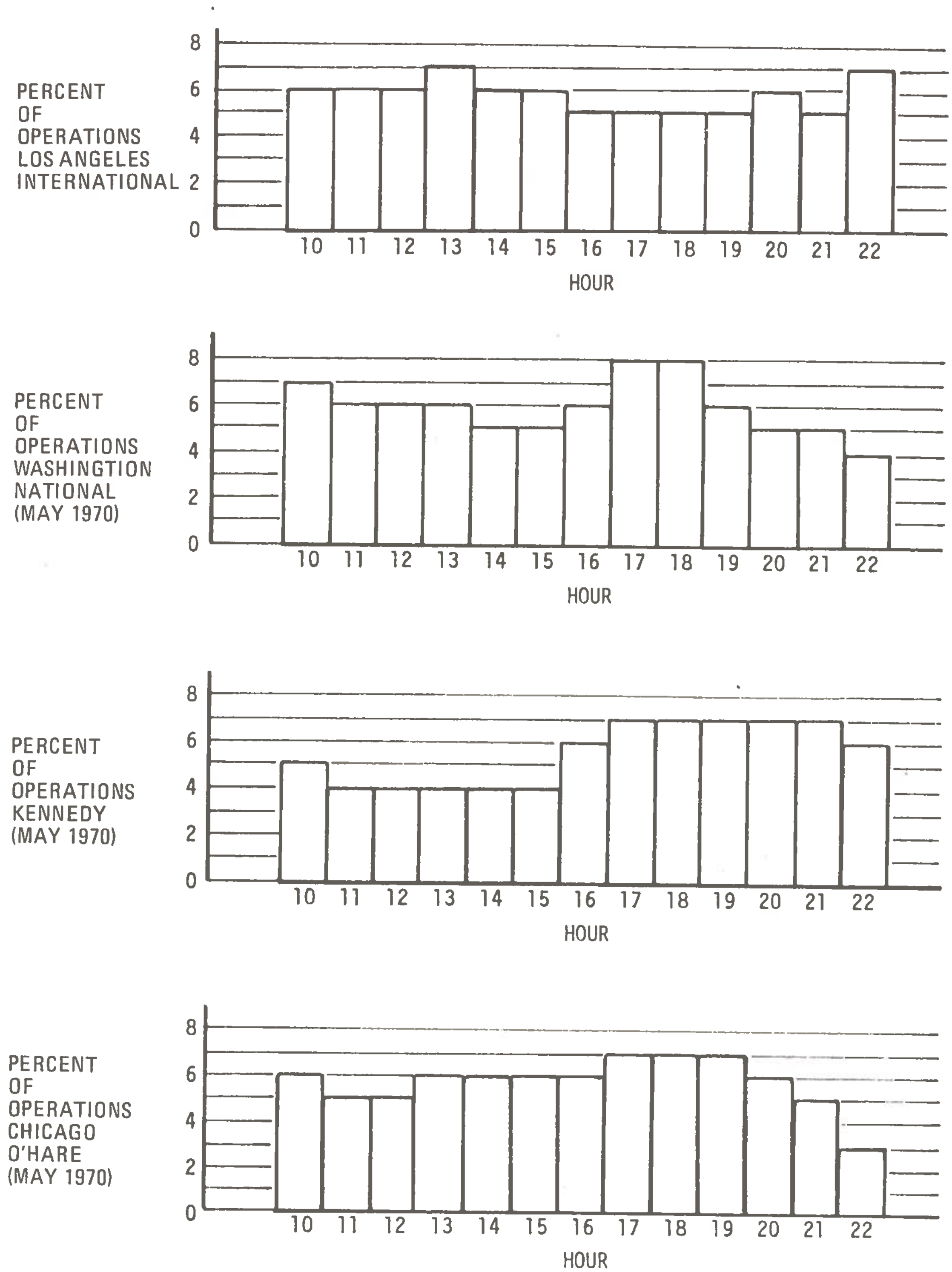


FIGURE 8-18.—HISTOGRAMS OF PERCENT OF OPERATIONS PER HOUR AT SELECTED AIRPORTS

1972 manual vectoring delay cost and is $6.2 million more than the basic metering and spacing concept, both differences for traffic levels of almost double.

Comparing the 1995 delay cost directly, the results indicate that the average delay will be 1.13 minutes if strategic control is employed and 61.7 minutes if basic metering and spacing is used. A 61.7-minute average delay would be totally unacceptable to the airlines and to the airline passengers. With metering and spacing, the average delay for an average airplane would cost $1475 per operation, at LAX. The annual loss at LAX for delay would be $1,147 million. Since there will be 2000 air carrier operations at LAX per day, daily cost of delay for the air carrier fleet would be in excess of $3 million in direct operating costs.

Traffic delay also results in lost productivity of individuals, businesses, and eventually, the nation. In addition to lost man-hours and accompanying overhead costs, a sequence of other causes and effects are initiated that translate into delays in industrial productivity.

This complex relationship of factors and benefits was analyzed and a straightforward approach was taken to develop a realistic but conservative solution. In this methodology only the effect in terms of lost man-hours resulting from airplane hours of delay was considered as the basis for calculations.

Los Angeles International Airport average delay of 61.7 minutes for basic metering and spacing is compared to 1.13 minutes of delay for strategic control in 1995. The 60-minute saving in time per passenger is translated into dollars saved by placing a $10.00 per man-hour value upon the flying customer's time. Each passenger's gain for time saved, on the average, is $10.00. Assuming an average airplane load of 100 passengers and with 389,000 approaches at LAX in 1995, the gain becomes $389 million at Los Angeles alone.

8.6.3 Approach Time Reduction

Los Angeles International Airport total air carrier operations for 1995 are 778,000, of which half are approaches. At 2 minutes saved per approach operation, the time saved will be 12,966 hours. At the fleet average cost per block-hour of $1435, total DOC savings at Los Angeles International is $18.65 million.

The other airports having a requirement for strategic control would achieve greater or lesser savings depending upon the reduced delay time achievable, runway utilization improvements possible, etc. These airports, their estimated air carrier operations, and their growth rates from the present time to 1995 are shown in table 8-21, reference 8-12.

Total operations of the entire domestic air carrier fleet—24.6 million operations—was determined by multiplying the airplane types by their corresponding estimated operations per year. The 23 airports requiring strategic control have a total unconstrained demand of 11,680,000 air carrier operations, 47.47% of the total operations of the entire domestic fleet in 1995.

The percent of various types of airplanes making up the fleet mix was determined for those air carrier airplanes equipped with avionics equipment capable of four-dimensional RNAV and sophisticated enough for use in the strategic control environment. The fleet mix, airplane types, operations per year, etc., are shown in table 8-22.

