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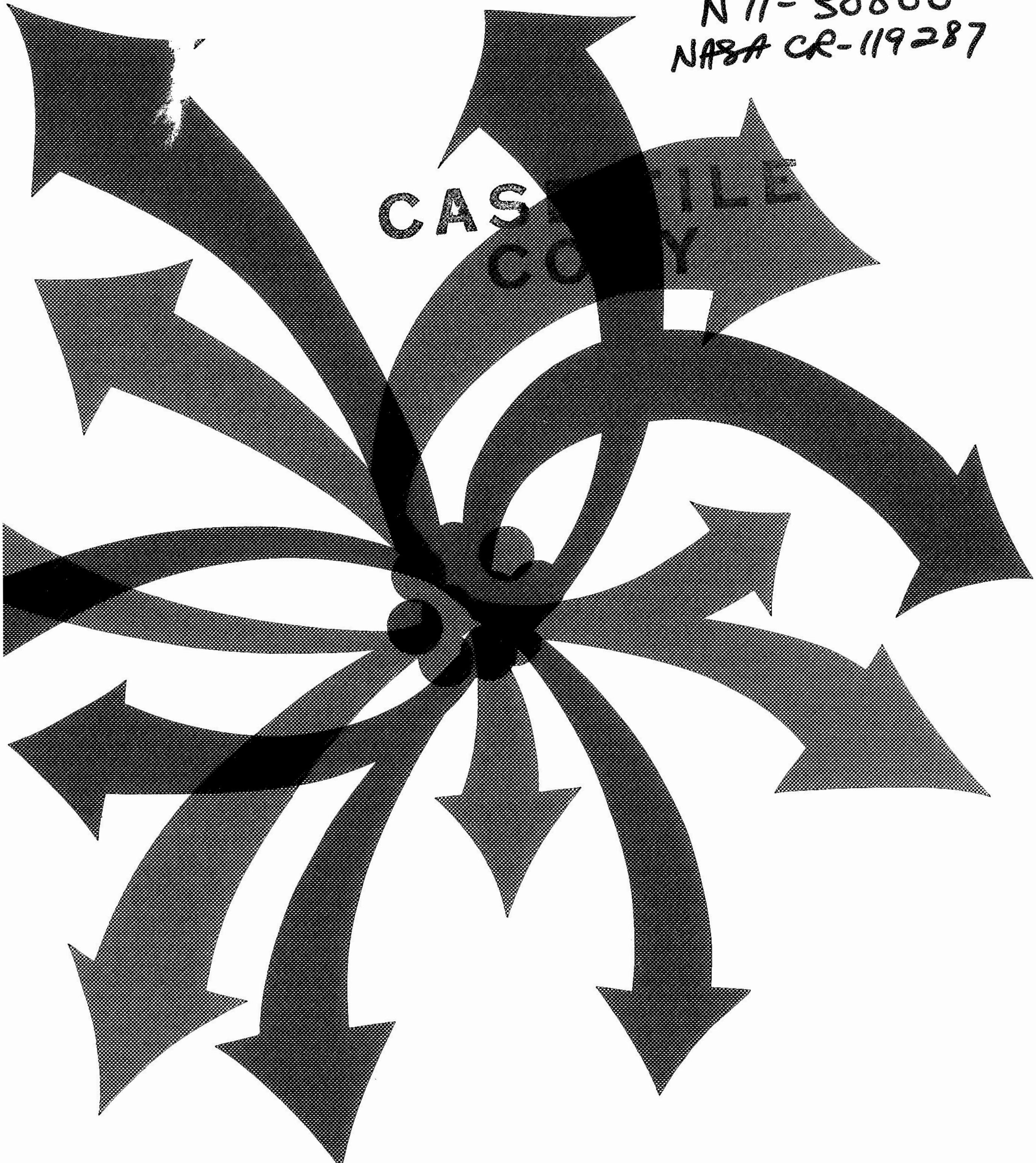

Future Air Traffic: A Study of the Terminal Area

1970 NASA-WVU Summer Predoctoral Fellowship Program in Engineering Systems Design • Langley Research Center and West Virginia University • NASA Grant NGT 49-001-045

FUTURE AIR TRAFFIC:
A STUDY OF THE TERMINAL AREA

NASA LANGLEY RESEARCH CENTER
WEST VIRGINIA UNIVERSITY

Summer Pre-doctoral Fellowship Program
In Engineering Systems Design
1970

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PREFACE

A primary factor in the development of future air transportation is the terminal area air traffic control system. The system must permit the maximum flow of aircraft into and out of the terminal area, safely and economically, so that delays are either eliminated or brought to a theorectical minimum. The system must be capable of eliminating not only today's terminal area delays but also the potential delays of future years based on passenger, aircraft, and airport projections.

The following report considers the "systems design" of terminal area air traffic control systems now through the year 2000. It considers the air traffic control procedures and hardware, including takeoff and landing and air collision avoidance. It considers the impact of passenger and aircraft demand. It considers the impact of aircraft and airport characteristics. Finally, it develops a generalized model which may be used to determine the impact upon terminal area operating time caused by any proposed air traffic control system, airport system or aircraft characteristic.

The design is proposed by the twenty participants of the National Aeronautics and Space Administration - West Virginia University Summer Pre-Doctoral Fellowship Program in Engineering Systems Design as a result of their eleven week study performed at the NASA Langley Research Center. In addition to attaining this design, the purposes of the program were to give the participants a systems design experience and a better awareness of our nation's efforts in aeronautics and astronautics.

Engineering Systems Design Programs have become well recognized for the many benefits they give the participants. They obtain an appreciation of and experience with the overall problems which are involved in preparing a preliminary design. At the same time, each participant has the opportunity to investigate in considerable detail and become expert in one or two particular aspects of the system. A participant learns that he must understand the concepts of other disciplines and how these disciplines relate with his own; he must be able to talk and work with others as a design team; and he must be able to handle systems design problems where often the questions cannot even be properly asked until they are at least partially answered.

The National Aeronautics and Space Administration has encouraged the development of university engineering systems design programs through sponsorship of summer faculty training programs at NASA centers and student pre-doctoral fellowships at universities. As a result, the number of universities offering systems design courses continues to grow; however, the total number remains small. Not all students have the opportunity to take such a course because of the limited curriculum of their institutions. Recognizing this, NASA and West Virginia University have agreed to present a summer program in engineering systems design for which all pre-doctoral students in the country are eligible to apply. The participants receive academic credit from West Virginia University which may be transferred to their home institutions. The twenty participants who prepared the following air traffic control design represent thirteen institutions from across the United States. The NASA and West Virginia University also agreed that there would be added benefit by conducting the program at the Langley Research Center where advantage could be made of the professional staff, facilities, and environment.

This report represents the results of the second NASA-West Virginia University Summer Systems Design Program. The first program conducted during the summer of 1969 resulted in the design "United States Air Transportation 1980."

All design teams hope that their design will contribute to the advancement of society. It is believed that the following design, in addition to the experience it has given the participants, is significant in many respects. It approaches terminal area air traffic control as not merely a combination of procedures and hardware, but as a complex system involving also people, aircraft, and airports. It also proposes a generalized model which may be used to determine the impact of any characteristic upon terminal area operation time.

It is hoped that the following report will aid both the systems design engineer looking at the overall problems associated with future air traffic control systems and also the component engineer looking at a single aspect of the system.

Emil Steinhardt
Program Director and
Associate Professor
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ORGANIZATION

The 1970 NASA-West Virginia University Summer Pre-Doctoral Fellowship Program was a group effort concerned with air terminal systems design. The program was organized into the following three phases:

1. Introductory Work
2. Research and Preliminary Design
3. Final Design and Report

The first phase, covering the initial two weeks of the eleven week program, was devoted to defining a particular problem area which would be investigated and to examining methods of approaching this problem. Once these aspects were completed, the members divided themselves into the following three groups:

1. Aircraft Group
2. Air Traffic Control Procedures and Hardware Group
3. Simulation Group

Each group had the responsibility of fulfilling its own goals as well as meeting the interfaces established with the other two groups. Coordination within the groups was carried on by elected group leaders, and coordination between the groups was conducted by the project manager who also was elected.

The second phase, lasting five weeks, was spent primarily on research. The participants were greatly aided during this phase of the program by the backgroud lectures provided by members of the Langley Research Center staff as well as by experts from industry and government agencies. At the end of this phase, two preliminary briefings were given, one at

Langley Research Center and the other at the Federal Aviation Administration in Washington, D.C. These presentations were made not only to display the results which had been obtained at this point, but more importantly to ascertain the comments and criticisms of the audience. The ideas and improvements which were developed as a result of their remarks were then incorporated into this final report.

The third phase, covering the final four weeks, began with the election of a new project manager and new group leaders. The primary task now was to organize all the material heretofore used, draw conclusions, and integrate this information into the final report. The program concluded with a final presentation at the Langley Research Center.

ACKNOWLEDGEMENT

The members of the 1970 NASA - West Virginia University team express their gratitude to all who have made the successful completion of this report possible. To the many individuals who aided us with their technical advice, timely suggestions, and friendly encouragement we are indebted.

Although it is impossible to single out everyone who gave assistance to the program, certain personnel have been instrumental in insuring its success. Our sincere gratitude is extended to our NASA technical advisors, Mr. George B. Graves and Mr. Harry M. Lawrence for their contributions. In addition, we would like to thank Mr. Malcolm P. Clark, Mr. Joshua R. Foyles, and all the personnel of Langley Research Center who gave us their enthusiastic cooperation. Our gratitude is also extended to the many individuals who addressed us and supplied essential background information. These speakers are listed in Appendix I.

A note of thanks is especially due to the Federal Aviation Administration for the conderation they showed with regard to our requests for technical literature. The reports they supplied proved to be most useful.

Finally, as editor, I would personally like to thank our two secretaries, Mrs. Teresa Parnham and Miss Lucia Eager, for their diligent support. Moreover, I am most grateful to the associate editors of this report. Most importantly, though, I wish to thank my fellow participants in this program for all the consideration, support, and encouragement they have displayed throughout the summer.

R. E. S.

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CHAPTER I

INTRODUCTION

The design of an Air Traffic Control System for the next thirty years has been called "engineering's greatest challenge for the next decade."[1] Air traffic congestion is a growing problem at terminal airport facilities, particularly in large metropolitan areas. Insufficient airport capacity during peak traffic periods has resulted in prolonged delays, deliberate work slowdowns, overtaxed equipment causing frequent failures, and numerous reported near midair collisions. In addition, aviation activity is predicted to at least double by 1980 and to double again by 1995. A problem such as this will not be solved by any single group; the solution will come from the combination of many design teams, each using portions of earlier studies and adding contributions of their own. This was the approach taken by this group.

Several studies exist which provide good backgroud for the air traffic control problem. Among these are the "Report of the Department of Transportation Air Traffic Control Advisory Committee"[2] and the "Report of the Transportation Workshop, Air Transportation 1975 and Beyond."[3] Already, many groups have attempted to extend the results of these two studies.[4,5] This study will extend these two reports by concentrating on a specific subsystem of the total air transportation system.

The area of concentration chosen was the air traffic control system for the terminal area. This was selected because it is one of the most critical parts of the total air transportation system. The final approach and the runway are the bottlenecks of today's system and will continue to be for the future system. The air traffic control system also has all the aspects of a "systems design" problem. Many diverse areas must be surveyed and some of these areas must be looked at in depth. One must design this system with emphasis on the interactions among the various components to insure that the total system works properly.

To attack the problem, the project was divided among three smaller groups and a primary responsibility was assigned to each. The three groups were the Aircraft Group, the Simulation Group, and the Air Traffic Control Procedures and Hardware Group. The responsibility of the Aircraft Group was to determine the demand and terminal area performance characteristics of aircraft now through the year 2000. The Aircraft Group would look at today's demand and types of aircraft and extrapolate this data to the year 2000. With this input data, the other two groups could design an Air Traffic Control System for the future.

The responsibility of the Air Traffic Control Group was to develop air traffic control methods, takeoff and landing criteria and air collision avoidance procedures and hardware to minimize, safely and economically, terminal area operation time for the year 2000. As a start, this group had to become experts in today's air traffic control procedures and hardware. With this background, the air traffic control group could formulate the procedure and hardware which would be needed for the demand and type of aircraft predicted for the year 2000.

The responsibility of the Simulation Group was to develop a simulation model for terminal area operations for the present day system and for the future system. A good working model was necessary to test the procedures developed by the Air Traffic Control Group. A model would also allow trade-off studies such as new runways versus new airports or straight-in approaches versus curved approaches. Thus, a model was needed to evaluate the overall work of the other groups.

Each group had a primary responsibility, but they also had the responsibility of working together in order to make a contribution to the total air traffic control problem. The Aircraft Group would furnish demand and aircraft characteristics to the Air Traffic Control Group. The Air Traffic Control Group would furnish procedure and hardware characteristics to the Simulation Group. The Simulation Group would test these procedures and hardware characteristics and make recommendations to the other two groups. With this type of group relationships the design of an air traffic control system for the year 2000 was carried out.

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CHAPTER II

DEMAND AND PERFORMACE CHARACTERISTICS FOR AIRCRAFT NOW THROUGH THE YEAR 2000

2.1 INTRODUCTION

In order to develop an air traffic control system for the year 2000, it is necessary to have an idea of the terminal area performance characteristics of the aircraft which will then be in service. Also, it is necessary to know approximately how many and of what type the aircraft will be. In this regard, four areas were investigated:

1. Passenger and Cargo Demand. Aircraft in service (especially air carrier and cargo aircraft) are direct reflections of the demand for air transportation. Demand was not pursued as an end in itself but rather as a means to determine the type and number of aircraft in service in the year 2000.

2. Aircraft Fleet. The number and types of aircraft for the year 2000 were determined using the passenger and cargo demand data.

3. Aircraft Performance. This area included the responsibility of determining the terminal area characteristics of present and future aircraft.

4. Wake Vortices. Although this area of study does not fall precisely into the realm of aircraft performance, it was decided to investigate this important problem.

The approaches taken and results obtained in the above four areas are presented in this chapter.

2.2 DEMAND THROUGH THE YEAR 2000

While some projections of the total aircraft fleet of the future have been made, very little work has been done in the area of projecting the number of aircraft, by type, that will be in service in the year 2000. Since this information was required to study the effectiveness of the air traffic control procedures that have been proposed for the future, a technique for predicting the number of future aircraft has been developed that depends on projections of passenger enplanements and cargo ton-miles plus certain assumptions regarding the characteristics of the air-craft. Thus, the following projections are prerequisite to the determination of the passenger and cargo aircraft fleets for the year 2000.

Passenger Demand

Several projections of passenger demand and passenger enplanements have been made for the period 1980-1985, but due to the many variables involved very little work has been done beyond 1985. For the purpose of this report it was decided to use passenger enplanements rather than passenger demand since this is more directly related to aircraft departures and thus the size of the aircraft fleet. In order to determine enplanements through the year 2000 the Federal Aviation Administration projection through 1981[1] was accepted as the best available data. This data was then extrapolated using the following assumptions:

1. 10% annual increase through 1985
2. 5% annual increase from 1985 through 1995
3. 10% annual increase from 1995 through 2000

The results of this extrapolation are shown in Figure 2.1.