TABLE 8-21.—SELECTED AIRPORT AIR CARRIER OPERATIONS GROWTH

AIRPORT	AIRPORT SYMBOL	1973 AIR CARRIER OPERATIONS *	1995 UNCONSTRAINED AIR CARRIER OPERATIONS	GROWTH
SAN FRANCISCO	SFO	267,000	821,000	3.1
LA GUARDIA, N.Y.C.	LGA	264,000	553,000	2.1
ST. LOUIS	STL	166,000	445,000	2.7
WASHINGTON NATIONAL	DCA	223,000	413,000	1.9
CLEVELAND	CLE	113,000	233,000	2.1
O'HARE	ORD	532,000	1,061,000	2.0
BOSTON	BOS	201,000	566,000	2.8
NEWARK	EWR	179,000	540,000	3.0
PHILADELPHIA	PHL	175,000	525,000	3.0
ATLANTA	ATL	369,000	986,000	2.7
NEW ORLEANS	MSY	102,000	292,000	2.9
LAS VEGAS	LAS	92,000	280,000	3.0
DENVER	DEN	183,000	526,000	2.9
J.F.KENNEDY, N.Y.C.	JFK	318,000	655,000	2.1
OAKLAND	OAK	68,000	240,000	3.5
LOS ANGELES	LAX	381,000	778,000	2.0
SAN DIEGO	SAN	76,000	235,000	3.1
DALLAS	DAL	293,000	713,000	2.4
MIAMI	MIA	241,000	594,000	2.5
HOUSTON	IAH	132,000	324,000	2.5
MINNEAPOLIS	MSP	118,000	252,000	2.1
PITTSBURGH	PIT	162,000	451,000	2.8
BALTIMORE	BAL	170,000	197,000	1.2
TOTAL 1995 AIR CARRIER OPERATIONS			11,680,000	

* REFERENCE 8-8

TABLE 8-22.—SUMMARY SHEET 1995 DOMESTIC OPERATIONS

AIRPLANE TYPE CATEGORIES	SEATS/ AIRPLANE [1]	FLEET SIZE [2]	OPERATIONS/ AIRPLANE/ YEAR [1]	OPERATIONS/ FLEET/ YEAR	STRATEGIC APPROACH OPERATIONS
LONG HAUL					
SST	200	100	3500	350,000	156,030
4 ENGINE JUMBO	600	400	1500	600,000	267,480
MEDIUM HAUL					
4 ENGINE STRETCH	300	500	200	100,000	44,580
3 ENGINE JUMBO	400	1500	2500	3,750,000	1,671,760
SHORT HAUL					
3 ENGINE STRETCH	250	250	4000	1,000,000	445,800
2 ENGINE JUMBO	200	550	5000	2,750,000	1,225,950
2 ENGINE STRETCH	120	300	5500	1,650,000	735,570
2 ENGINE STANDARD	80	150	6000	900,000	401,220
2 ENGINE JUMBO	100	500	4000	2,000,000	891,600
					5,840,000

[1] AATMS PROGRAM REQUIREMENTS SPECIFICATION, MITRE (12-29-72) TABLE C1-9

[2] SAME DOCUMENT AS ABOVE, TABLE 2.1.3.1-5

Computed savings to the airlines based on 2 minutes' saving per approach due to strategic control is shown in table 8-23 for the 23 airports at which strategic control would be implemented. With 5,840,000 strategic approaches made in 1995, the total time saved is 194,700 hours and the direct operating cost saving is $279 million.

8.6.4 Control Workload Reduction

With the introduction of strategic control the workload of the controller will be reduced considerably. He will now monitor progress rather than actively engage in tactical vectoring. The instrument operations per controller in 1973 is approximately 7000 at the large TRACON (ref. 8-13). If no gain in productivity occurred, about 111 controllers would be required to handle LAX traffic in 1995.

Reference 8-13 also indicates that basic metering and spacing, air/ground data link, three- and four-dimensional navigation, and improved displays should increase the productivity by 2.1 to 3.3 times. Using a figure of 2.14 times increases productivity per controller from 7000 to 15,000 instrument operations per year and reduces the LAX TRACON controller population from 111 to 51 controllers in 1995.

With the introduction of strategic control, the data link and voice circuit traffic will be reduced from five links to three links. Relative workload will be reduced as indicated in figure 8-19.

Using methodology developed in references 8-8 and 8-13, productivity should increase 1.6 times to 24,000 instrument operations per controller. This will reduce the LAX TRACON controller requirements to 32 for a reduction of 19 controllers. Assuming salary and benefits of a controller at $25,000 per year, the savings at Los Angeles International Airport would be $475,000 per year.

TABLE 8-23.—REDUCED APPROACH TIME COST SAVINGS

AIRPORTS	UNCONSTRAINED OPERATIONS (000)	STRATEGIC APPROACHES (000)	GROWTH '73 TO '95	SAVINGS DUE TO 2 MIN. SAVINGS IN TIME
SAN FRANCISCO	821	410.5	3.0749	19,635,105
ST. LOUIS	445	222.5	2.6807	10,641,960
LA GUARDIA	553	276.5	2.0946	13,224,060
WASHINGTON NATIONAL	413	206.5	1.8520	9,877,105
CLEVELAND	233	116.5	2.0619	5,572,105
O'HARE	1,061	530.5	1.9943	25,375,105
BOSTON	566	283.0	2.8159	13,536,355
NEWARK	540	270.0	3.0167	12,915,000
PHILADELPHIA	525	262.5	3.0000	12,556,250
ATLANTA	986	493.0	2.6720	23,581,355
NEW ORLEANS	292	146.0	2.8627	6,982,710
LAS VEGAS	280	140.0	3.0434	6,695,710
DENVER	526	263.0	2.8743	12,579,210
J. F. KENNEDY	655	327.5	2.059	15,664,460
OAKLAND	240	120.0	3.5294	5,740,000
LOS ANGELES	778	389.0	2.0419	18,606,210
SAN DIEGO	235	117.5	3.1184	5,619,460
DALLAS	713	356.5	2.4334	17,052,105
MIAMI	594	297.0	2.4647	14,206,500
HOUSTON	324	162.0	2.4545	7,749,000
MINNEAPOLIS	252	126.0	2.1355	6,027,000
PITTSBURGH	451	225.5	2.7839	10,785,460
BALTIMORE	197	98.5	1.1588	4,711,105
	11,680	5840.0		$279,345,710

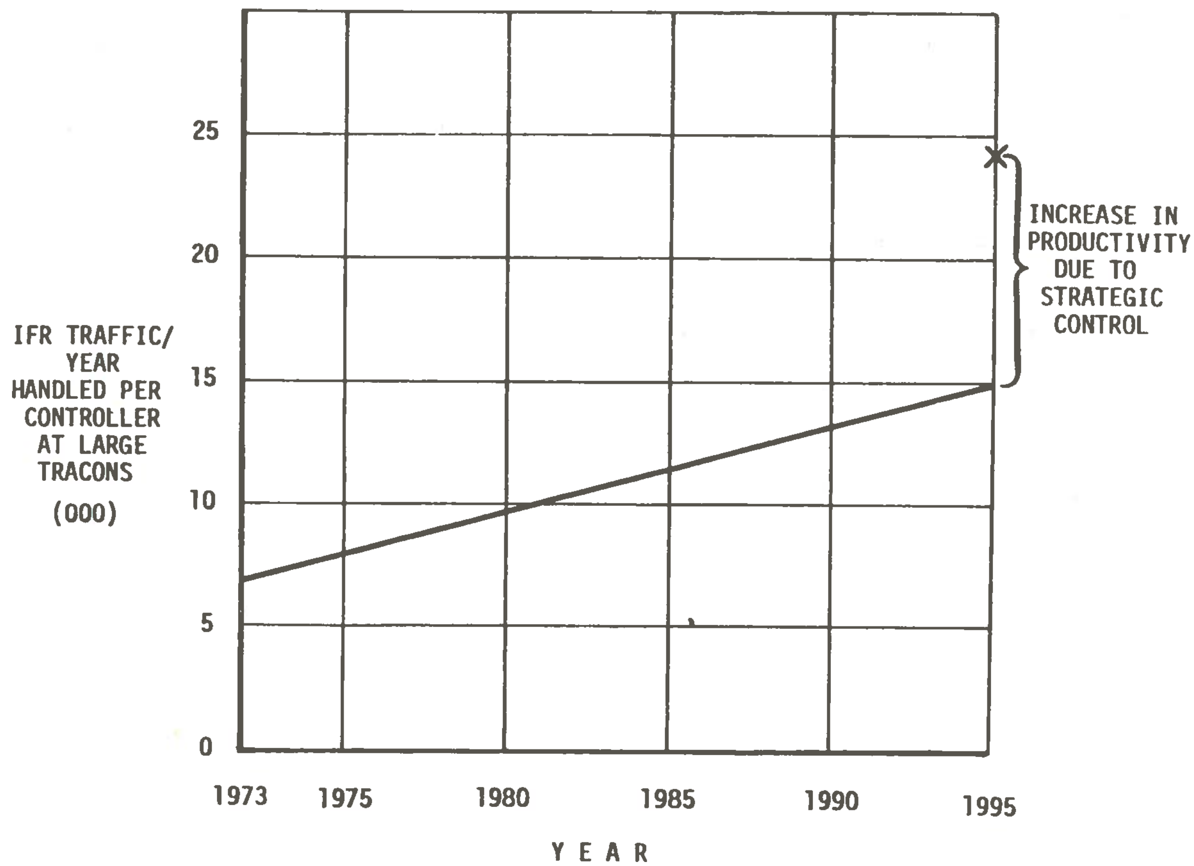


FIGURE 8-19.—LOS ANGELES TRACON PRODUCTIVITY

9.0 STRATEGIC CONTROL RDT&E PLAN

This section presents a research, development, test, and evaluation (RDT&E) plan proposed for developing the strategic control capability so that in 1982 it can be considered for implementation as the primary method in the advanced air traffic management system for controlling air carrier and other high-performance airplanes along the high-density air routes and in high-density terminal areas.

9.1 DEVELOPMENT RATIONALE

The objectives of the strategic control research and development program are to:

- Establish the feasibility of strategic control
- Determine the performance of strategic control
- Develop the concept to a level that will provide the confidence to initiate acquisition of the operational capability

The research and development program is directed toward developing strategic control in levels of increasing capability. This provides a controlled program in which each succeeding effort can be adjusted according to the success of the preceding effort in an efficient manner, especially relative to the risk of committing resources without complete substantiation that the program will proceed as planned.

The levels of increasing capability chosen to pace the program are:

1) The basic strategic control capability to control arriving airplanes from multiple entry fixes to one or more parallel runways. Other terminal area control operations will be accomplished tactically.

2) The complete capability to control all arrival terminal area operations to any runway configuration and including handling system disturbances (i.e., go-arounds, diversions, runway reversal/changes, etc.) using strategic control.

3) The capability to strategically control all terminal area operations by adding the capability to control departures.

4) The study of extended strategic control capabilities including further optimization of operations and application to en route control.

The research and development plan recognizes the following constraints and considerations:

1) Analytical efforts are low-cost items and should be used to obtain maximum information before committing to efforts involving hardware and testing.

2) Feasibility must be established using a real-time simulation since a fleet of properly equipped airplanes will not exist and would be inordinately expensive to obtain and operate.

3) At least one airplane test bed must be used to establish the performance and feasibility of the airborne portion of the system and provide a real subject for the real-time simulation.

Each level of capability is approached by: (1) an analysis effort in which the planning and mathematical formulation is completed; (2) development of the software program to implement the capability in a real-time simulation environment; (3) evaluation of the capability in a sophisticated real-time simulation; and (4) a parallel flight test program to substantiate the airborne equipment feasibility and provide a real input to the real-time simulation.

9.2 GENERAL PLAN

The overall plan is shown in figure 9-1. Task 1, development of the basic arrival control capability, encompasses seven subtasks. The analysis of basic arrival control provides the basis for software development and test and includes a functional definition of how a completely strategic controlled terminal area functions. The software is tested in a real-time simulation (such as the National Aviation Facility Experimental Center, NAFEC). The complete simulation includes multiple simulated airplanes, a cockpit simulator, and a live airplane.

Four-dimensional navigation and guidance equipment for strategic control is specified and flight tested to establish a description of its performance. These data are used in the simulated airplane in the real-time simulation.

The avionics is then refined to provide the basic arrival control capability as defined in the analysis. This refined avionics is tested in the operational ARTS III and metering and spacing environment to disclose operating environment requirements and then used as the live airplane in the real-time simulation.

The task 2 analysis defines the method for complete strategic control of all arrival operations. Software to implement this method is developed and tested in the real-time simulation. No airplane test is planned: however, a cockpit simulator will be integrated with the simulator airplane.

The task 3 analysis defines the method for departure control and provides a complete strategic terminal area control system. The software program is extended to incorporate departure control and provide an integrated capability. Both departure control and the integrated capability are tested in the real-time simulation.

In task 3 the avionics is upgraded to include both complete arrival and departure capabilities. This integrated avionics system is flown in the real-time simulation.

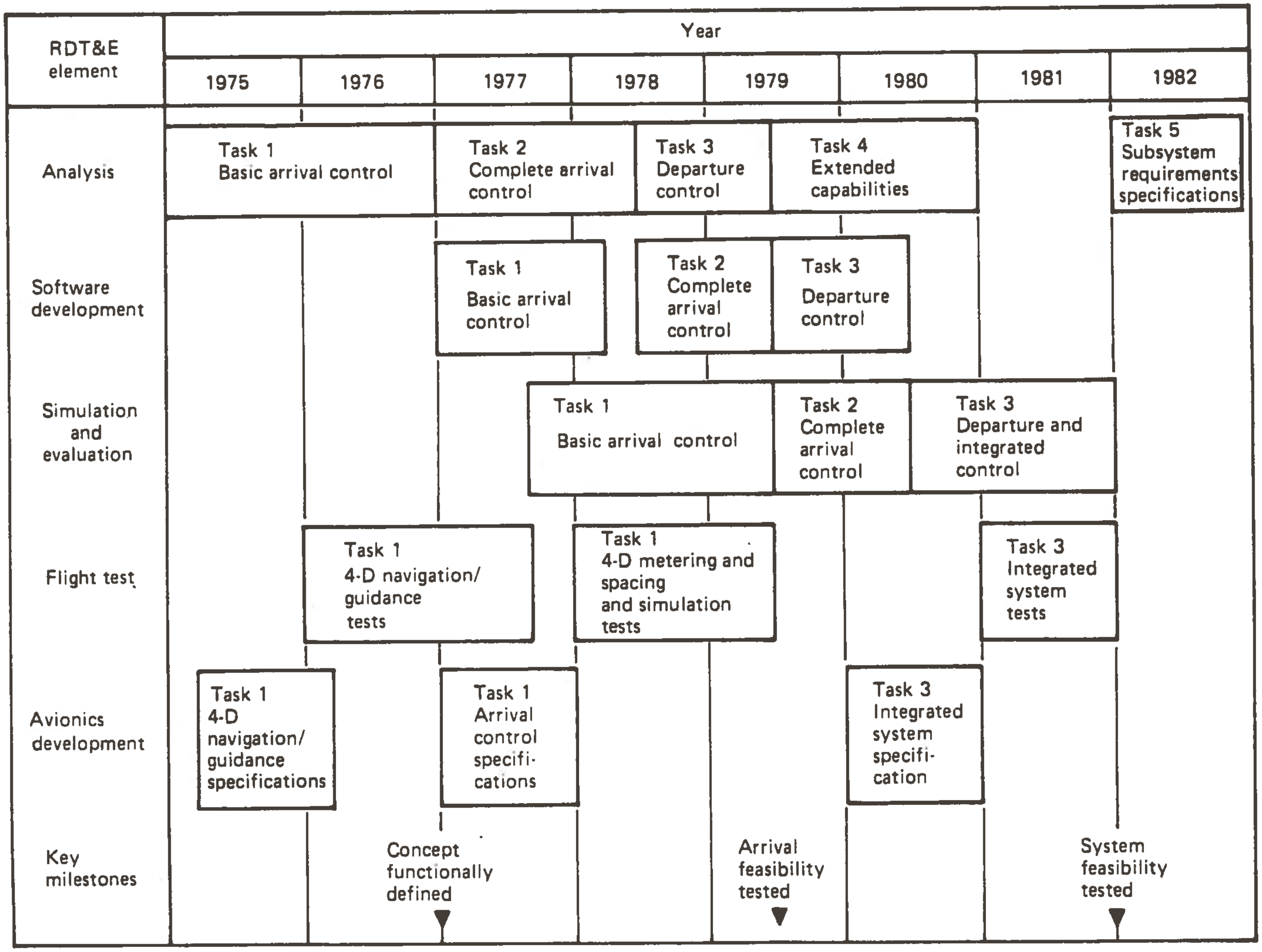


FIGURE 9-1.—GENERAL RDT&E PLAN FOR STRATEGIC CONTROL DEVELOPMENT

Task 4 is a purely analytical effort to investigate means of further refining terminal area control and extending strategic control into the en route system.