The above assumptions have been based on the belief that presently proposed improvements, if implemented on schedule, and the introduction of limited STOL operations on separate runways at existing airports,

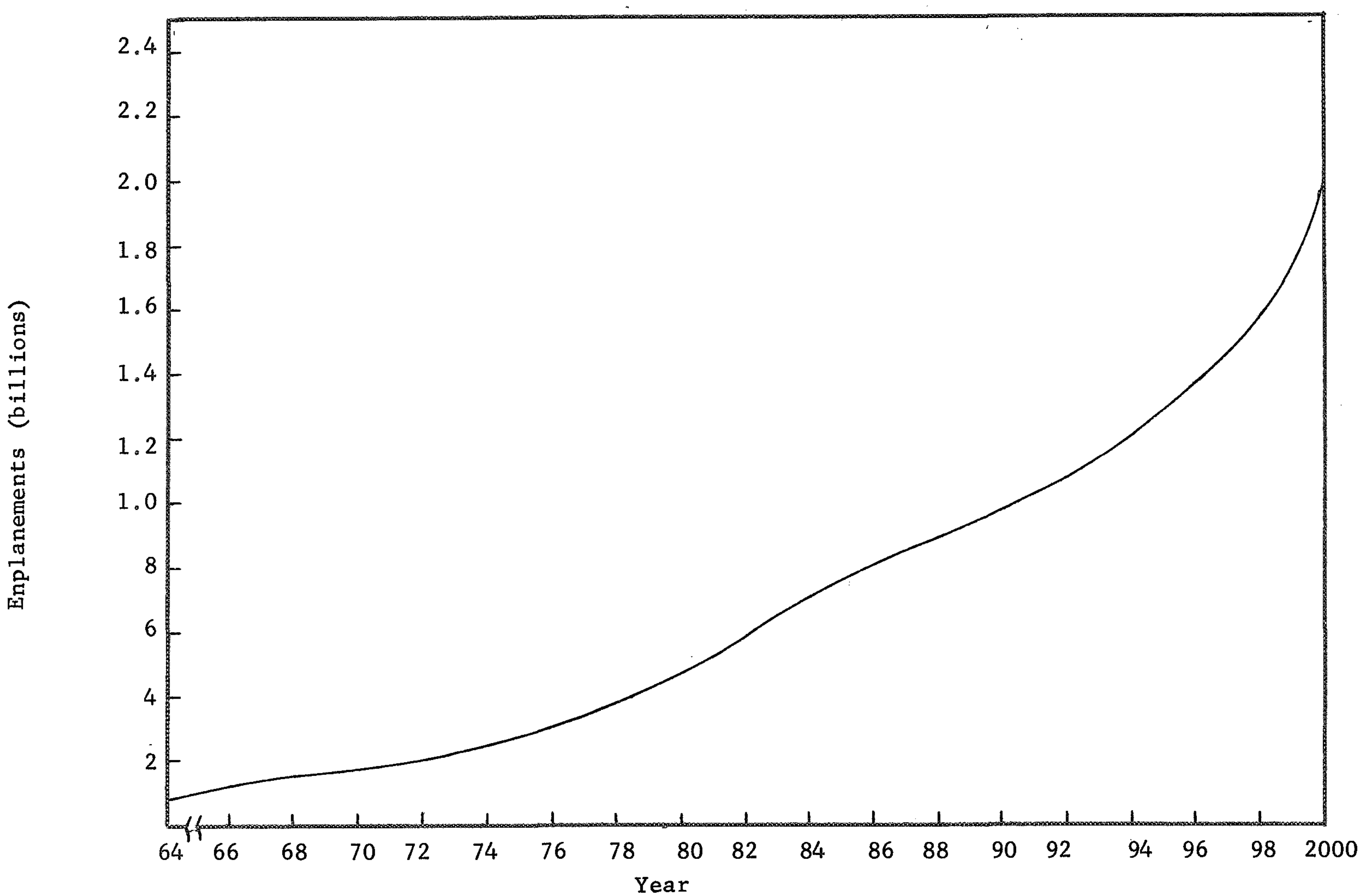

Figure 2.1 Passenger enplanements

will provide a sufficient increase in the system's capacity to accomodate the rapidly increasing passenger demand through 1985 without a significant increase in present-day congestion. However, by 1985 saturation will start to limit the number of operations per day and improvements will not be rapid enough to keep up with demand. This belief is reflected in the reduction from 10% to 5% annual increase in passenger enplanements from 1985 through 1995. During this ten-year period there will be improvements in air traffic control equipment, primarily in the area of computerized operations. However, the main factor affecting the system's ability to handle the increasing demand will be the introduction of STOL and VTOL service on a large scale basis and operating from separate stolports in downtown locations. The above improvements, plus future medium and long range aircraft that seat approximately 1000 passengers, will allow the system to handle the increase in traffic from 1995 through 2000.

Cargo Demand

Before attempting any projections of air cargo demand, it should be noted that a dearth of data exists for the air cargo fleet. As a result, projected cargo demand can be nearly anything to prove nearly any point. Considerable value judgement, based on conversations with various aviation officials, has been used in arriving at the final results. This is not meant as a criticism of the final numbers: it is intended as a guide such that the conclusions may be placed in perspective.

The basis for the year 2000 projections has been the Lockheed-Georgia Report CMRS 99[2] which projected cargo demand to the year 1985.

Lockheed-Georgia has done considerable work in the area of cargo demand. Furthermore, the 1985 projections of the Lockheed report are approximately an average of the other 1985 projections that were available.

The Lockheed projections were broken down into two major subdivisions, belly cargo and all-cargo aircraft. Belly cargo refers to the cargo carried by passenger aircraft; all-cargo refers to aircraft carrying cargo exclusively. The all-cargo aircraft were further subdivided into large jet, medium jet, and small jet. The aircraft are synonymous with range and payload: large jet corresponds to air craft with a range greater than 2500 miles, medium jet refers to aircraft with a range 1500 to 2500 miles, and small jets are aircraft with a range less than 1500 miles. These 1985 projections have been extended to the year 2000. The ton-mile cargo demand has been projected for both domestic and international cargo. This projection has assumed for the time interval 1985-2000 a 17% annual growth rate in domestic cargo, and a 13% annual growth rate in international cargo. This has yielded a 15.5% annual growth rate for the total cargo demand, and is illustrated in Figure 2.2. The 1985 base and the year 2000 projections are illustrated in Table 2.1.

To determine the amount of cargo carried by a type of aircraft over a given distance, a matrix has been developed using the type of aircraft versus its range. The elements of the matrix represent the percentage of total-miles of cargo for a given aircraft at a given range. Note that the matrix assumes four types of cargo aircraft: short haul jet, medium jet, 747 jet, and transonic transport (TST). These types will be discussed later in the aircraft section (Section 2.3). The matrices for domestic and international cargo demand are shown in Table 2.2.

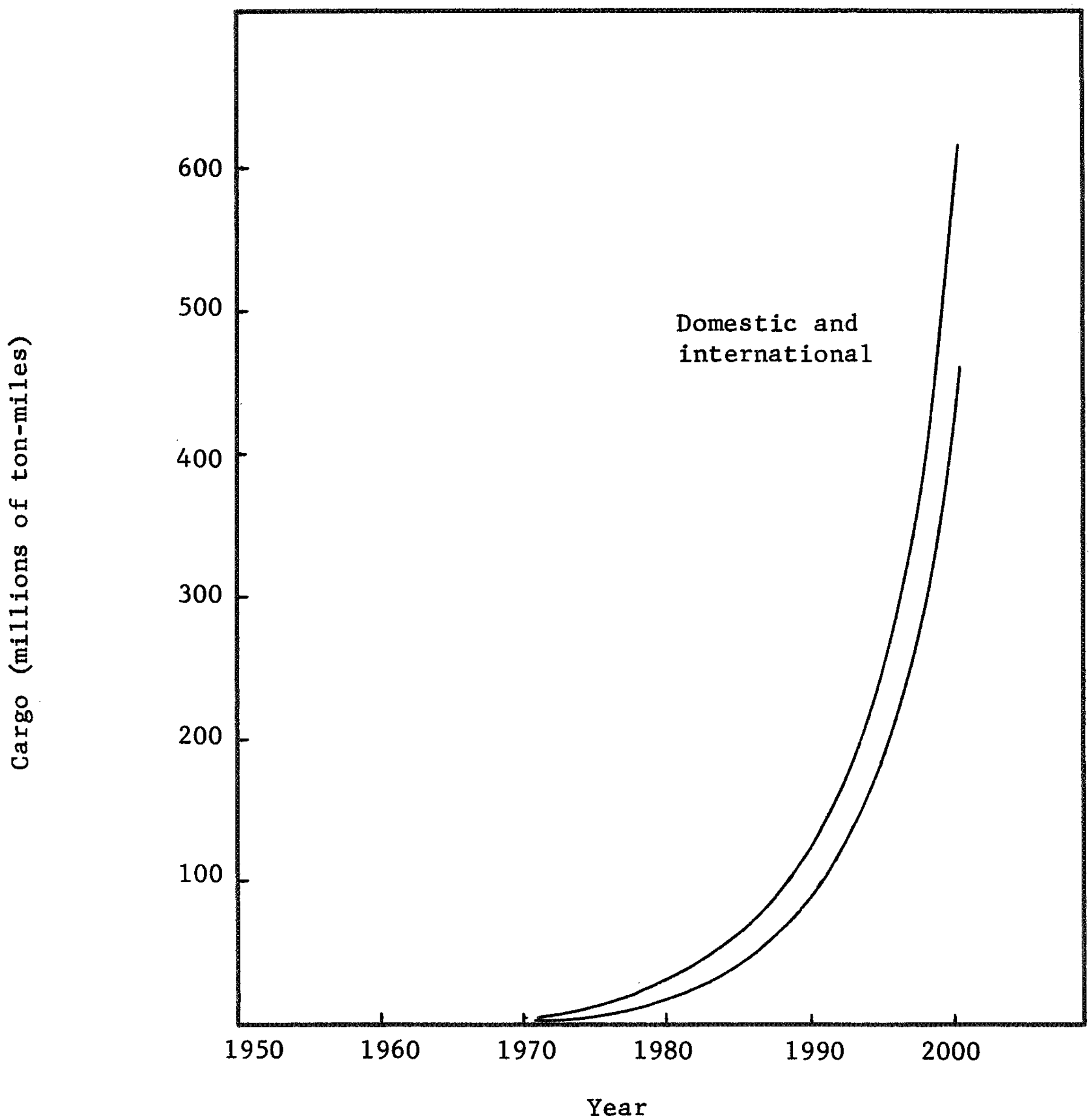

Figure 2.2 Cargo demand.

TABLE 2.1 AMERICAN AIR CARRIER CARGO DEMAND 1985 - 2000

INTERNATIONAL AIR CARGO DEMAND

	MILLION OF TON MILES 1985	% OF 1985 TOTAL	ANNUAL GROWTH RATE	MILLION OF TON MILES 2000	% OF 2000 TOTAL
Total	26,852	100	12.9	166,482	100.0
Belly	2,213	8.2	0.9	1,665	1.0
All Cargo	24,639	91.8	13.4	164,817	99.0
1. Over 2500 miles	23,362	87.0	13.7	162,320	97.5
2. 1500 - 2500 mi.	659	2.5	6.7	1,665	1.0
3. 0 - 1500 miles	618	2.3	1.7	832	0.5

DOMESTIC AIR CARGO DEMAND

	MILLION OF TON MILES 1985	% OF 1985 TOTAL	ANNUAL GROWTH RATE	MILLION OF TON MILES 2000	% OF 2000 TOTAL
Total	41,000	100	17.0	434,600	100.0
Belly	3,463	8.4	1.5	4,346	1.0
All Cargo	37,537	91.6	17.6	430,254	99.0
1. Over 2500 miles	33,406	81.5	18.4	412,870	95.0
2. 1500 - 2500 mi.	1,879	4.6	13.6	13,038	33.0
3. 0 - 1500 miles	2,252	5.5	4.5	4,346	1.0

TOTAL AIR CARGO DEMAND

	MILLION OF TON MILES 1985	% OF 1985 TOTAL	ANNUAL GROWTH RATE	MILLION OF TON MILES 2000	% OF 2000 TOTAL
Total	67,852	100	15.5	601,082	100.0
Belly	5,676	8.4	1	6,011	1.0
All Cargo	62,176	91.6	16.4	595,071	99.0
1. Over 2500 miles	56,768	83.7	16.8	575,190	95.7
2. 1500 - 2500 mi.	2,538	3.7	12.6	14,703	2.4
3. 0 - 1500 miles	2,870	4.2	3.9	5,178	0.9

TABLE 2.2

YEAR 2000 CARGO MATRIX
AIRCRAFT TYPE AND RANGE
(PERCENTAGE OF TON-MILES OF CARGO)

INTERNATIONAL

Range (Miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500
VSTOL	0	0	0	0	0
Short Haul Jet	4.5%	10%	22.5%	0	0
Medium Jet	.5%	10%	45.0%	10.0%	0
747 Jet	0	0	7.5%	80.0%	10.0%
T.S.T.	0	0	0	10.0%	90.0%
S.S.T.	0	0	0	0	0
Total Percentage	5.0%	20.0%	75.0%	100.0%	100.0%

100%

DOMESTIC

Range (Miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500
VSTOL	0	0	0	0	0
Short Haul Jet	4.5%	12.5%	28%	0	0
Medium Jet	.5%	12.5%	42%	10%	0
747 Jet	0	0	0	70%	40%
T.S.T.	0	0	0	20%	60%
S.S.T.	0	0	0	0	0
Total Percentage	5.0%	25.0%	70.0%	100.0%	100.0%

100%

Belly cargo has been projected to be less than 1% of the total cargo (as seen in Figure 2.3) and this is not included in the matrix. The total ton-miles by type and range of aircraft is obtained by multiplying the matrix elements by the total projected ton-miles in each range (0-1500, 1500-2500, > 2500). This gives the ton-miles per aircraft operating at a given range, and is shown in Table 2.3.

2.3 AIRCRAFT PROJECTIONS FOR THE YEAR 2000

In the year 2000, the aircraft fleet is expected not only to be larger, but also to consist of aircraft with characteristics quite different from those in service today. Jumbo jets will double in size and VTOL aircraft and supersonic transports will come into service. A large number of cargo aircraft will be developed to handle the rapidly increasing demand for air cargo. In addition the general aviation fleet will rapidly increase in size.

General Aviation

Although general aviation is not a passenger or cargo service it does comprise a sizeable portion of the air traffic in the terminal area. In addition this segment of air traffic is very difficult to control since most general aviation aircraft are not equipped for IFR conditions. Therefore, some estimate of the size of the general aviation fleet was necessary before recommendations, such as segregated airspace or separate runways could be made.

The total number of aircraft in the general aviation fleet, as well as the number of aircraft in each of ten specific general aviation categories were determined. The primary assumption for these projections

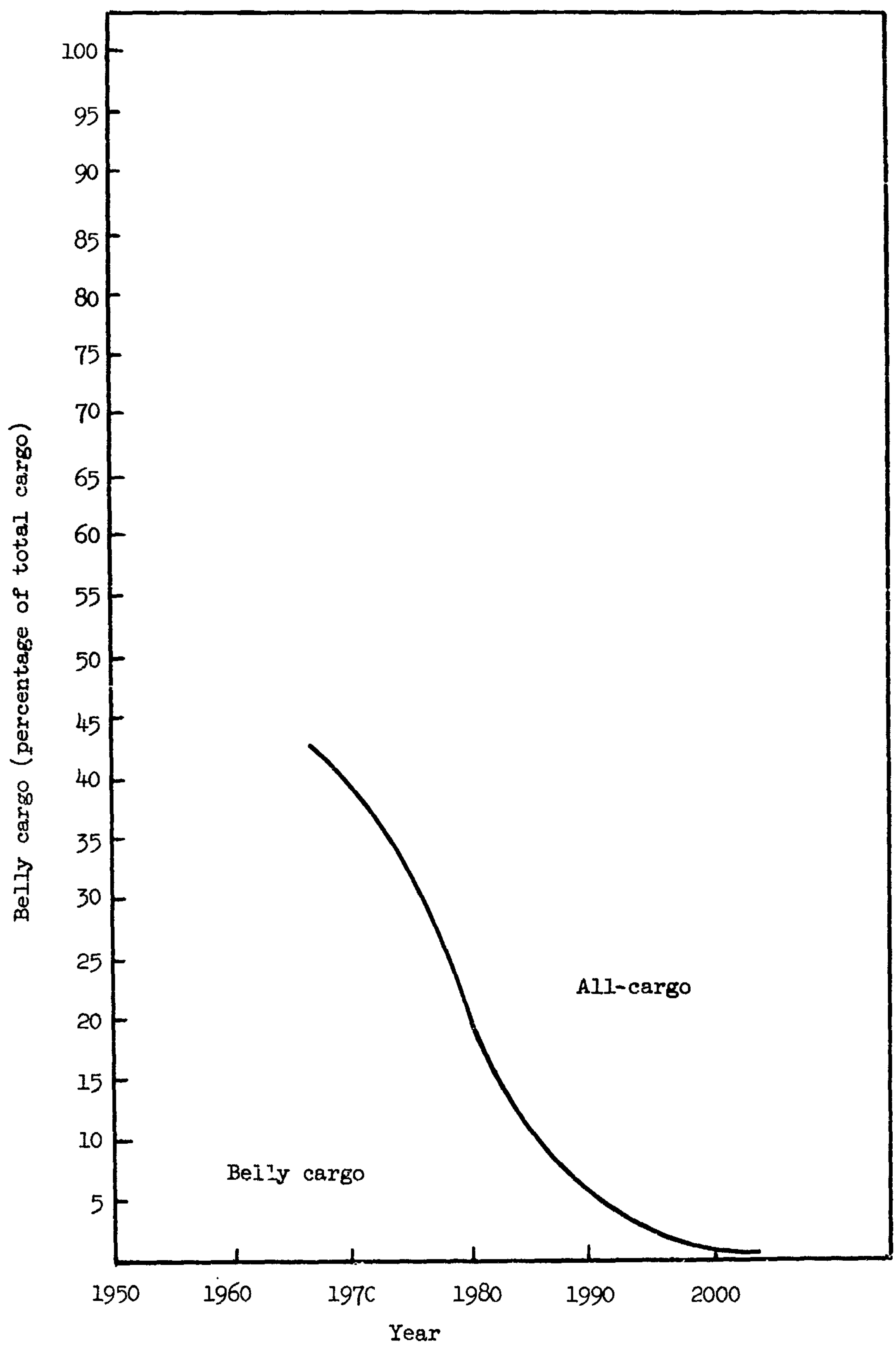

Figure 2.3.- Belly cargo versus all cargo service.

TABLE 2.3 YEAR 2000 CARGO MATRIX
AIRCRAFT TYPE AND RANGE
(MILLIONS OF TON-MILES OF CARGO)

INTERNATIONAL

Range (miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500
VSTOL	0	0	0	0	0
Short Haul Jet	37	83	188	0	0
Medium Jet	4	83	374	166	0
747 Jet	0	0	63	1333	16232
T.S.T.	0	0	0	166	146088
S.S.T.	0	0	0	0	0
Total	41	166	625	1665	162320

DOMESTIC

Range (miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500
VSTOL	0	0	0	0	0
Short Haul Jet	196	543	1217	0	0
Medium Jet	22	543	1825	1304	0
747 Jet	0	0	0	9127	165148
T.S.T.	0	0	0	2607	247722
S.S.T.	0	0	0	0	0
Total	218	1086	3042	13038	412870

was that general aviation would be allowed to grow unconstrained in the future as it has in the past.

Total Fleet Size

Of the three sources[1, 3, 4] used for the projection of the general aviation fleet the Speas' Analysis was considered the most extensive and therefore the most realistic prediction. Several prediction methods were tried by the Speas' Associates and it was found that Gross National Product was, in fact, the best predictor of the fleet size (See Figure 2.4).

The equation ultimately developed and adopted for Speas' forecast of the general aviation fleet contains the important refinement of time lag. It was shown that the best correlation results when a one-year time lag is introduced between measuring the GNP and measuring the fleet size. That is, the 1953 GNP best explains the 1954 fleet. An additional refinement which was incorporated in the model was the discovery that the use of GNP in current dollars yielded significantly better results than using constant dollars. The equation developed is as follows:

$$Y = 7.14 + .142X$$

The value of the GNP (X in the equation) is in billions of current dollars and the resulting estimate of the fleet (Y in the equation), is in thousands of "eligible" aircraft.[+]

[+]The FAA does not include in its number of "eligible" aircraft under a continuous maintenance program, aircraft whose annual inspection reports are delayed or mis-routed, and aircraft whose eligibility lapses (even though it may only be for a short period of time). The Speas' associates contend that these aircraft should be counted and thus come up with a number of "active" aircraft which turns out to be about 6.8 percent higher than the number of eligible aircraft.

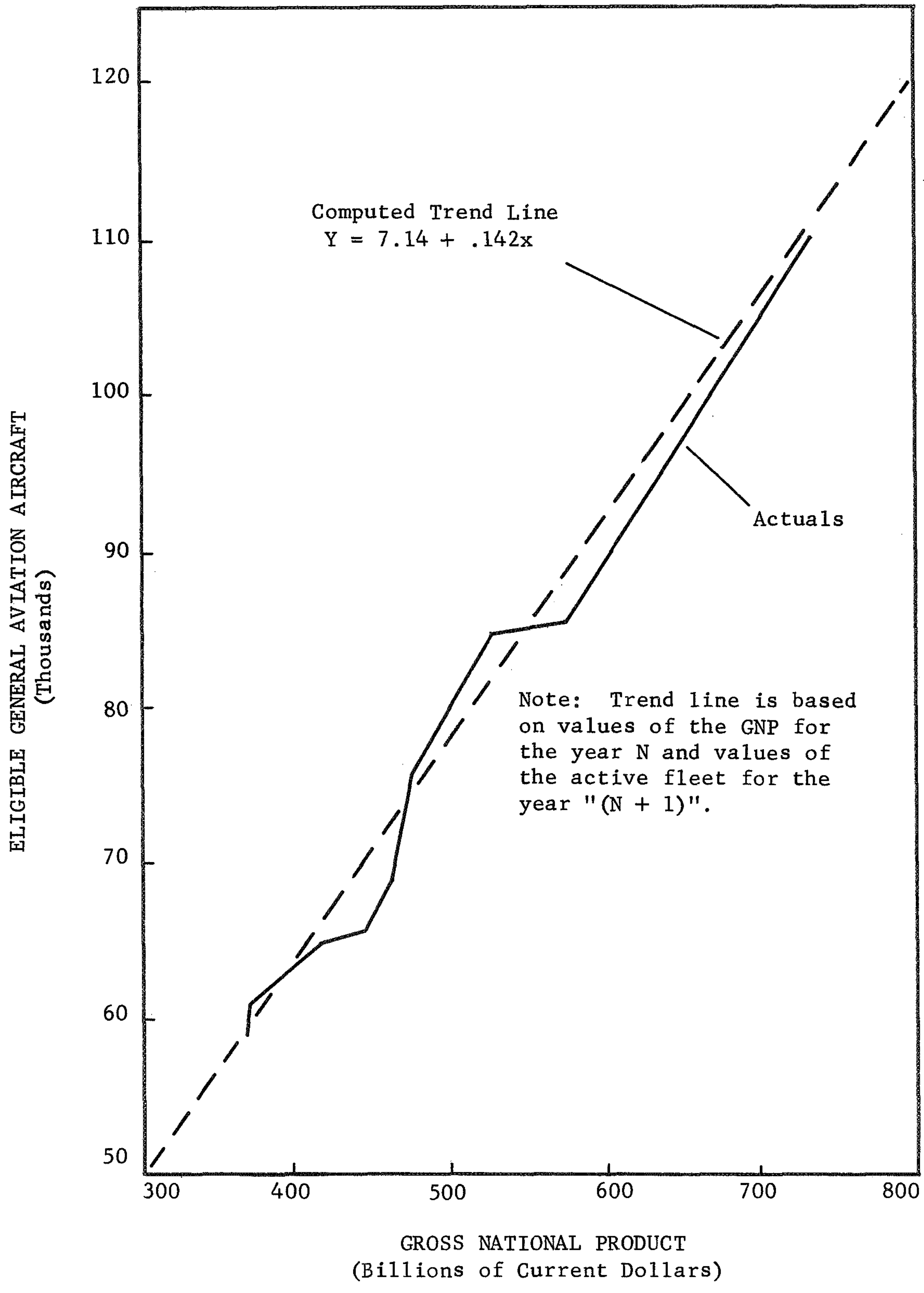

Figure 2.4 COMPARISON OF ACTUAL AND COMPUTED GENERAL AVIATION AIRCRAFT 1953-1957

Speas adopted this equation in preference to several other acceptable ones because it proved very accurate, and was completely in keeping with economic theory. It is a simple statistical equation and all of the statistical tests normally applied to analysis of this type yielded acceptable values. The differences between the actual historical fleet size and the size as estimated by the equation were very low, suggesting no apparent pattern other than a linear relationship.

Figure 2.4 demonstrates the closeness of the fit between the values forecasted by the equation and the actual values.

The preceding equation was modified by the application of a 6.8 percent factor to account for the difference between the number of FAA "sligible" aircraft and the number of "active" aircraft determined by Speas' Analysis. This modification results in the final equation

$Y = 1.068\ (7.14 + .142X)$,

where Y now is in thousands of "active" aircraft.

The GNP forecast and the corresponding forecast of the general aviation fleet (along with the ATCAC[4] and FAA[1] forecasts) are shown in Figures 2.5 and 2.6 respectively.

Listed in Table 2.4 are the predicted GNP and general aviation fleet size from now through 2000.

> It is important to note once again that these projections are based on the assumption that no new material constraints on the growth of General Aviation will develop. In fact, however, during 1969 several developments have tended to limit the demand for General Aviation services. An even greater number of limitations are expected before corrective action can be influential in reversing this trend at several of the major U.S. air transportation hubs.
>
> Again, in this sense, the forecasts are a projection of potential demand, given the discretionary spending desires of individuals and the recognized utility of general aviation to U.S. businessmen.[3]

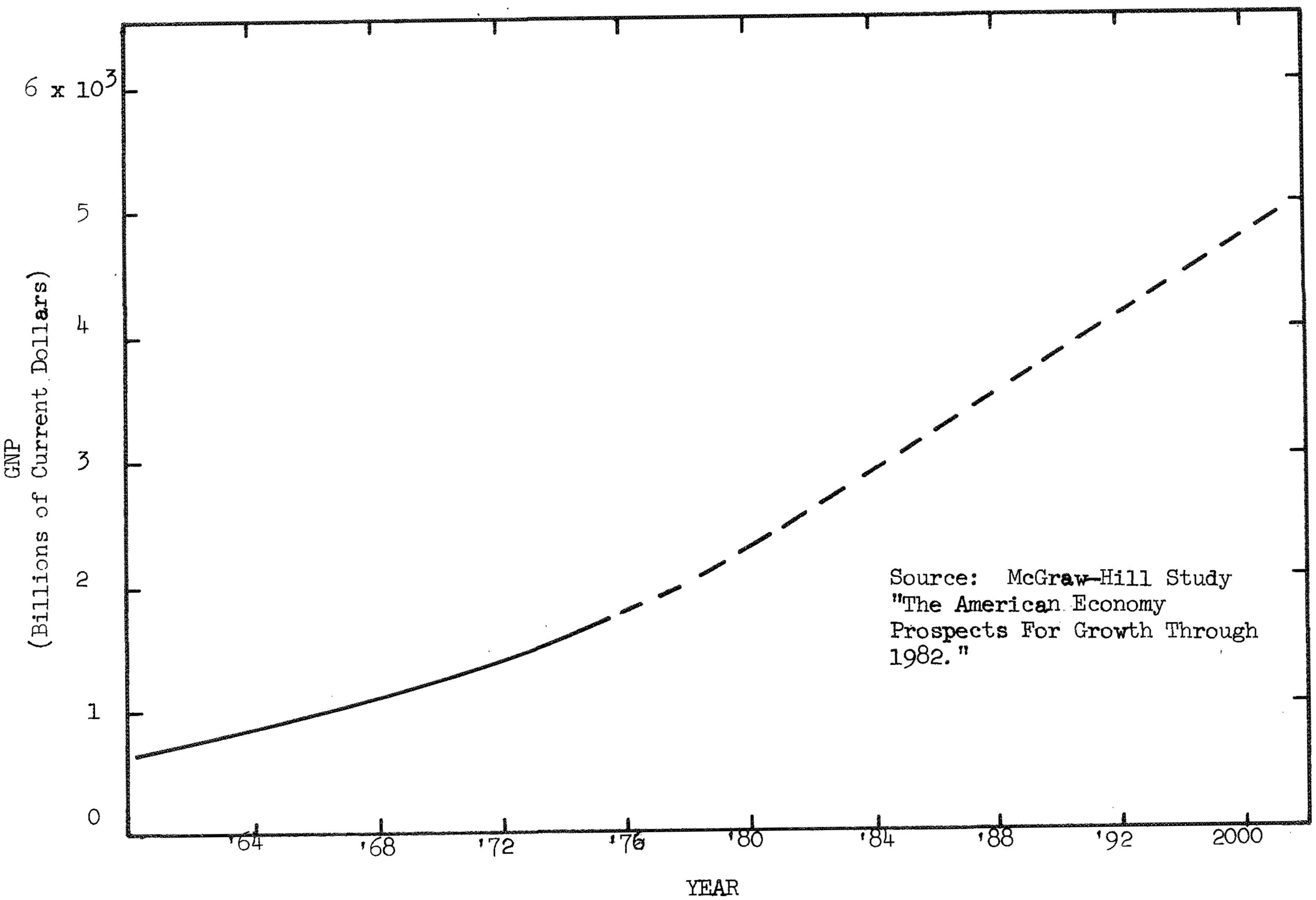

Figure 2.5 FORECAST OF U.S. GROSS NATIONAL PRODUCT

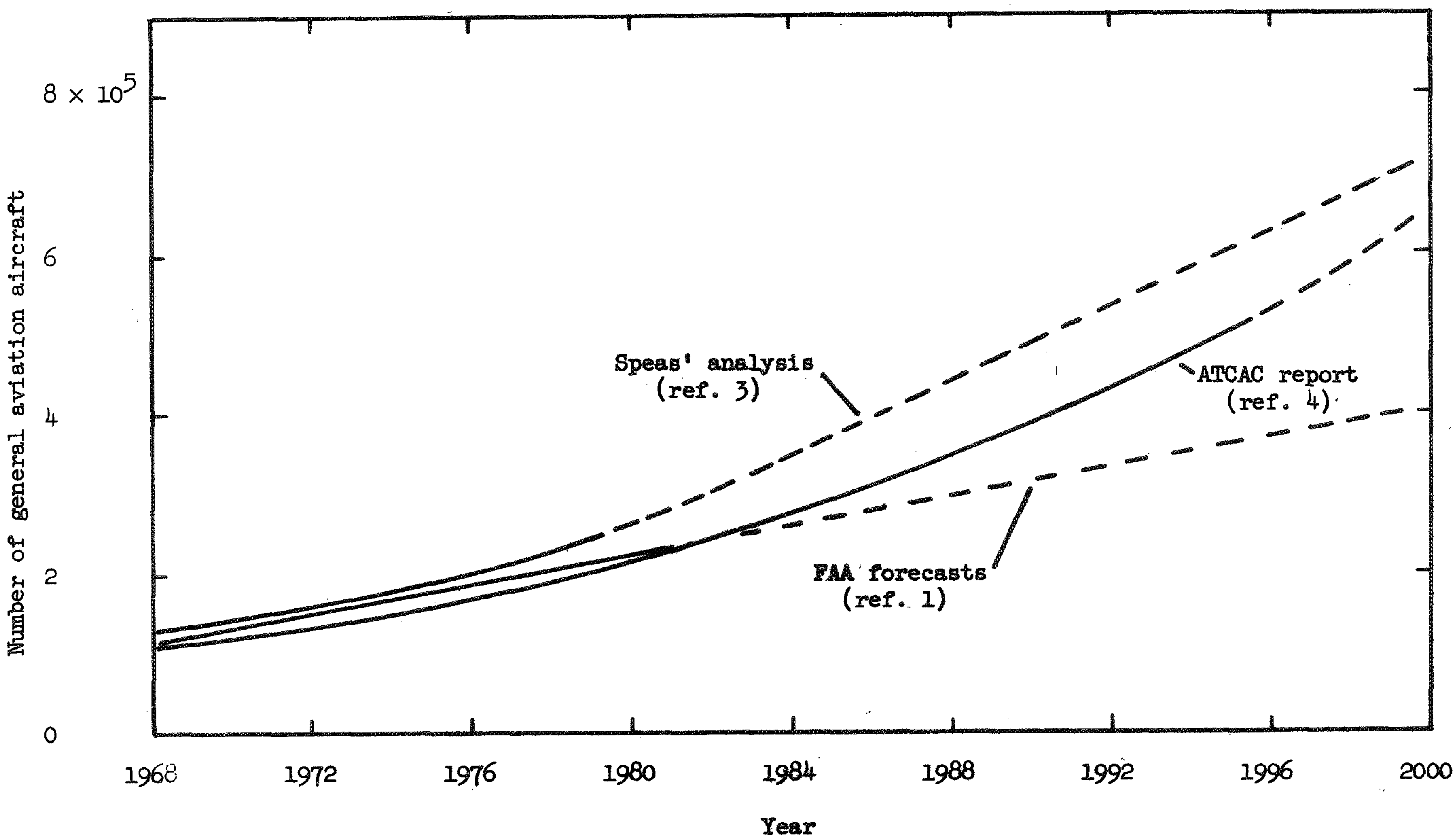

Figure 2.6.- Forecast of General Aviation aircraft in the United States.