Task 5 provides a system specification as a basis for initiating acquisition of an operational system.

The plan provides a continuing set of program checkpoints. The completion of each subtask provides significant items for review and evaluation. The key milestones are:

- At the end of the task 1 analysis where the complete system is functionally defined
- At the end of the task 1 simulation and evaluation where the feasibility of arrival control has been tested and total concept operational feasibility can be inferred

9.3 DETAIL PLAN

Each subtask involved in the strategic control research and development plan is shown in figure 9-2, including the principal inputs and outputs. The following is a description of each subtask involved in the plan.

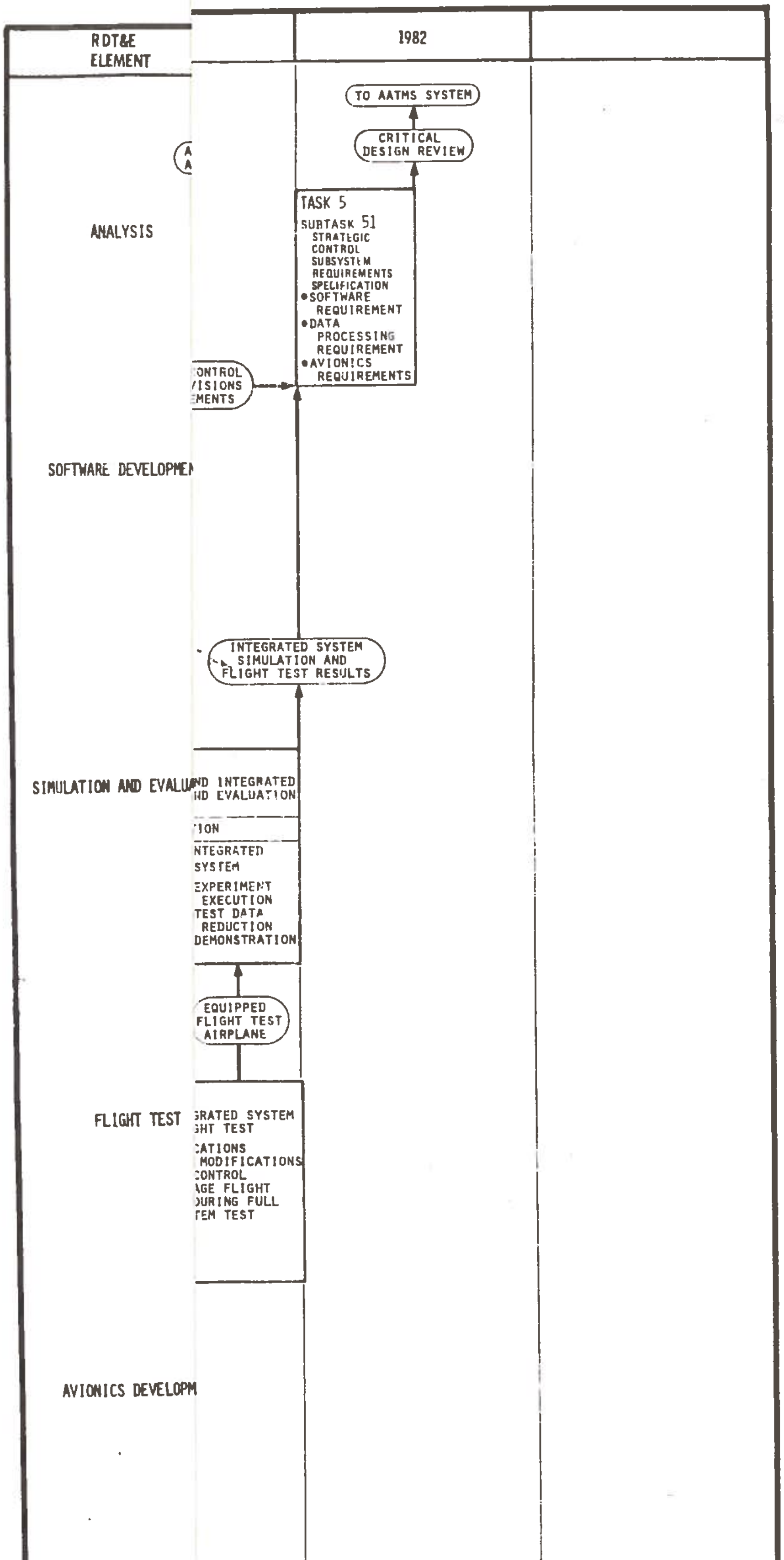
9.3.1 Task 1—Development of Basic Arrival Control Capability

Task 1 develops a basic arrival control capability for the strategic control of arriving airplanes from multiple terminal area entry fixes to single or parallel runways. The task includes the analyses, simulations, and flight tests to demonstrate and evaluate this capability.

Task 1 is presented as a self-contained effort without dependency on previous or concurrent outside programs. However, the following outside programs are recognized and will be considered as described.

1) *Strategic Control Algorithm Development (Contract DOT-TSC-538).*
   This contract will develop a strategic control arrival algorithm and a fast-time terminal area simulation for testing the algorithm. This will be a workable algorithm; however, it will require further work to optimize it into a finalized form for acquisition and use in the operational ATC system. Thus, both the algorithm and fast-time simulation model from this contract will provide a technical base for the analytical work in task 1.

2) *Three- and Four-Dimensional Area Navigation Study (FAA Contract), Advanced Electronics Display System—ADEDS (DOT/FAA Contract), and STOLAND (NASA Contract).*
   These three contracts involve four-dimensional navigation and guidance system development testing. Although the avionics will not be the optimum configurations for strategic control, both the design features (pilot controls) and



9-2.—STRATEGIC CONTROL RDT&E PROGRAM

demonstrated performance will be useful for the task 1 analysis and avionics development efforts. The progress of these programs will be monitored, and the possibility of using the avionics for the equipped airplanes in the task 1 flight tests will be assessed.

9.3.1.1 Subtask 11—Basic Arrival Control Analysis

The objectives of this task are to:

1) Develop the logic for the total strategic control concept

2) Mathematically define the algorithm for the software program to accomplish arrival control

3) Define the simulation experiments required to evaluate the basic arrival control software

The major items of work are:

Item 1: Basic Arrival Control Mathematical Formulation—Analyze airplane performance, arrival control requirements, and runway demand schedules to mathematically define the algorithm for strategic control of arrivals. This development will use fast-time terminal area simulation to evolve the algorithm.

Item 2: Avionics Functional Requirements—Define the functional capability required in the airplane to accomplish strategic control.

Item 3: Data Processing System Requirements—Develop an initial estimate of the ground-based data processing required to accomplish strategic control.

Item 4: Complete Strategic Control Functional Concept—From a functional standpoint, develop a description of how strategic control can be used to accomplish all of the terminal area arrival and departure operations.

Item 5: Arrival Control Performance Analysis—Using the fast-time simulation from item 1 as a source of data, assess the terminal area performance achievable by strategic control in terms of capacity, peak flow rates, and control communication workload indicators.