TABLE 2.4[3]

GROSS NATIONAL PRODUCT AND GENERAL AVIATION FLEET POPULATION
-ACTUAL AND FORECAST-

Year	GNP Billions of Current Dollars	Population of the General Aviation Fleet: FAA Data[b] Eligible a.c.	Population of the General Aviation Fleet: SPEAS Estimate and Forecast[c] Active a.c.
Actual			
1953	365.4		
1954	363.1	61,290	
1955	398.0	58,790	
1956	419.2	62,886	
1957	442.8	66,520	
1958	447.3	67,839	
1959	482.1	68,727	
1960	503.8	76,550	
1961	520.1	80,632	
1962	560.3	84,121	
1963	590.5	85,088	
1964	631.7	88,742	
1965	681.2	95,442	
1966	739.6	104,706	
1967	793.5	114,186	122,200
1968	865.7	122,200	130,000

(TABLE 2.4[3] continued on next page)

TABLE 2.4[3]
(Continued)

GROSS NATIONAL PRODUCT AND GENERAL AVIATION
FLEET POPULATION
-ACTUAL AND FORECAST-

Year Forecast[a]	GNP Billions of Current Dollars	Population of the General Aviation Fleet: FAA Data[b] Eligible a.c.	Population of the General Aviation Fleet: SPEAS Estimate and Forecast[c] Active a.c.
1969	885.3		136,000
1970	939.7		143,000
1971	997.6		152,000
1972	1059.8		161,000
1973	1127.5		170,000
1974	1200.0		181,000
1975	1276.7		192,000
1976	1357.6		204,000
1977	1444.5		216,000
1978	1539.2		229,000
1979	1640.8		244,000
1980	1749.7		260,000
1985[d]	2400.0		375,000
1990	3200.0		490,000
1995	3950.0		610,000
2000	4750.0		700,000

[a]GNP forecast includes 2% inflation in the general economy.
[b]FAA reported statistics.
[c]Based on SPEAS adjustment of base year data for 1967 and a 1-year time lag correlation between GNP and the active fleet.
[d]Projections for 1985 and beyond are an extrapolation of the SPEAS analysis

Fleet Size By Category

In the preceding section, the size of the total general aviation fleet was forecast through 2000. In addition, an analysis and evaluation was undertaken to determine the approximate size of the following groups of aircraft types or categories which comprise the total fleet (these categories are those used by the Speas' analysis):

Reciprocating Engine

1. Single Engine, 1-3 place
2. Single Engine, 4 or more place
3. Multi-Engine, to 12,500 pounds, to 600 HP
4. Multi-Engine, to 12,500 pounds, over 600 HP
5. Multi-Engine, over 12,500 pounds

Turbine Engine

6. Turboprop Single and Multi-Engine, to 12,500 pounds
7. Turboprop Single and Multi-Engine, over 12,500 pounds
8. Turbo-Jet

Other

9. Rotocraft
10. Unspecified (gliders, blimps, etc.)

Although the Speas' Analysis was conducted only through the year 1980, it is felt that no radical changes in general aviation aircraft design (and therefore no radical change in aircraft types) will occur between 1980 and 2000, and that the trends predicted through 1980 will continue through the year 2000. Although both assumptions may be somewhat erroneous (especially the latter), Speas' Analysis seems to be the best available starting point for projecting the general aviation fleet for the year 2000.

Two approaches have been used to predict the number of aircraft in each general aviation category for the year 2000. The first approach was to extend the Speas' prediction of the number of aircraft in each category through 1980 on out through 2000. Shown in Figures 2.7, 2.8, 2.9, and 2.10 are these extended predictions. These predictions were adjusted so that they total 700,000 the projection for the total fleet, but yet retain their original percentage composition. The second approach was to extend the Speas' predictions of the percent of the total fleet each aircraft type would comprise on through 2000 (Figures 2.11 and 2.12). The predicted percentages for 2000 were normalized and then based on the normalized percentages and an assumed fleet size of 700,000, the aircraft fleet was broken down by category. The results of both approaches are presented in Table 2.5. Based on the results of the previously mentioned approaches and fleet size for 1980 predicted by Speas', the fleet distribution for 2000 (Table 2.6) was determined.

<u>Passenger Aircraft</u>

To determine the number of passenger aircraft in service at some future date using the passenger enplanement projection, the following procedure has been used:

a. Assume aircraft type and characteristics
    1. Capacity
    2. Speed
    3. Utilization
    4. Percent of Market
b. Determine number of enplanements by trip length
c. Determine enplanements per departure
d. Determine departures per aircraft per day

While this procedure will work for any future date, only data for the year 2000 has been developed.

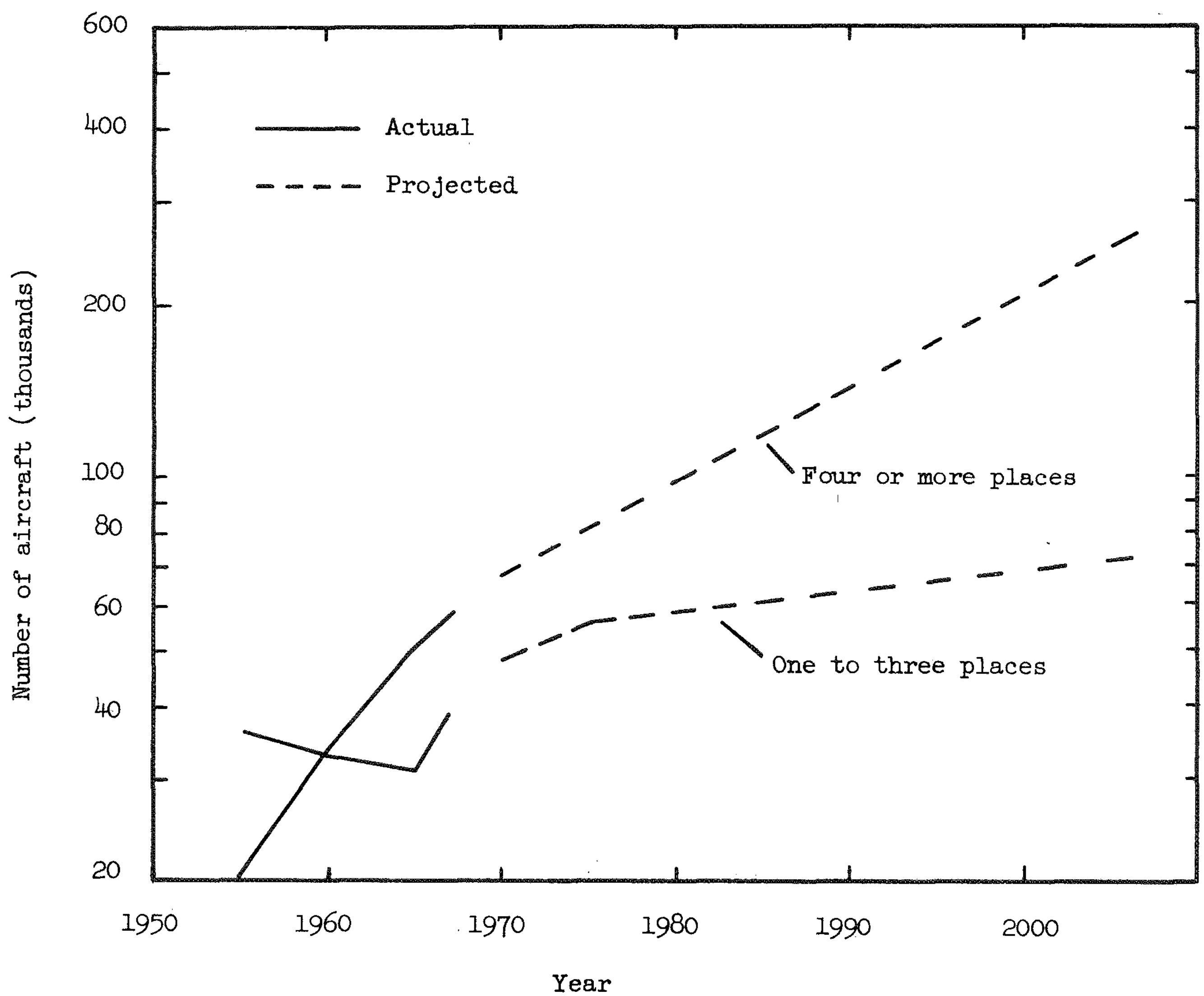

Figure 2.7.- General Aviation active fleet population (single-engine, reciprocating).

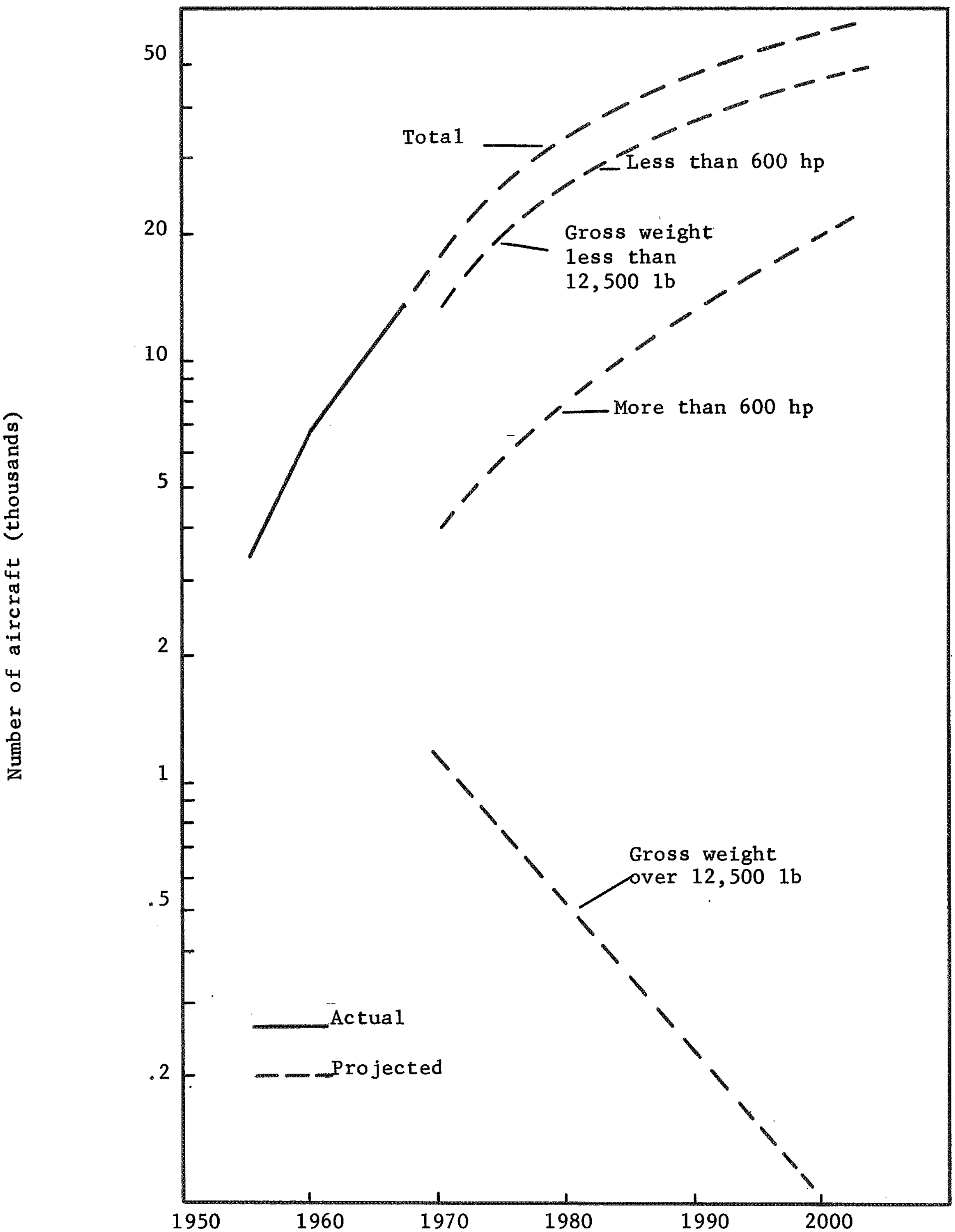

Figure 2.8 General Aviation active fleet population (multi-engine, reciprocating).

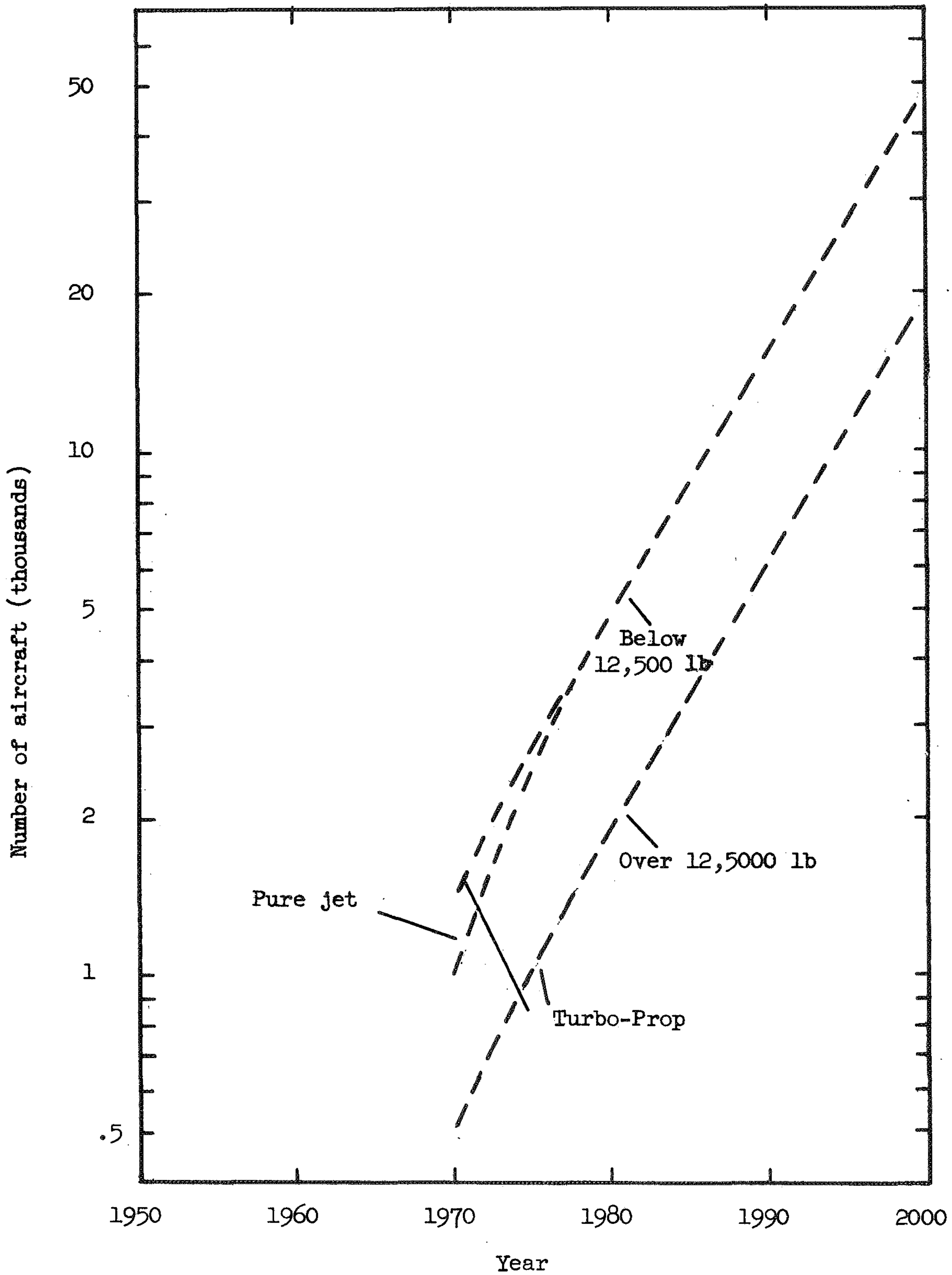

Figure 2.9.- General Aviation active fleet population (turbine-powered aircraft).

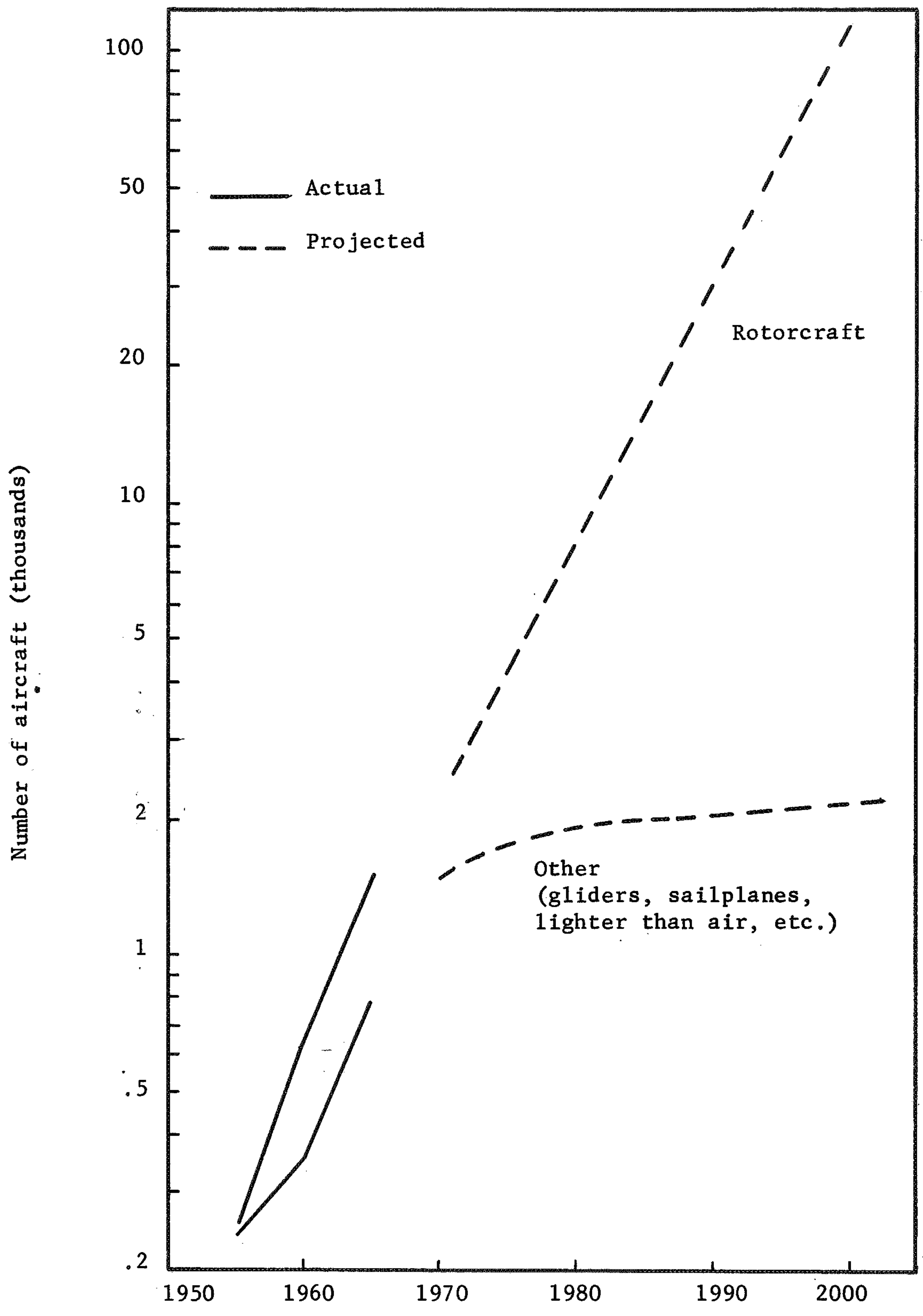

Figure 2.10 General Aviation active fleet population.

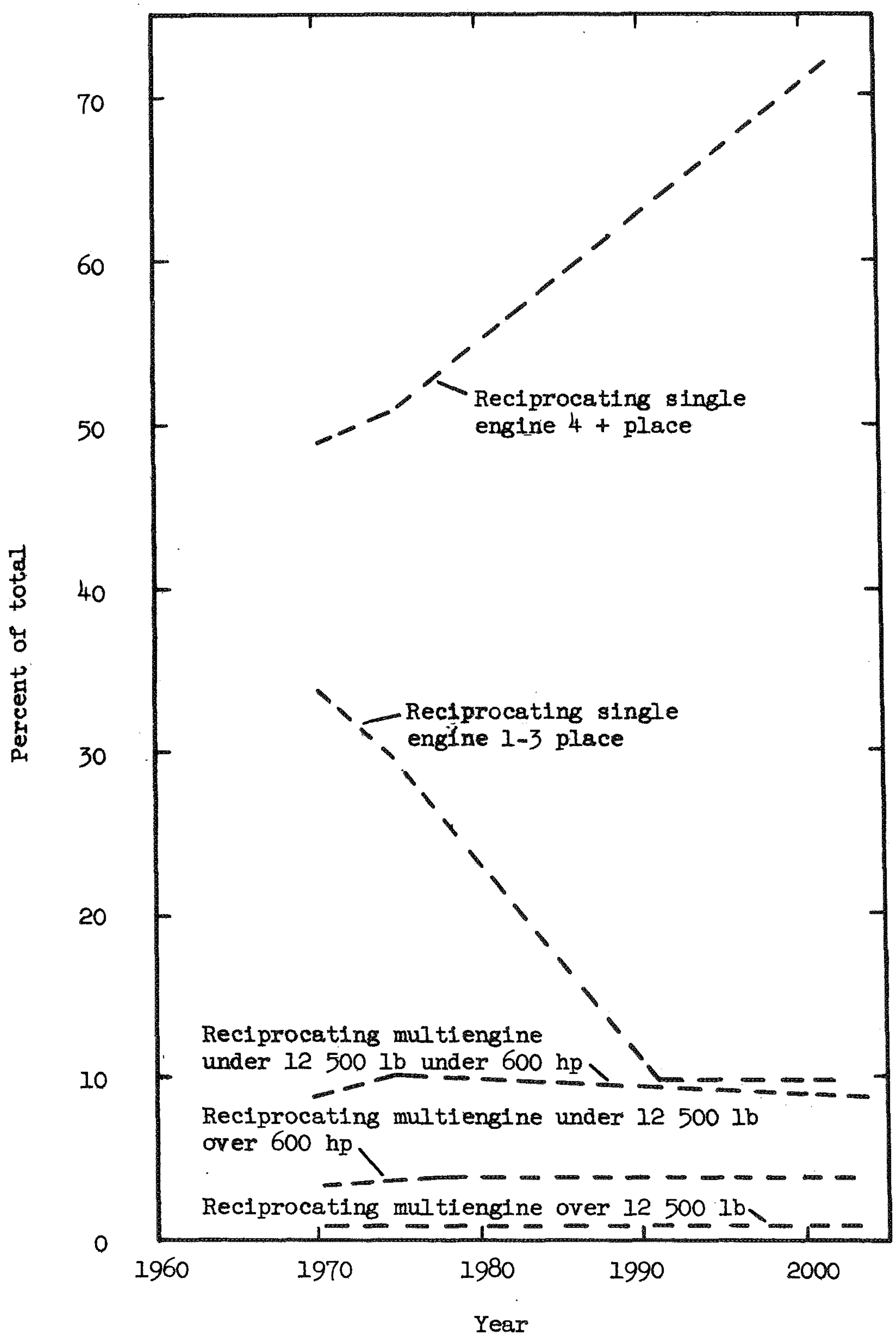

Figure 2.11.- Percentage composition of total fleet population.

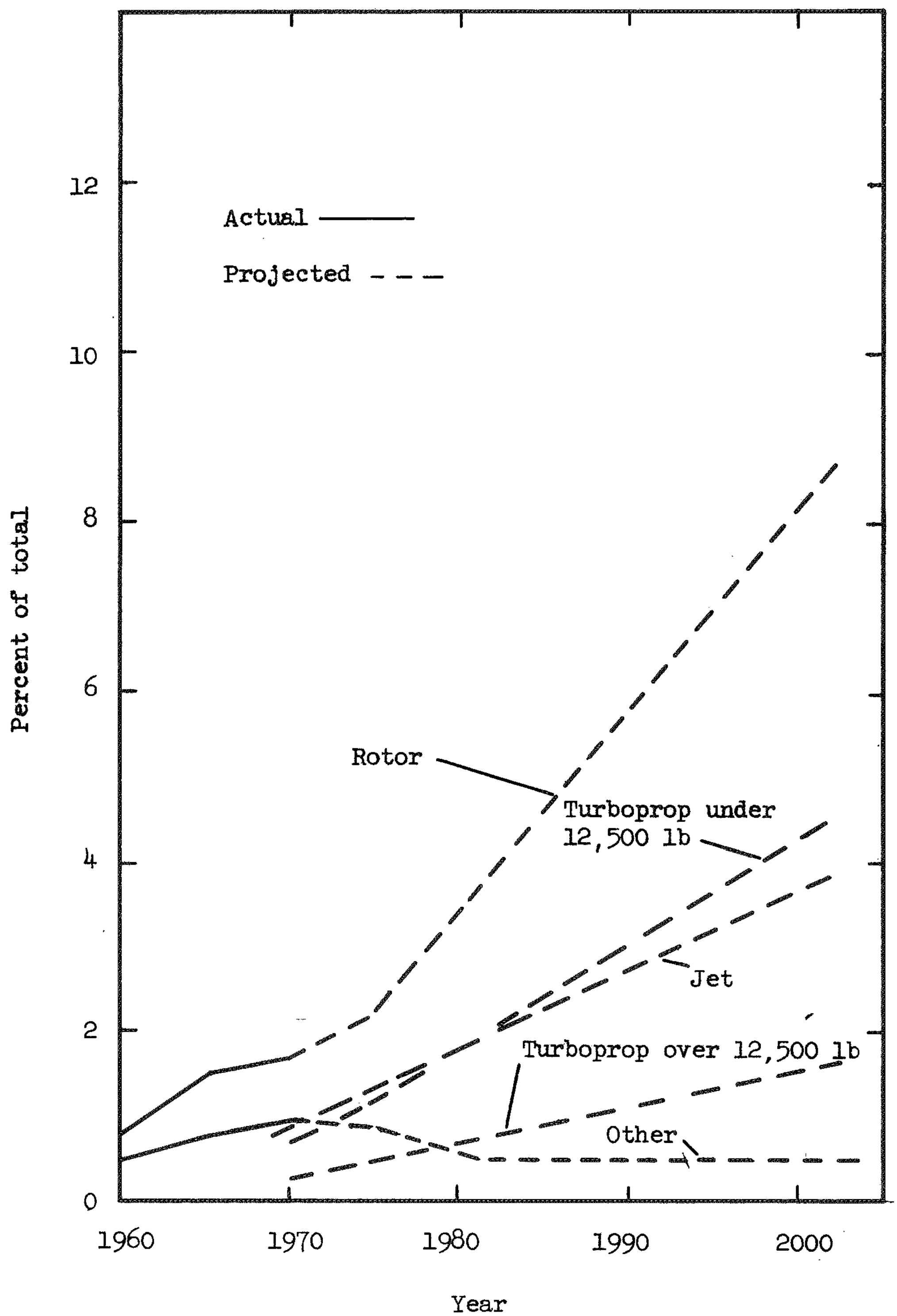

Figure 2.12.- Percentage composition of total fleet population.

TABLE 2.5

COMPARISON OF APPROACHES USED TO OBTAIN

A GENERAL AVIATION FLEET FOR 2000

	First approach (Projected number)	Second approach (Projected percentage)
Single engine, 1-3 place	85,400	63,000
Single engine, 4 place	256,000	435,000
Multi-engine, to 12,500 lbs to 600 hp	56,200	56,000
Multi-engine, to 12,500 lbs over 600 hp	24,400	24,500
Multi-engine, over 12,500 lbs	0	6,300
Turboprop single and multi-engine, to 12,500 lbs	58,600	28,000
Turboprop single and multi-engine, over 12,500 lbs	24,400	9,000
Turbojet	58,600	24,500
Rotocraft	135,100	49,000
Unspecified or other (mainly gliders)	2,680	2,800
	700,380	698,100

TABLE 2.6

PREDICTED GENERAL AVIATION FLEET 1967-2000

	1967*	1975	1980	2000
Single engine, 1-3 place	41,760	55,400	58,700	80,000
Single engine, 4 place	61,319	98,200	143,900	400,000
Multi-engine, to 12,000 lbs to 600 hp	10,423	19,500	26,000	56,000
Multip-engine, to 12,500 lbs over 600 hp	2,864	6,200	8,700	24,000
Multi-engine, over 12,500 lbs	1,222	800	500	500
Turboprop single and multi-engine, to 12,500 lbs	475	2,400	4,800	30,000
Turboprop single and multi-engine, over 12,500 lbs	323	1,000	1,900	9,000
Turbojet	787	2,600	4,900	30,000
Rotorcraft	1,875	4,200	8,700	70,000
Unspecified or other (mainly gliders)	1,152	1,700	1,900	2,800
	122,200	192,000	260,000	702,300

*Values adjusted to active fleet

The passenger aircraft for the year 2000 have been divided into four categories. These are V/STOL, short haul jet, transonic jet (TST), and SST. While each of these categories will consist of several different types and sizes of aircraft, it is felt that the capacities and speeds chosen are representative of the average. Since V/STOL service does not exist today, it was studied in detail to determine its feasibility and impact on air travel (See Appendix A). In addition to the aircraft types and characteristics, assumptions have been made as to the percent of the market and the number of enplanements per departure by trip length for each aircraft type. This information is shown in Table 2.7 and is based on the following conditions existing in the year 2000:

a. V/STOL will dominate the short-haul market, especially the northeast corridor and other regions of high density population.

b. SST will be banned from overland supersonic flight

To determine the enplanements per day by trip length, the total enplanement projection has been divided by 365 and a percentage by trip length applied. The percentages used were obtained by averaging the percentages published by the Civil Aeronautics Board for the years 1961, 1962, 1964, 1966, and 1968[5, 6, 7, 8, 9] and assuming that these averages will remain essentially constant. The actual and average percentages and enplanements are shown in Table 2.8. Table 2.8 shows the percentage for 0-500 miles dropping for the last few years while the percentages for the longer trip lengths have increased. This lower percentage of short-haul traffic will probably continue for several years. By 2000, though, V/STOL aircraft will have had such an impact on the short-haul market that its percentage of the total will be at least 51.4%.