Item 6: Flight Test Requirements—Define the flight test conditions and data collection requirements for the four-dimensional navigation guidance performance and ARTS III and metering and spacing environment flight tests.

Item 7: Simulation and Evaluation Requirements—Define the test conditions and data collection/analysis requirements for the real-time simulation experiments.

Item 8: Communication System Requirements—Using the strategic concept functional description and fast-time simulations, define the communication capabilities required to support strategic control.

9.3.1.2 Subtask 12—Basic Arrival Control Simulation Software Development

The objective of this subtask is to provide the detailed computer program for mechanizing the basic strategic control arrival capability. The output is the computer program in a form suitable for implementation and testing on the basic arrival control simulation. The inputs for this subtask will be a mathematical description of the geometry, scheduling strategy, route-time profile generation technique, demand requirements, aero-performance definition, and simulation objectives from the basic arrival control analysis (subtask 11). The simulator hardware/software interfaces are also input from the simulation effort (subtask 13).

The principal effort involves: (1) defining a suitable programming strategy; (2) developing the required logic flowcharts, timing diagrams, software checkout procedure, memory format and utilization; and (3) developing a coded algorithm suitable for implementation on the simulator. As this basic arrival control software will grow to encompass the complete arrival control capability (subtasks 12 and 22) and the departure control capability (subtasks 13 and 23), the resulting program must be modular in construction with the space and provisions provided for these expected future additions.

9.3.1.3 Subtask 13—Basic Arrival Control Simulation and Evaluation

The objective of this subtask is to provide a real-time simulator and the simulation capability to test and evaluate the basic strategic arrival control capability. This simulation effort will provide the capability to include complete arrival control and departure control to be implemented in future subtasks (subtasks 23 and 33). In addition, the simulation must be capable of accommodating flight test airplanes as part of the real-time mechanization.

This simulation subtask is divided into three distinct work items: (1) simulation design, (2) implementation, and (3) evaluation.

Item 1: Simulation Design—Beginning with the simulation experiment requirements resulting from the basic arrival control analysis (subtask 11), a simulator hardware and software implementation plan is to be prepared, and specifications formulated to define the interface requirements for the evolving basic arrival control program (subtask 12) and the flight test airplane (subtask 17).

A simulation test plan will be prepared that will satisfy the experimental requirements and specify the test data reduction requirements. All simulation software requirements, to test the basic arrival control program, will be delineated. The scope of the simulation is expected to include computer simulated airplanes, a cockpit simulator with characteristic commercial airplane response, and the capability of substituting a flight test airplane, including an instrumented test range and data-link air-ground-air capability. The simulation will model an extended terminal area from en route altitudes to runway exit.

Item 2: Implementation—During implementation all necessary hardware and software is prepared for accomplishing the simulation test plan. All simulation software required to provide stimulus and data acquisition will be prepared and integrated with the basic arrival control program (subtask 12). Software for test data reduction will be prepared and all software/hardware will be checked out.

Item 3: Evaluation—During evaluation the simulation capability prepared during design and implementation will be used to execute the simulation test plan for basic arrival control. The simulation will include two distinct tests: (1) tests using simulated airplanes including ground-based cockpits, and (2) tests using flight test airplanes in addition to simulated airplanes. The principal output of this subtask is the simulation test results, reduced to a form suitable for further analysis, for the basic arrival control capability.

9.3.1.4 Subtask 14—Four-Dimensional Navigation/Guidance Avionics Analysis and Specifications

The objective of this subtask is to provide a specification for the four-dimensional navigation/guidance avionics, which can be: (1) used to determine by flight test the performance capability of an airplane flying four-dimensional paths and (2) modified to incorporate the required strategic arrival and departure capabilities that are to be defined in subsequent analyses (subtasks 11, 21, and 31).

The major items of work are:

Item 1: Avionics Functional Design—Using the basic avionics functional requirements from subtask 11, determine how each function will be accomplished by the avionics.

Item 2: Guidance Algorithm Definition—Analyze and evaluate alternative guidance concepts, using real-time simulation as required, to select the guidance algorithms and design the software program.

Item 3: Flight Control Definition—Develop autopilot design criteria, control laws, and functional features for four-dimensional control of the airplane. Emphasis will be on integrated pitch axis/autothrottle control laws for precise along-track position control. Real-time simulation will be used as needed.

Item 4: Avionics Performance Analysis (Four Dimensional)—Analytically and using real-time simulation, determine the accuracy with which the selected four-dimensional navigation/guidance configuration can be expected to follow assigned four-dimensional flightpaths considering the effects of winds, flightpath shapes, and navigation aid location and errors.

Item 5: On-Board Computation Requirements—Considering self-check, reasonableness checks, and reliability requirements, the required software package will be developed for the four-dimensional navigation/guidance performance flight tests. This software will be tested on a real-time simulation. Similarly, an estimate of the total avionics software requirements that will eventually be needed for complete strategic control operation will be developed.

Item 6: Flight Test Avionics Subsystem Specification—A design/procurement specification for the avionics to be used in the four-dimensional navigation/guidance flight test will be prepared. The specification will provide for growth/modification to accommodate total strategic control. Specification will include: (1) interface requirements to the communication data link, display system, and flight control system; (2) data processing hardware requirements (storage, speed, architecture, and special-purpose equipment); and (3) the guidance and flight control software requirements.

9.3.1.5 Subtask 15—Four-Dimensional Navigation/Guidance Flight Test

The objective of this subtask is to measure the performance capability of an airplane using a four-dimensional navigation/guidance system to flying a predefined four-dimensional track. These results are to be used in the analysis of strategic control system performance and as inputs to the simulator airplanes (subtask 13) representing strategically controlled airplanes.

The major items of work are:

Item 1: Avionics Procurement—The flight test avionics specification from subtask 14 will be used as the basis for procuring a four-dimensional navigation/guidance system for the flight test airplane. Consideration will be given to using existing avionics or equipped airplanes (e.g., STOLAND, ADEDS, etc.).

During this phase the flight test plans will be developed in detail and the required airplane modifications will be specified.

Item 2: Flight Test Preparations—The avionics will be installed in the airplane, the airplane modified as required for the test, and the aircrew trained to operate the system. At the same time the flight test instrumentation, both ground and airborne, will be obtained, prepared, and tested.

Item 3: Flight Test—The planned flight tests will be flown at an appropriately instrumented range (e.g., NAFEC). Test data will be collected and reduced to the form required by the subtask 11 flight test experiment requirements.

9.3.1.6 Subtask 16—Arrival Control Avionics Analysis and Specification

The objective of this subtask is to provide a specification for modifying the avionics developed in subtasks 14 and 15 to provide the capabilities required for strategic arrival control as defined in the output of subtask 11.

The major items of work are:

Item 1: Arrival Control Avionics Definition—Using the arrival control avionics requirements from subtask 11, develop the guidance software, control/display configuration, and flight control system to meet these requirements. This effort will include real-time simulation and crew workload studies as required to select the desired configuration.

Based on the findings from the four-dimensional navigation/guidance flight tests, determine the modifications to the guidance and flight control systems necessary to provide improved capability.

Item 2: Avionics Performance Analysis (Strategic Arrival)—Using analysis and real-time simulation, determine the performance (primarily four-dimensional path-following accuracy) expected from the arrival control avionics configuration considering the arrival paths to be flown, wind effects, and quality of the navigation aids.

Item 3: Arrival Control Avionics Specification—Prepare a specification for the avionics reflecting the results of the four-dimensional navigation/guidance flight tests and arrival control requirements. This specification must recognize the need to modify the avionics configuration specified in subtask 14 into the specified arrival control configuration.