TABLE 2.7

AIRCRAFT CHARACTERISTICS FOR THE YEAR 2000

AC type	Seats	Speed (mph)	Percent of market					Enplanements per departure (%-#)				
			0-500	500-1000	1000-1500	1500-2500	Over 2500	0-500	500-1000	1000-1500	1500-2500	Over 2500
V/STOL	270	550	70	10	0	0	0	60-162	50-135	------	------	------
Short Haul jet	650	585	30	70	10	0	0	50-325	40-260	30-195	------	------
Transonic transport	1000	650	0	20	80	60	10	------	30-300	30-300	40-400	40-400
S.S.T.	600	1800	0	0	10	40	90	------	------	35-210	50-300	60-360

TABLE 2.8 ENPLANEMENTS PER DAY BY TRIP LENGTH

Distance (Miles)	1961 %	1962 %	1964 %	1966 %	1968 %	Average	Enplane-ments for 2000 (mlns)
0-500	53	52.9	52.8	50.3	48.2	51.4	2.8356
500-1000	23.7	23.9	23.9	24.6	25.6	24.3	1.341
1000-1500	12.3	11.9	11.7	12.2	13.4	12.3	.6786
1500-2500	9.5	9.9	10.1	11.2	11.1	10.4	.5738
Over 2500	1.5	1.4	1.5	1.7	1.6	1.5	.08277

The number of departures per aircraft per day has been determined on the assumption of 2000 hours annual utilization (5.5 hours per day). Using this with the aircraft's cruise speed and a 30-minute penalty per trip for ground time and time lost during climb and descent, the departures per day have been calculated and appear in Table 2.9.

With the above information the size of the air carrier fleet for the year 2000 has been determined and the results are shown in Table 2.10.

TABLE 2.9 AIRCRAFT DEPARTURES PER DAY

Aircraft	Departures				
	0-500	500-1000	1000-1500	1500-2500	Over 2500
V/STOL	3.9	2.4	----	----	----
Short Haul Jet	4.1	2.5	1.8	----	----
Future Jumbo Jet	----	2.7	2.0	1.3	1.0
SST	----	----	4.1	2.9	2.5

TABLE 2.10

AIRCRAFT FOR THE YEAR 2000

	V/STOL	S.H.J.	T.S.T	S.S.T.
Dist (0-500)				
ENP/DAY (2.8356)	1.985	0.851		
ENP/DEP	162	325		
DEP/DAY	12,253	2,618		
DEP/AC/DAY	3.9	4.1		
#Aircraft	3.142	639		
(500--1000)				
ENP/DAY (1.341)	0.1341	0.9384	0.2681	
ENP/DEP	135	260	300	
DEP/DAY	993	3609	893	
DEP/AC/DAY	2.4	2.5	2.7	
#Aircraft	414	1444	331	
(1000--1500)				
ENP/DAY (0.6786)		0.06786	0.5429	0.06786
ENP/DEP		195	300	210
DEP/DAY		348	1809	323
DEP/AC/DAY		1.8	2.0	4.1
#Aircraft		194	905	79
(0--2500)				
ENP/DAY (0.5738)			0.3443	0.2295
ENP/DEP			400	300
DEP/DAY			860	765
DEP/AC/DAY			1.3	2.9
#Aircraft			663	264
Dist (0--3000)				
ENP/DAY (0.08277)			0.008277	0.0745
ENP/DEP			400	360
DEP/DAY			20	206
DEP/AC/DAY			1.0	2.5
#Aircraft			21	83
TOTAL	3556	2277	1920	426
Percentage	43.47	27.83	23.47	5.21

Cargo Aircraft

Cargo payload for the year 2000 has been projected from a study done by the Aerospace Industries Association of America[10] (Figure 2.13). Based on these projections alone, a cargo aircraft with a payload of one million pounds could be expected by the year 2000. This aircraft would have a gross weight of between 2.5 and 4.5 million pounds (Figure 2.14). An aircraft weighing 4.5 million pounds was judged to be too big. However, an aircraft with a payload capacity of 600,000 pounds and a gross weight of 1.5 to 2 million pounds was considered to be feasible. This aircraft is the TST referred to in the Cargo Demand projection. A summary of projected aircraft is shown below:

CARGO AIRCRAFT IN THE YEAR 2000

1. Short Haul Jet

Maximum Operating Range:	1500 miles
Speed:	585 miles/hour
Payload:	77 tons
Aircraft Utilization:	2000 hours/year
Utilization Factor:	.901 X 10^8 ton miles/aircraft/years

2. Medium Cargo Jet

Maximum Operating Range:	2500 miles
Speed:	500 miles/hour
Payload:	100 tons
Aircraft Utilization:	2000 hours/year
Utilization Factor:	10^8 ton-miles/aircraft/year

3. 747 Type Jet

Maximum Operating Range	Over 2500 miles
Speed:	600 miles/hour
Payload:	150 tons
Aircraft Utilization:	2000 hours/year
Utilization Factor	1.8 X 10^8 ton-miles/aircraft/year

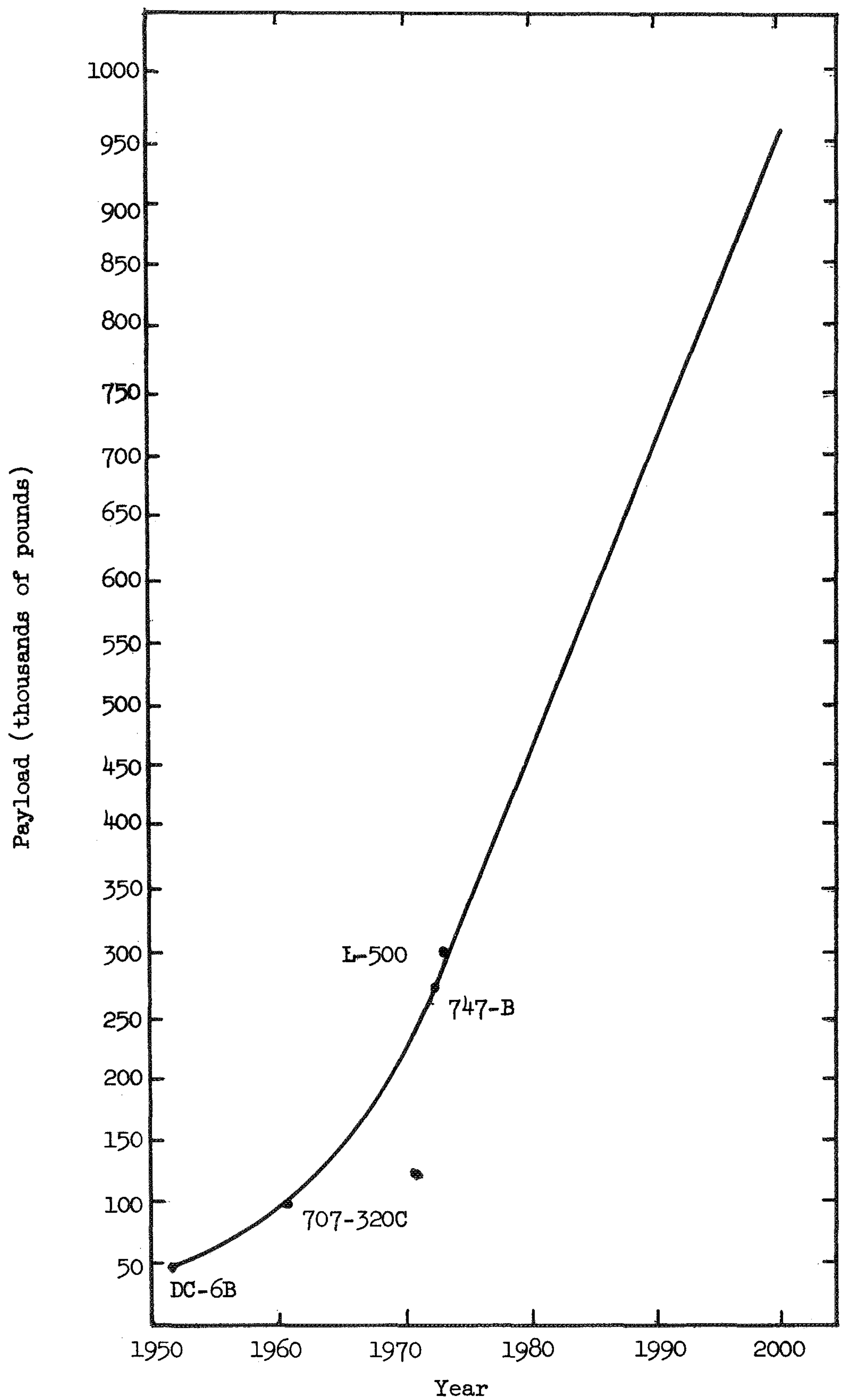

Figure 2.13.- Payload capacity.

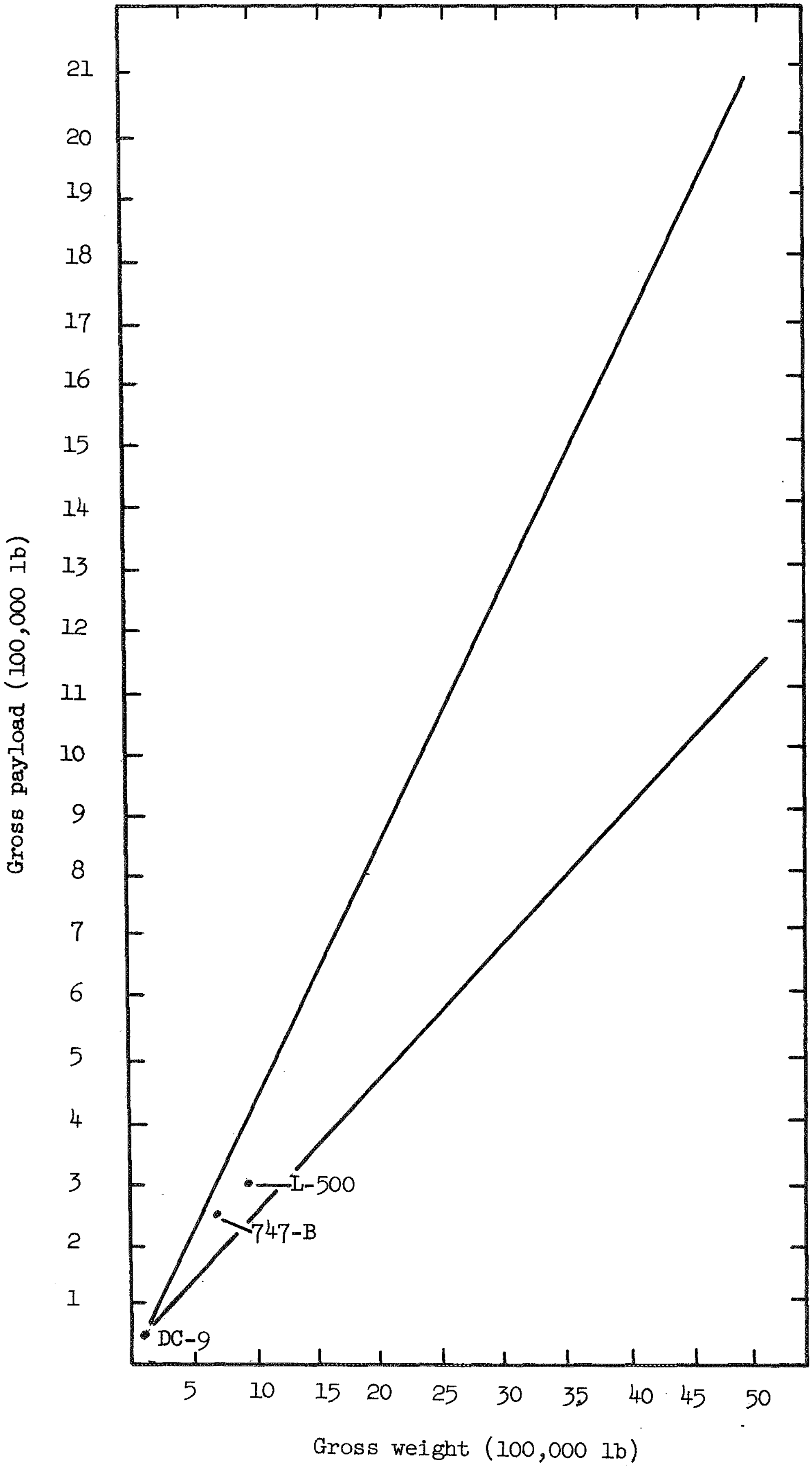

Figure 2.14.- Cargo payload trend.

4. Transonic Transport

Maximum Operating Range:	Over 2500 miles
Speed:	650 miles/hour
Payload:	273 tons
Aircraft Utilization:	2000 hours/year
Utilization Factor:	3.55×10^8 ton-miles/aircraft/year

To determine the actual number of all-cargo aircraft a utilization factor was defined. The utilization factor is a measure of an aircraft's cargo potential. It is the product of three factors, aircraft payload, aircraft utilization, and aircraft speed, or:

Utilization Factor = (Aircraft Payload) X (Aircraft Utilization) X (Aircraft Speed)

It has the dimensions of ton-miles per aircraft per year. The utilization factors for the year 2000 aircraft are shown above. The cargo ton-miles per aircraft operating within a given range have previously been obtained (elements of the matrix of Table 2.3). This number was then divided by the utilization factor to yield the number of projected aircraft operating within a given range. The results of this analysis are shown in Table 2.11.

2.4 AIRCRAFT PERFORMANCE

Aircraft performance is a vital parameter in the study of air traffic control. In order to be able to design a future air traffic control system, knowledge of present and future aircraft performance characteristics, particularly those relevant to terminal area operations, is necessary. Knowledge of present aircraft proved to be necessary since this data was essential input to the simulation model which is developed in Chapter IV. It was also necessary to gain a realization of future aircraft performance since this information would be of great importance

TABLE 2.11 NUMBER OF ALL-CARGO AIRCRAFT
YEAR 2000
(BY TYPE AND RANGE)

INTERNATIONAL

Range (miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500	Total
V/STOL	0	0	0	0	0	0
Short Haul Jet	1	1	2	0	0	4
Medium Jet	0	1	4	2	0	7
747 Jet	0	0	1	8	902	911
TST	0	0	0	1	412	413
SST	0	0	0	0	0	0
Total	1	2	7	11	1314	1335

DOMESTIC

Range (miles)

TYPE	0-500	500-1000	1000-1500	1500-2500	2500	Total
V/STOL	0	0	0	0	0	0
Short Haul Jet	2	6	14	0	0	22
Medium Jet	0	5	18	13	0	36
747 Jet	0	0	0	51	917	968
TST	0	0	0	81	698	779
SST	0	0	0	0	0	0
Total	2	11	32	145	1615	1805

in designing a future air traffic control system. However, the interest in future aircraft performance was not confined to terminal area performance. In the development of future aircraft, cruise performance was of primary interest. This is in line with the views of the aircraft industry who design airplanes with cruise performance as the most important characteristic since it is this factor which is fundamental to the airplane's ability to operate at maximum profit. Thus, the air traffic control system devised for the future will be built to accomodate the aircraft rather than the aircraft to accomodate the system.

Present Aircraft Performance in the Terminal Area

At the start of this study, it was hoped that traffic into and out of the terminal area could be treated with such detail that the information on present aircraft performance characteristics could be based upon a literature search including such references as Jane's All the World's Aircraft and The World's Airliners, by Brooks. Unfortunately, this was not the case.

In an effort to simplify the simulation problem, it was decided to create seven composite aircraft which would provide a simple, yet reasonably accurate, air fleet upon which to base the simulation. The composition of the categories of aircraft was determined by grouping present aircraft on the basis of their maximum takeoff weight. This basis of categorization was chosen because it yielded a fairly homogeneous grouping of aircraft with respect to other aircraft performance parameters relevant to operations in the terminal area.

Recognizing that the study of aircraft performance is a non-linear problem, it was decided not to average the performance characteristics of several aircraft in a given category. It was felt, however, that averaging the geometry and power loadings of aircraft in a particular category and using classical performance analysis techniques to determine performance characteristics would lead to valid results. The composite aircraft geometry is given in Table 2.12.

TABLE 2.12 COMPOSITE AIRCRAFT GEOMETRY

TYPICAL AIRCRAFT	CATEGORY	SPAN (ft)	WING AREA (ft)	MAXIMUM TAKEOFF WEIGHT	MAXIMUM POWER LOADING (lb/shp or lb/lb s.t.)
Cessna 150	I	34	165	2700	13.51
Beech King Air	II	43	230	7200	9.09
Lear Jet	III	67	560	33100	NA
DC-9	IV	96	1200	111000	NA
707	V	140	2700	260000	NA
747	VI	170	4200	510000	NA
SST	VII	115	5200	560000	NA

Peformance figures for the seven categories of aircraft were obtained by noting performance profiles used by the FAA for one of their simulation studies[11] and making judicious generalizations. These performance figures are given in Table 2.13.

A program for the CDC 6600 Computer was written to facilitate and increase the accuracy of performance calculations. It was assumed that aircraft in the year 2000 will be analyzed by the techniques in use today. The program, therefore, is not capable of analyzing airplane designs employing unconventional methods of producing lift and is not able to calculate the takeoff performance of deflected slipstream or vectored thrust V/STOL vehicles.

TABLE 2.13 COMPOSITE AIRCRAFT PERFORMANCE CHARACTERISTICS

Category	Final Speed (kts)	Approach Speed (kts)	Transition Speed (kts)	Climb Speed (kts)	Rate of Climb (fpm)	Rate of Sink (fpm)
I	80	95	140	90	900	500
II	105	120	150	105	1200	500
III	115	135	156	155	1000	1000
IV	130	150	175	175	1200	1500
V	150	170	200	290	1500	2000
VI	155	180	205	270	1200	2000
VII	165	185	215	315	2000	2500

The following section describes the variables calculated in the program and lists the assumptions used in the performance analysis. Table 2.14 contains a list of symbols used in the program development.

Drag Analysis

After basic aircraft geometry and altitude parameters were calculated, the zero-lift drag was found. Reynolds numbers for wing fuselage horizontal tail and verticle tail were computed for each velocity and altitude and the skin friction coefficients were then found assuming a turbulent boundary layer. The skin friction drag was found by adding the drag on the individual components to C_D for interference. In all cases, a parabolic drag polar was used. The compressibility effects were taken into account assuming a supercritical wing with a divergent mach number of .95. For all speed ranges, the parabolic form of equation 2.1 was used to compute the drag coefficient C_D.

TABLE 2.14 LIST OF VARIABLES

Variable	Units	Analytic Symbol
Drag Coefficient	---	C_D
Zero-Lift Drag Coeffieient	---	C_{DO}
Lift Coefficient	---	C_L
Aspect Ratio	---	A
Velocity	ft./sec.	V
Horsepower	Horsepower	H_p
Lift-to-Drag Ratio	---	(L/D)
Specific Fuel Consumption	$\frac{\text{lb.}}{\text{hr.}}$	C
Initial Weight	lbs.	W_i
Final Weight	lbs.	S_{Fi}
Air Density	slugs/ft.^{3}	ρ
Wing Area	ft.^{2}	S
Oswald's Subsonic Wing Efficiency	---	e
Thrust Specific Fuel Consumption	$\frac{\text{lb.}}{\text{lb. x Hr.}}$	C^1
Vertical Velocity	ft./sec.	V_v
Density Ratio	---	σ
Normal Load Fact	---	n
Rate of Climb	ft./min.	$(^R/C)$
Bank Angle	radians	Φ

$$C_D = C_{DO} + \frac{C_L^2}{\pi e A} \qquad (2.1)$$

Available Power Analysis

The available power was computed by various methods depending on whether the airplane under investigation was propeller drive, turbojet or turboprop. The turboprop analysis is not included in this report.

The propeller power available was found by calculating the advance ration, J, as in equation 2.2.

$$J = \frac{V}{ND} \qquad (2.2)$$

where

$$N = \frac{RPM}{60}$$

D = Propeller Diameter

Assuming that the propeller was variable pitch and that it always operated at peak efficiency, the efficiency, η, could then be calculated by a third order curve fit obtained in Reference 12.

$$\eta = .5951 + .455J + .2335J^2 + .0334J^3 \qquad (2.3)$$

The power available for propellers was then calculated by equation 2.4.

$$P_A = 550\eta H_p \qquad (2.4)$$

The power available for turbine driven jet aircraft was obtained from equation 2.5. In the analysis, the thrust, T, was assumed constant for each altitude.

$$P_A = TV \qquad (2.5)$$

Range and Endurance Analysis

Range, R, was found by using the Brequet range equation. For propellers, the range in statute miles is computed by equation 2.6.

The range was then multiplied by .85 to compensate for the pilot's inability to fly at a constant lift-to-drag ratio.

$$R = \frac{375.0}{C} \left[\frac{L}{D}\right] 7 \ln\left[\frac{W}{Wfi}\right] \tag{2.6}$$

The endurance, E, for propeller driven aircraft was also computed by Breguet relationships and multiplied by 0.85.

$$E = 778 \frac{\eta}{C} \frac{C_L}{C_D} \tag{2.7}$$

The maximum range for propellers was calculated analytically by requiring a maximum lift-to-drag ratio.

$$\text{i.e.} \quad L/D_{max} = \frac{\pi eA}{4C_{DO}} \tag{2.8}$$

$$\text{Speed for maximum range} = \frac{2Wi}{\rho SC_{DO} \pi eA} \tag{2.9}$$

$$R_{max} = .85 \; \frac{375}{C} \left[\frac{L}{D}\right]_{max} \eta \; \ln\left[\frac{Wi}{Wfi}\right] \tag{2.10}$$

Maximum endurance calculations require that

$$\frac{C_L^{\;2}}{\pi eA} = 3 C_{DO} \tag{2.11}$$

With the above requirement, the maximum endurance and speed for maximum endurance can be computed. The velocity for maximum endurance, V_E, was found by equation 2.12.

$$V_E = \left[\frac{2Wi}{\rho S (3C_{DO} \pi eA)^{\frac{1}{2}}}\right]^{\frac{1}{2}} \tag{2.12}$$

Range and endurance calculations for turbine powered aircraft were also included in the program and, again, the Breguet relations were used. Turbine powered aircraft range was computed using equation 2.13, while endurance was found from equation 2.14.

$$R = .85 \left[\frac{2}{C'} \left[\frac{C_L^{\frac{1}{2}}}{C_D}\right] \sqrt{\frac{391 \; Wi}{\sigma S}} \left[1 - \left[\frac{Wfi}{Wi}\right]^{\frac{1}{2}} \right] \right] \tag{2.13}$$

$$E = -\frac{.85}{C'}\left[\frac{L}{D}\right] \ln\left[\frac{Wfi}{Wi}\right] \quad (2.14)$$

The range and endurance were calculated at constant velocity with no provisions for climb or descent. The calculations were conducted for each velocity and altitude throughout the flight envelope. One thousand foot increments in altitude were used along with 10 fps increments in velocity. Maximum range and endurance for turbine powered aircraft were calculated by means of equations 2.15 and 2.16 respectively.

$$R_{max} = .85\left[\frac{2}{C'}\left[\frac{C_L^{\frac{1}{2}}}{C_D}\right]_{max}\sqrt{\frac{391\ Wi}{\sigma S}}\left[1-\left[\frac{Wfi}{Wi}\right]^{\frac{1}{2}}\right]\right] \quad (2.15)$$

$$E_{max} = -\frac{.85}{C'}\left[\frac{L}{D}\right]_{max} \ln\left[\frac{Wfi}{Wi}\right] \quad (2.16)$$

Climb and Descent Analysis

Climb and sink rates were found by dividing the difference between the power available and the power required by the weight. Sink rates were based on the assumption that propeller driven aircraft carry 10 percent of the available power while the jet aircraft retain 70 percent power. Climb and descent rates were also calculated as a function of velocity and altitude. The flight path angles, γ, were found by equation 2.17.

$$\gamma = \sin^{-1}\frac{V_V}{V} \quad (2.17)$$

Turn Analysis

The turn radius was computed for all aircraft assuming the thrust angle of inclination and the flight path angle are small. The radium, was then calculated for a 1.2 g turn by equation 2.18.

$$\text{Radius} = \frac{2Wi}{\rho \, g C_L S \sin\Phi} \qquad (2.18)$$

$$n = 1.2 = \frac{1}{\cos\Phi}$$

where Φ = Bank Angle

Takeoff and Landing Analysis

Takeoff distances necessary to clear a 50 foot obstacle were obtained by a method presented in Reference 13. This method assumes the takeoff speed to be approximately 20 percent above stall speed and no account is taken of large thrust angles or thrust deflection. Takeoff distance was computed as a function of wing loading, thrust loading, takeoff lift coefficient, and altitude. Takeoff lift coefficient was defined to be 70 percent of the maximum lift coefficient.

Reference 13 also presents a method for calculating landing distance, S_L, over a fifty foot obstacle. Equation 2.19 calculates that distance.

$$S_L = \frac{118}{\sigma \, C_{Lmax}} \left[\frac{Wi}{S}\right] + 400 \qquad (2.19)$$

The above equation assumes that the speed at the fifty foot obstacle is the approach speed and is 30 percent greater than stall speed while landing speed is assumed to be 15 percent greater than stall speed. The landing distance calculated in the program is Federal Air Regulations field length and is found by equations 2.19 and 2.20.

$$\text{Far Field Length} = \frac{S_L}{.6} \qquad (2.20)$$

Maximum Speed Analysis

The computer program finds the maximum speed by constantly checking the difference between the available power and the required power. When these two quantities are equal the maximum speed is achieved. After the maximum level speed is reached, the altitude is increased by 1000 feet. The altitude loop is terminated at the absolute ceiling defined as the altitude at which the airplane can no longer sustain level flight.

External Analysis

Originally, the program was designed to perform a hodographic analysis internally in which various climb and glide data could be evaluated. Because of lack of time, this portion of the analysis was not finished and the remainder of the analysis was performed outside the program. A modified hodograph appears in Figure 2.15 along with some of the quantities obtained from such a graph. An example is shown in Figure 2.18.

Another external analysis involves the determination of service ceiling and times to climb to altitude. Graphs like that shown in Figure 2.16 were generated to find the minimum times to climb from one altitude to another. The time to climb from one altitude h_1 to another h_2 can be expressed as in equation 2.21.

$$t = \int_{h_1}^{h_2} \frac{dh}{R/C} \qquad (2.21)$$

This time is equal to the shaded area under the curve, and can be determined graphically. Service ceiling can also be found by graphs like Figure 2.16. The altitude at which the maximum rate of climb is reduced to 100 feet per minute is defined as the service ceiling.

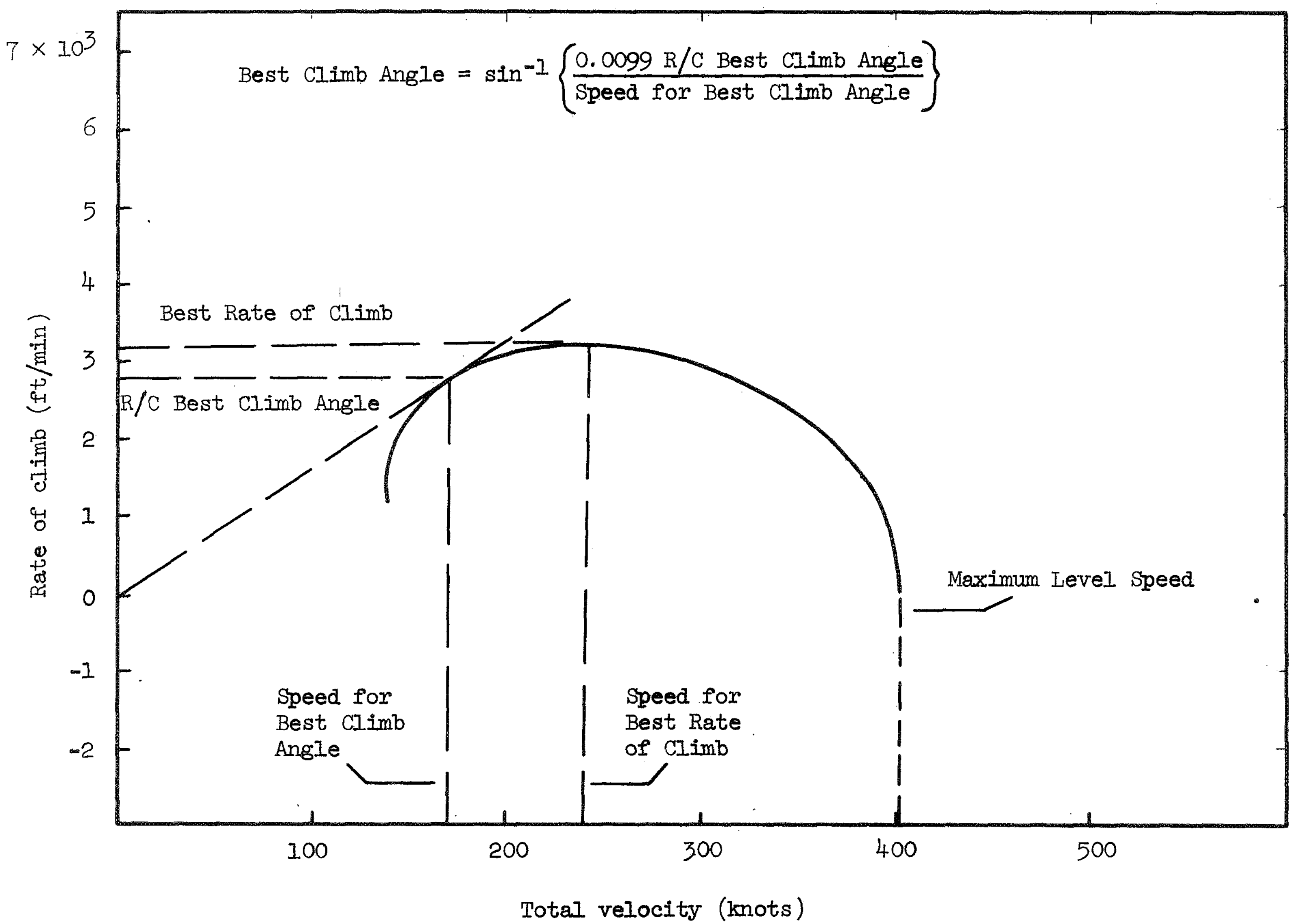

Figure 2.15.- Modified hodograph.