9.3.1.7 Subtask 17—Four-Dimensional Metering and Spacing and Basic Control Simulation Flight Tests

The objectives of this subtask are to:

1) Test the effectiveness of the functional design in a real world situation by flying the four-dimensional equipped airplane in a four-dimensional mode achieved by minimal modification of an ARTS III with metering and spacing environment.

2) Provide an equipped four-dimensional airplane for the basic arrival real-time simulation.

The major items of work are:

Item 1: Four-Dimensional Metering and Spacing Flight Test—The airplane and avionics will be modified to the flight test arrival control avionics specification from subtask 16. An ARTS III with metering and spacing (M&S) site will be selected and the flight test planned. It is envisioned that the arrival route schedule developed in the M&S computer will be data linked to the airplane and airplane performance monitored on the ASR (or instrumentation radar, should the site be at NAFEC). Test flights will be conducted during the night when no other traffic exists and possibly on a noninterference basis during hours containing traffic.

Item 2: Basic Arrival Control Simulation Flight Test—The same airplane and avionics as used in the metering and spacing flight test above will be modified to interface with the basic arrival control simulation. The airplane will fly according to the flight test plan developed in subtask 13, Basic Arrival Control Simulation and Evaluation.

9.3.2 Task 2—Development of Complete Arrival Control Capability

Task 2 develops a complete strategic arrival control capability including operation onto crossing runways, go-arounds, runway changes, "pop-up" demand, dynamic rerouting, and optimal scheduling.

9.3.2.1 Subtask 21—Complete Arrival Control Analyses

The objectives of this task are to:

1) Develop the logic for strategic control of all terminal area arrival operations

2) Mathematically define the algorithm for the software program to accomplish complete arrival control

3) Define the simulation tests and experiments required to evaluate the software program

The major items of work are:

Item 1: Complete Arrival Control Mathematical Formulation—Analyze airplane performance and control requirements to mathematically define the algorithm for strategic control of all operations associated with arrival operations, and test the algorithm in a fast-time simulation.

Item 2: Simulation and Evaluation Requirements—Define the test conditions and data collection/analysis required for the real-time simulation experiments.

Item 3: System Analysis—Extend the system performance, concept, and subsystem requirements definitions from subtask 11 to include complete arrival control.

9.3.2.2 Subtask 22—Complete Arrival Control Simulation Software Development

The objective of this subtask is to provide the detailed computer program for mechanizing the complete strategic arrival control capability. The output is the computer program in a form suitable for implementation and testing on the complete arrival control simulation. The inputs for this subtask will be a mathematical description of the geometry, scheduling strategy, route-time profile generation technique, demand requirements, aero-performance definition, and simulation objectives from the complete arrival control analysis (subtask 21). These inputs specifically involve the increased capability to be added to the previously programmed (subtask 12) basic arrival control capability. Included in these additions will be a capability for crossing runways, go-around, and runway reversal rescheduling and path assignment.

The principal effort involves defining a suitable programming strategy, evolving the logic flowcharts, timing diagrams, software checkout procedure, memory format and utilization, and finally a coded algorithm suitable for implementation on the simulator. This algorithm will include the basic arrival capability (subtask 12) as a subset.

9.3.2.3 Subtask 23—Complete Arrival Control Simulation and Evaluation

The objective of this subtask is to provide the real-time simulation capability to test and evaluate the complete arrival control mechanization (subtask 22). This simulation effort will be an extension of that resulting from the basic arrival control simulation (subtask 13). The effort will include simulated airplanes only, with flight test deferred to integrated system simulation and flight test (subtask 33). This simulation subtask is divided into two work items: implementation and evaluation. The simulation design is assumed to be as designed in the basic arrival control simulation (subtask 13).

Item 1: Implementation—This implementation item will prepare the necessary simulation test plan for the complete arrival capability and perform the software/hardware integration and checkout. This test plan will be designed to accomplish the work scoped by the simulation experiment requirements resulting from the complete arrival control analysis (subtask 21). The basic software input is the coded complete arrival control program (subtask 22). In addition, the preparation and checkout of necessary test data reduction software will be accomplished.

Item 2: Evaluation—During evaluation, the simulation capability resulting from the implementation item above will be used to execute the simulation test plan for complete arrival control. The principal output of this subtask is the simulation test results, reduced to a form suitable for further analysis, for the complete arrival control capability.

9.3.3 Task 3—Development of Departure Control Capability

In task 3, the capability to strategically control departures integrated with complete control arrivals is developed.

9.3.3.1 Subtask 31—Departure Control Analysis

The objectives of this task are to:

1) Develop the logic for strategic control of departures including integration with the complete control of arrivals

2) Mathematically define the algorithm for the software program to accomplish departure and integrated control

3) Define the simulation tests and experiments required to evaluate the departure and integrated control software

The major items of work are:

Item 1: Departure Control Mathematical Formulation—Analyze airplane performance and departure control requirements and mathematically define the algorithm for strategic control of departures including integration with arrival control and test the algorithm in a fast-time simulation.

Item 2: Simulation and Evaluation Requirements—Define the test conditions and data collection/analysis required for the real-time simulation experiments.

Item 3: System Analysis—Extend the system performance, concept, and subsystem requirements definitions from subtasks 11 and 21 to include departure control.

9.3.3.2 Subtask 32—Departure Control Simulation Software Development

The objective of this subtask is to provide the detailed computer program for mechanizing the strategic departure capability. This program, when added to those of basic and complete arrival control, forms a total integrated strategic control capability. The output of this subtask is the coded computer program in a form suitable for implementation and testing of both departure control capability and as a totally integrated control system for arrivals and departures. The basic input to this subtask is the mathematics and concepts that describe departure control and its relationship to the arrival control capability as accomplished in preceding subtasks.

The principal effort involves: (1) defining a suitable programming strategy; (2) developing the required program flowcharts, timing diagrams, software checkout procedure, memory format and utilization requirements; and (3) developing a coded algorithm suitable for implementation on the simulator. This algorithm will include departure and integrated system capability.

9.3.3.3 Subtask 33—Departure Control and Integrated System Simulation and Evaluation

The objective of this subtask is to provide the real-time simulation capability to test and evaluate the departure control capability and the totally integrated strategic control capability. This integrated capability will include all features of basic and complete arrival control as well as departure control. Included will be a flight test airplane during the integrated system tests. During the separate departure control simulation experiments only simulated airplanes will be implemented.

This simulation subtask is divided into three items of work:

1) Implementation

2) Departure control test and evaluation

3) Integrated system simulation and flight test

Item 1: Implementation—During implementation the simulation test plan will be prepared to meet the experiment requirements for both departure control and integrated system testing as defined by the departure control analysis (subtask 31). The departure control program (subtask 32) will be integrated into the simulator and checked out. At this point, the simulator will encompass the integrated system capability. Necessary test data reduction software and flight test range interface software will be prepared and checked out. At the completion of this item of work, the simulation and data reduction capability will be complete for accomplishing the simulation test plan for departure control and integrated system tests.

Item 2: Departure Control Test and Evaluation—The portions of the simulation test plan pertaining to strategic departure control will be executed on the simulation prepared in item 1 above. The principal output of this item is the departure control experimental results, reduced to a form suitable for further analysis.

Item 3: Integrated System Simulation and Flight Test—This item of work will use the simulation capability to test and evaluate the fully integrated strategic control system to execute the experiments as required by the simulation test plan of item 1 above. This item includes tests with a strategically equipped flight test airplane in conjunction with simulated airplanes. The total system capability and technical feasibility is established at the completion of this item. The principal output is the simulation test results, in a form suitable for total system specification.

9.3.3.4 Subtask 34—Departure Control Avionics Analysis and Specification

The objective of this subtask is to provide a specification for modifying the avionics to provide the capabilities required for complete arrival control (as defined in subtask 21) and departure control (as defined in subtask 31).

The major items of work are:

Item 1: Complete Arrival and Departure Avionics Definition—Using the complete arrival control avionics requirements from subtask 21 and the departure control avionics requirements from subtask 31, develop the guidance software, control/display configuration, and flight control system to meet these requirements. This effort will include real-time simulation and crew workload studies as required to select the desired configuration.

Item 2: Avionics Performance Analysis (Strategic Departure)—Using analysis and real-time simulation, determine the performance expected from the complete arrival and departure avionics configuration considering the paths to be flown, wind effects, and quality of the navigation aid.

Item 3: Departure Control Avionics Specification—Prepare a specification for the avionics to be flight tested in the departure and integrated system flight tests. This specification must recognize the requirement to modify the avionics configuration specified in subtasks 14 and 16 into the final specified configuration.

9.3.3.5 Subtask 35—Integrated System Simulation Flight Test

The objective of this subtask is to provide an airplane into the real-time simulation of subtask 33 to test the departure and integrated strategic control capabilities.

The major items of work are:

Item 1: Airplane and Avionics Modification—The airplane and avionics from subtask 17 will be modified to the flight test departure control avionics specification from subtask 34.

Item 2: Integrated System Flight Test—The airplane will fly in the departure and integrated system real-time simulation according to the experiment plan developed in subtask 33, Departure Control and Integrated Systems Simulation and Evaluation.

9.3.4 Task 4—Analysis of Extended Capabilities

Task 4 is the analysis to identify and investigate strategic control system growth and improvement potentials.

9.3.4.1 Subtask 41–Extended Capability Analysis

Analyze airplane performance and control requirements to provide extended strategic control capabilities. Candidate areas of investigation will include, but not be limited, to:

1) Scheduling of arrivals and departures with complete flexibility as to paths flown by each individual flight without reference to a predetermined track system

2) Strategic control in en route airspace to solve traffic routing and conflicts

3) Advanced techniques for scheduling arrival and departure operations at an airfield

4) Strategic scheduling and control of terminal areas and along air routes to determine the feasibility and recommended form of completely scheduling a network of airports and air routes

9.3.5 Task 5–Subsystem Specification

Task 5 provides the strategic control subsystem specification necessary for initiating system acquisition.

9.3.5.1 Subtask 51–Strategic Control Subsystem Requirements Specification

Prepare a subsystem specification. This will include performance requirements for the data processing hardware, software, communications, and avionics subsystems.

9.4 STRATEGIC CONTROL RDT&E COSTS

In general, the RDT&E costing consisted of estimating similarities between the strategic control program and programs already in existence. An estimate of the probable number of program instructions provided a method of arriving at an estimate of man-months of effort required to develop software and produce the simulation program.

Man-months, computer hours, and flight test hours were converted to dollars and time phased over the applicable time required to complete the subtasks. Section 9.4.4 discusses in more detail the ground rules on cost estimating relationships used.

9.4.1 Cost Breakdown by Time-Phased Subtask

Figure 9-3 shows the various subtask costs including the cost of checkout computer rental. Figure 9-4 shows the same subtask costs, but has no cost included for computer time, a consideration if the NAFEC facility was used for both software development and simulation.

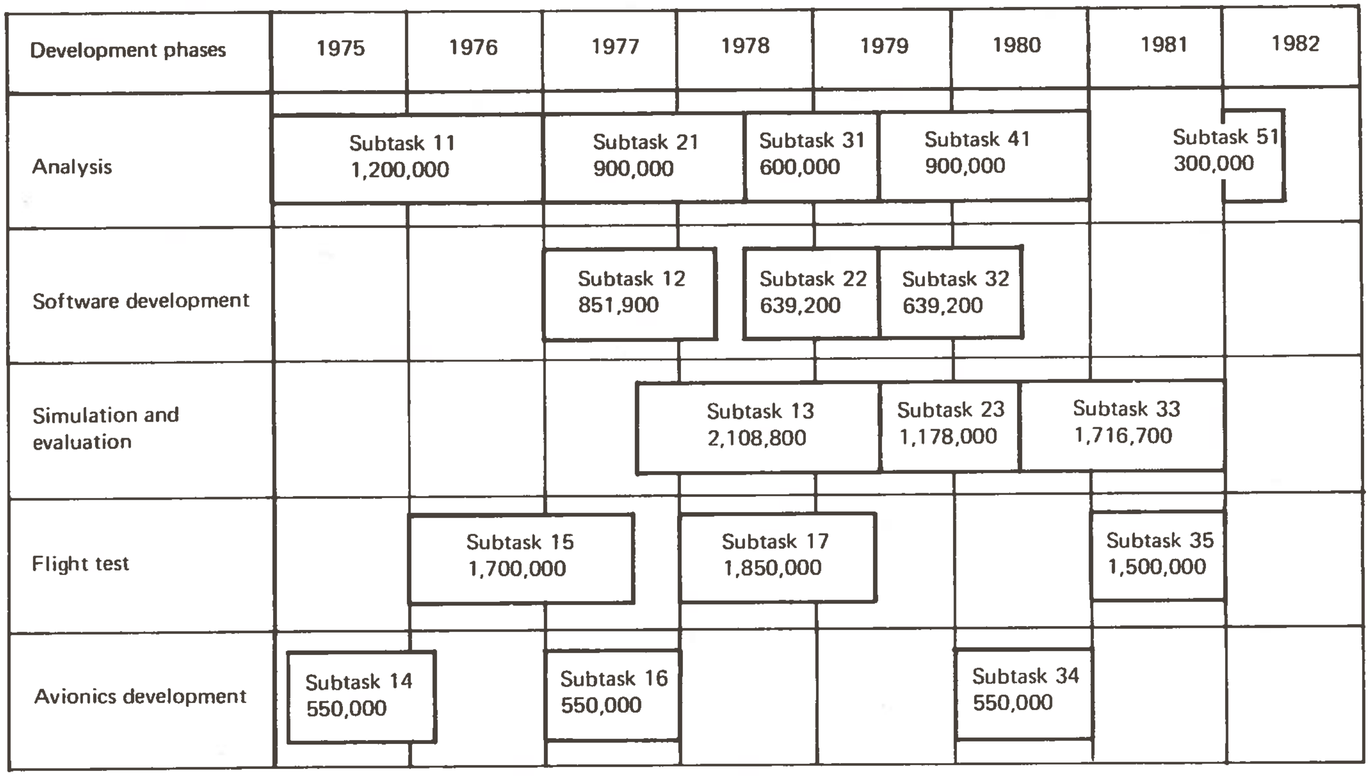


FIGURE 9-3.—STRATEGIC CONTROL RDT&E SUBTASK COSTS — DOLLARS

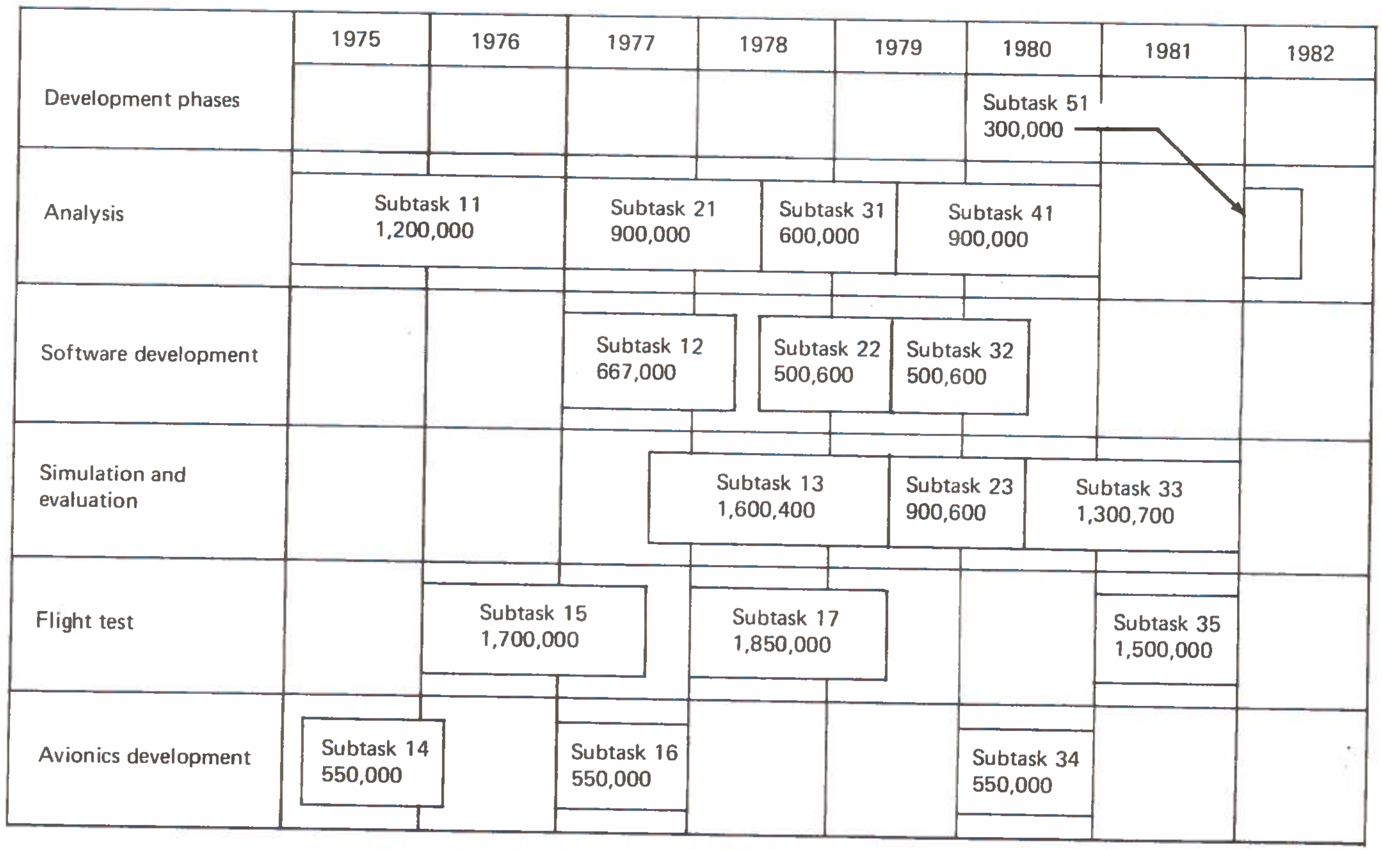


FIGURE 9-4.—STRATEGIC CONTROL RDT&E SUBTASK COSTS – DOLLARS (COMPUTER COST EXCLUDED)

9.4.2 Cost Breakdown by Program Phase and by Calendar Year

Figure 9-5 shows the cost per calendar year for the various phases of the program. Figure 9-6 shows the same breakdown of costs but excludes computer rental costs.

9.4.3 Detailed Subtask Cost Breakdown

Table 9-1 shows the costing detail that was used to assemble the subtask cost estimate. Table 9-2 shows the detail of the subtask costs but excludes the computer rental from facilities costs.

9.4.4 Cost Estimating Relationships (CER)

The cost estimating relationships used to make this estimate are listed as follows:

1) The software development and simulation programmer manning is based upon a program size of 50,000 instructions. The cost estimating relationships used assumes that a programmer can produce 200 instructions per month.

2) The computer time required per man for testing and checkout was assumed to be 10 minutes per day. The cost for using the computer was set at $400 per day. This cost appears in the Facilities column of table 9-1. The RDT&E cost model was exercised both with and without the computer use cost to show the effect of using a government-furnished equipment (GFE) computer.

3) Cost per man per year used was $50,000.

4) Documentation costs used are as follows:

   a) 33-1/3 instructions per page at a cost of $150 per page

   b) Drafting rate for the flow diagrams at three pages per day

   c) Technical review rate at 20 pages per day

Cost per flight hour for the instrumented test airplane was placed at $10,000. This cost includes airplane, crew, and data reduction equipment cost.

Development phases	1975	1976	1977	1978	1979	1980	1981	1982	Total
Analysis	600,000	600,000	600,000	600,000	600,000	600,000		300,000	3,900,000
Software development			639,000	532,500	639,200	319,600			2,130,300
Simulation and evaluation			383,400	1,150,200	1,164,200	1,161,300	1,144,400		5,003,500
Flight test		300,000	1,400,000	1,000,000	850,000		1,500,000		5,050,000
Avionics development	458,200	91,800	550,000			550,000			1,650,000
Total	1,058,200	991,800	3,572,400	3,282,700	3,253,400	2,630,900	2,644,400	300,000	17,733,800

FIGURE 9-5.—ANNUAL STRATEGIC CONTROL PROGRAM COSTS — DOLLARS

Development phases	1975	1976	1977	1978	1979	1980	1981	1982	Total
Analysis	600,000	600,000	600,000	600,000	600,000	600 000		300,000	3,900,000
Software development			500,300	417,000	500,600	250,300			1,668,200
Simulation and evaluation			291,000	872,900	886,800	883,900	867,100		3,801,700
Flight test		300,000	1,400,000	1,000,000	850,000		1,500,000		5,050,000
Avionics development	458,200	91,800	550,000			550,000			1,650,000
Total	1,058,200	991,800	3,341,300	2,889,900	2,837,400	2,284,200	2,367,100	300,000	16,069,900

FIGURE 9-6.—ANNUAL STRATEGIC CONTROL PROGRAM COSTS—DOLLARS (EXCLUDING COMPUTERS)

TABLE 9-1.—STRATEGIC CONTROL SUBTASK COST DETAIL—$

Subtask	Labor	Material and documentation	Facilities	Flight test	Total
11	1,200,000				1,200,000
12	533,300	133,700	184,900		851,900
13	1,466,700	133,700	508,400		2,108,800
14	500,000		50,000		500,000
15	500,000	1,000,000		200,000	1,700,000
16	500,000		50,000		550,000
17	450,000	1,000,000		400,000	1,850,000
21	900,000				900,000
22	400,000	100,600	138,600		639,200
23	800,000	100,600	277,400		1,178,000
31	600,000				600,000
32	400,000	100,600			639,200
33	1,200,000	100,700	416,000		1,716,700
34	500,000		50,000		550,000
35	300,000	1,000,000		200,000	1,500,000
41	900,000				900,000
51	300,000				300,000
Total	11,450,000	3,669,900	1,813,900	800,000	17,733,800

TABLE 9-2.—STRATEGIC CONTROL SUBTASK COST DETAIL—$ (COMPUTERS ASSUMED GFE)

Subtask	Labor	Material and documentation	Facilities	Flight test	Total
11	1,200,000				1,200,000
12	533,300	133,700			667,000
13	1,466,700	133,700			1,600,400
14	500,000		50,000		550,000
15	500,000	1,000,000		200,000	1,700,000
16	500,000		50,000		550,000
17	450,000	1,000,000		400,000	1,850,000
21	900,000				900,000
22	400,000	100,600			500,600
23	800,000	100,600			900,600
31	600,000				600,000
32	400,000	100,600			500,600
33	1,200,000	100,700			1,300,000
34	500,000		50,000		550,000
35	300,000	1,000,000		200,000	1,500,000
41	900,000				900,000
51	300,000				300,000
Total	11,450,000	3,669,900	150,000	800,000	16,069,900

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