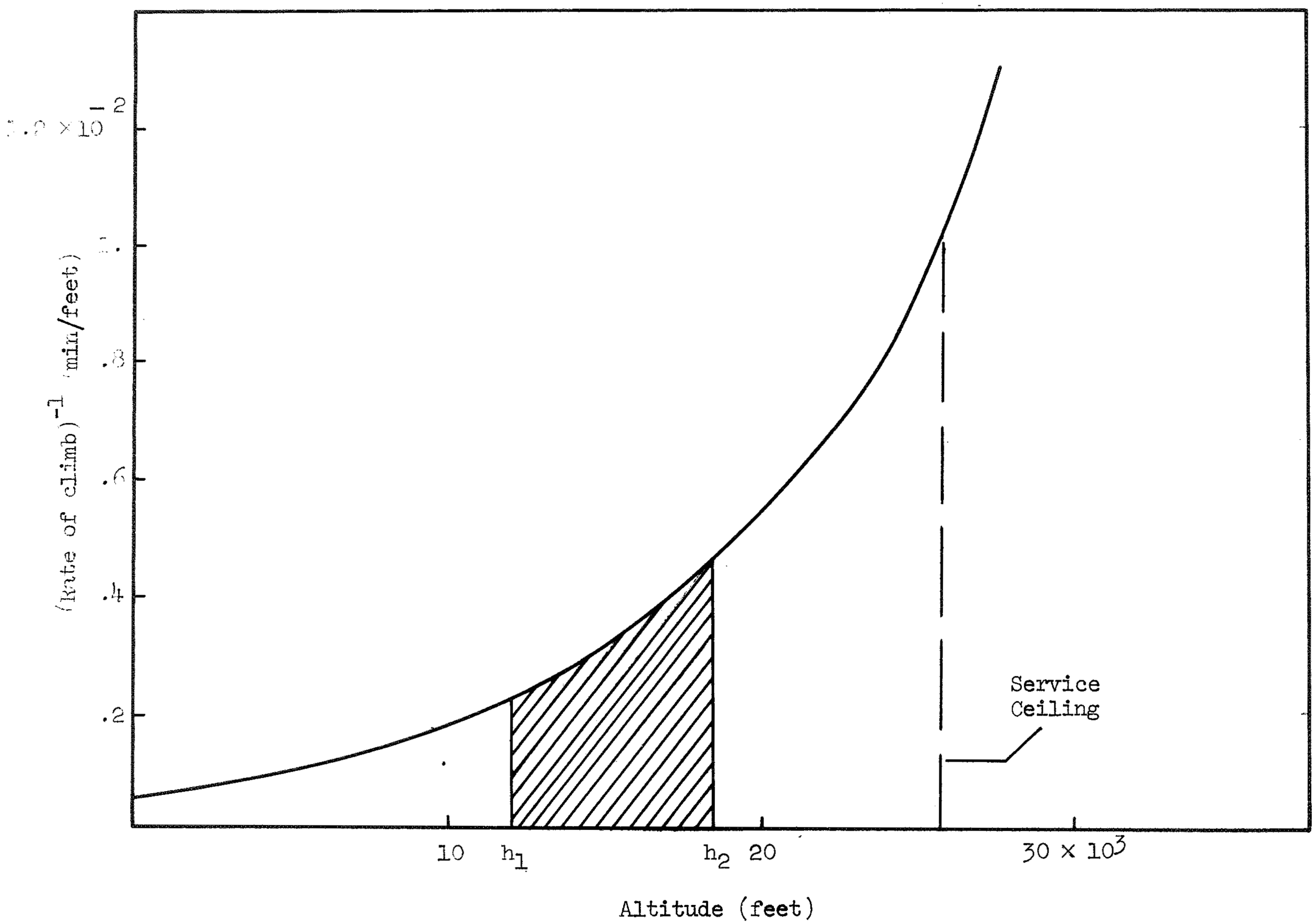

Figure 2.16.- Time to climb chart.

One of the important parameters in the development of aircraft performance analysis is the range-payload relationship. This computer program is designed to compute the vital points on a range-payload chart as shown in Figure 2.17. Each of the four points represent a different weight configuration and is analyzed as a function of speed and velocity. At point 1 the airplane is loaded with everything except usable fuel and its range is, of course, zero. Point 2 is the condition where the plane is loaded to the gross weight with the maximum payload and all usable fuel. Between points 2 and 3 the payload is being traded, pound for pound for fuel until a fuel volume limitation is reached at point 3. Between points 3 and 4 payload is simply being off loaded until there is none left. The range at this point is called the ferry range. Table 2.15 lists the initial and final weights used in the range analysis.

TABLE 2.15
INITIAL AND FINAL WEIGHTS

Point	Initial Weight	Final Weight
1	G/W-W_{FUEL}(Reg)	G/W-W_{FUEL}(Reg)
2	G/W	G/W-W_{FUEL}(Reg)
3	G/W	G/W-W_{FUEL}(Reg)-W_{FUEL}(Add)
4	OEW + W_{FUEL}(Reg) + W_{FUEL}(Add)	OEW

Future Aircraft

It was determined that, in the year 2000, there would be sufficient demand to merit the construction of a quick change transport (QC) Generally, the aircraft should be designed to carry 600,000 pounds of cargo or 1000 passengers depending on the configuration. The aircraft

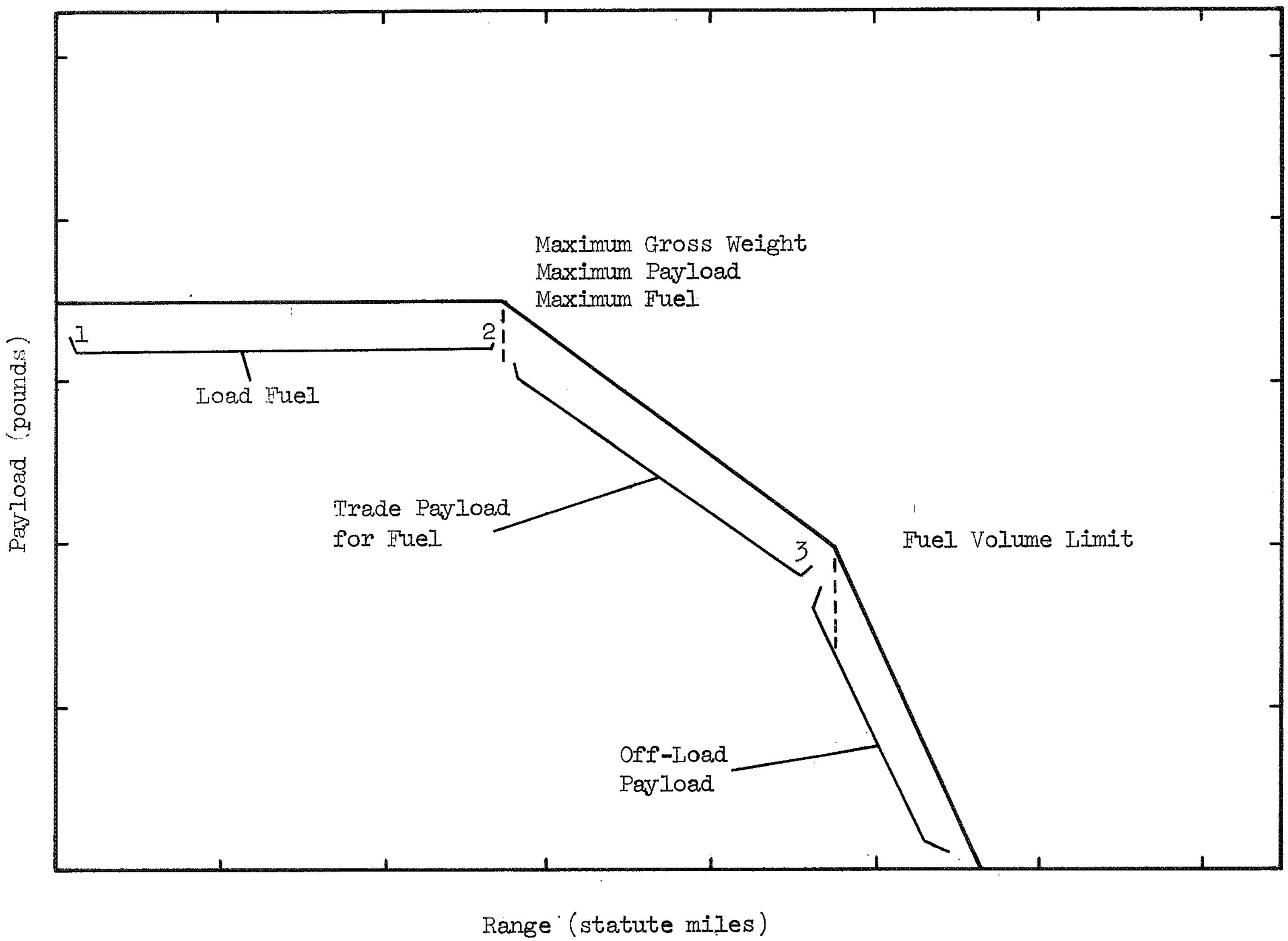

Figure 2.17.- Range-payload chart.

should be capable of traveling 3000 miles at 650 miles per hour. The aircraft group then worked on a preliminary design and performance analysis for such an aorcraft. The airplane has been designated as the TST (QC).

Geometry of the TST (QC)

In order to design an aircraft in compliance with the specific operational requirements detailed above, a preliminary design program was initiated. The resultant aircraft, the TST (Transonic Transport) is similar in external appearance to present-day jet transport aircraft. The two most readily apparent differences between the TST and current transport aircraft are 1) size and 2) the blended wing of the TST. The size of the TST was dictated by the range-payload requirements set out in the specific operational requirements. The blended wing of the TST was selected to provide increased volume available for fuel in the wing without degrading the aerodynamic efficiency of the aircraft.

Other differences between the TST and current aircraft which are not so readily apparent include:

1. Increased structural efficiencies
2. Increased capabilities of lift augmentation devices
3. Increased thrust levels of the engines.

These improvements, as well as others, in aircraft design technology reflect the growth of aircraft design technology predicted by several studies.[14, 15]

The geometry, weights, aerodynamics, and power loading of the TST are as follows:

Geometry:

(Wing)

Area	15000 ft.^{2}	C_{rt}	55 ft.
Span	325 ft.	C_{tp}	33 ft.
Taper ratio	0.6	t/C_{rt}	0.1
Sweep angle	29°	t/C_{tp}	0.06
Aspect ratio	7.04		

(Empennage)

Horizontal:

Area	5850 ft.^{2}	C_{rt}	45.6 ft.
Span	171 ft.	C_{tp}	22.7 ft.
Taper ratio	0.5		35. ft.
Sweep angle	15°		

Verticle:

Area	1950 ft.^{2}		42 ft.
Span	47 ft.		
Taper ratio	0.5		
Sweep angle	40°		

(Fuselage)

Length	310 ft.
Diameter (mean)	27.5 ft.
Wetted area	26900 ft.^{2}

Weights:

Structural weight	455000	
Engine weight	31000	
Fixed equipment weight	251000	
Operational empty weight	737000	
Payload weight	600000	
Fuel weight	413000	(Max. fuel weight. 1.013 X 10^6 lbs)
Maximum gross weight	1750000	

Aerodynamic and Engine Data:

(Aerodynamics)

C_L (max)	4.2
ΔC_D (Interference)	0.008
wing efficiency	0.82

(Engines)

6 @75000 pound thrust
total thrust 450000 pounds
power loading 3.5 lb/lb thrust

A sketch of the TST is shown in Figure 2.18.

Performance of TST

The performance of the aircraft shown in Figure 2.18 was calculated by the computer program described above and is given in Table 2.16. Table 2.16 also includes the figure number from which the data was taken

TABLE 2.16
TRANSONIC TRANSPORT PERFORMANCE CHARACTERISTICS

		Figure Number
Altitude Information:		
Cruise Altitude	26,000 ft.	2.22 and 2.23
Absolute Ceiling	42,300 ft.	2.24
Service Ceiling	42,000 ft.	2.24
Climb Information:		
Time to 260000 feet	7.2 minutes	2.19
Best Climb Angle (SL)	11.0°	2.20
Speed for Best Climb Angle (SL)	260 kts	2.20
Maximum Rate of Climb (SL)	7171 fpm	2.20
Speed for Maximum Rate of Climb (SL)	455 kts.	2.20
Range Information:		
Maximum Range	5255 miles	2.23
Speed for Maximum Range (26000)	545 kts.	2.22
Ferry Range	14648 miles	2.27
Speed Information:		
Stall Speed (SL)	91 kts.	2.20
Maximum Level Speed (26000 feet)	575 kts.	2.21
Approach Speed (SL)	118 kts.	

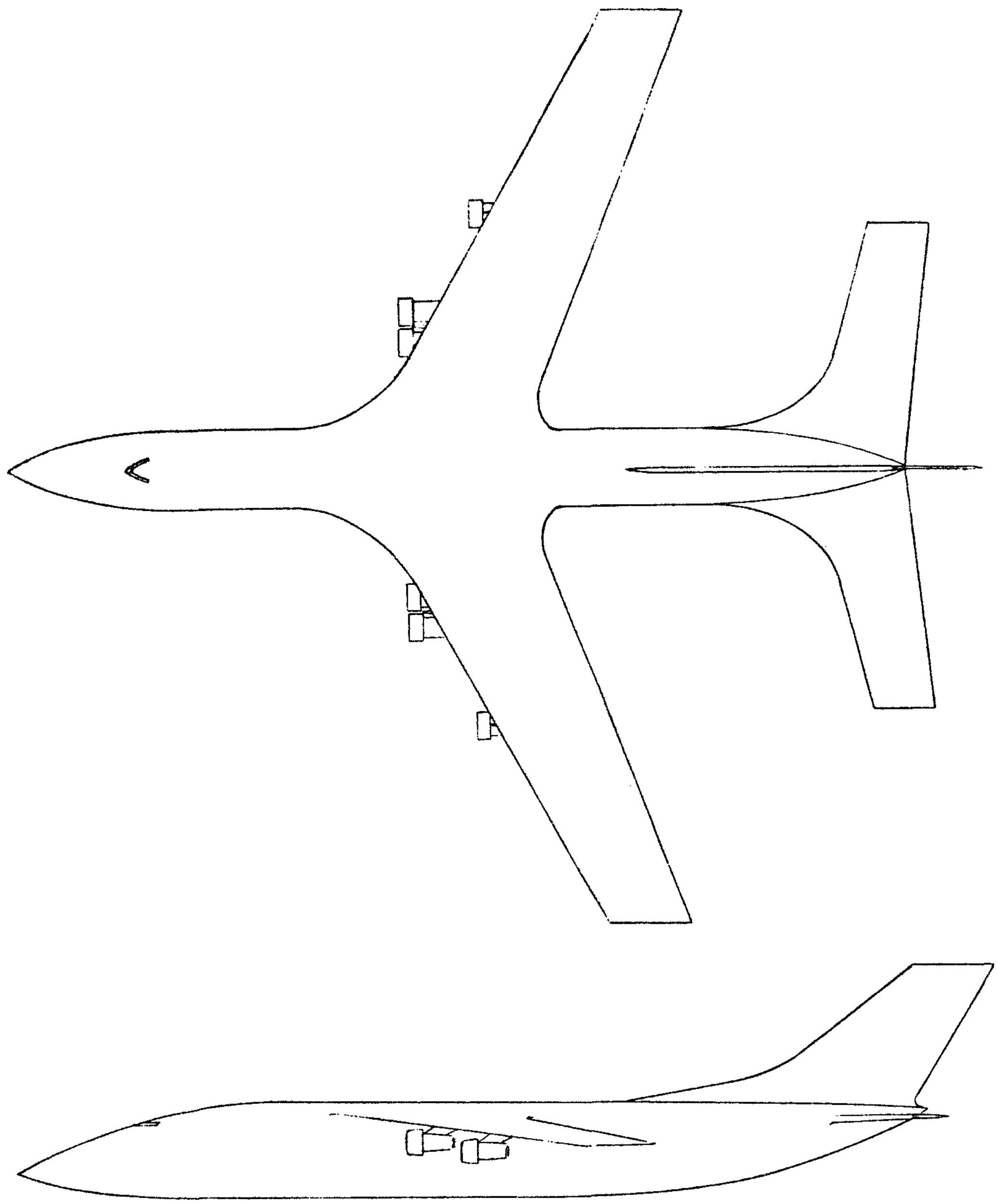

Figure 2.18 Sketch of TST preliminary design

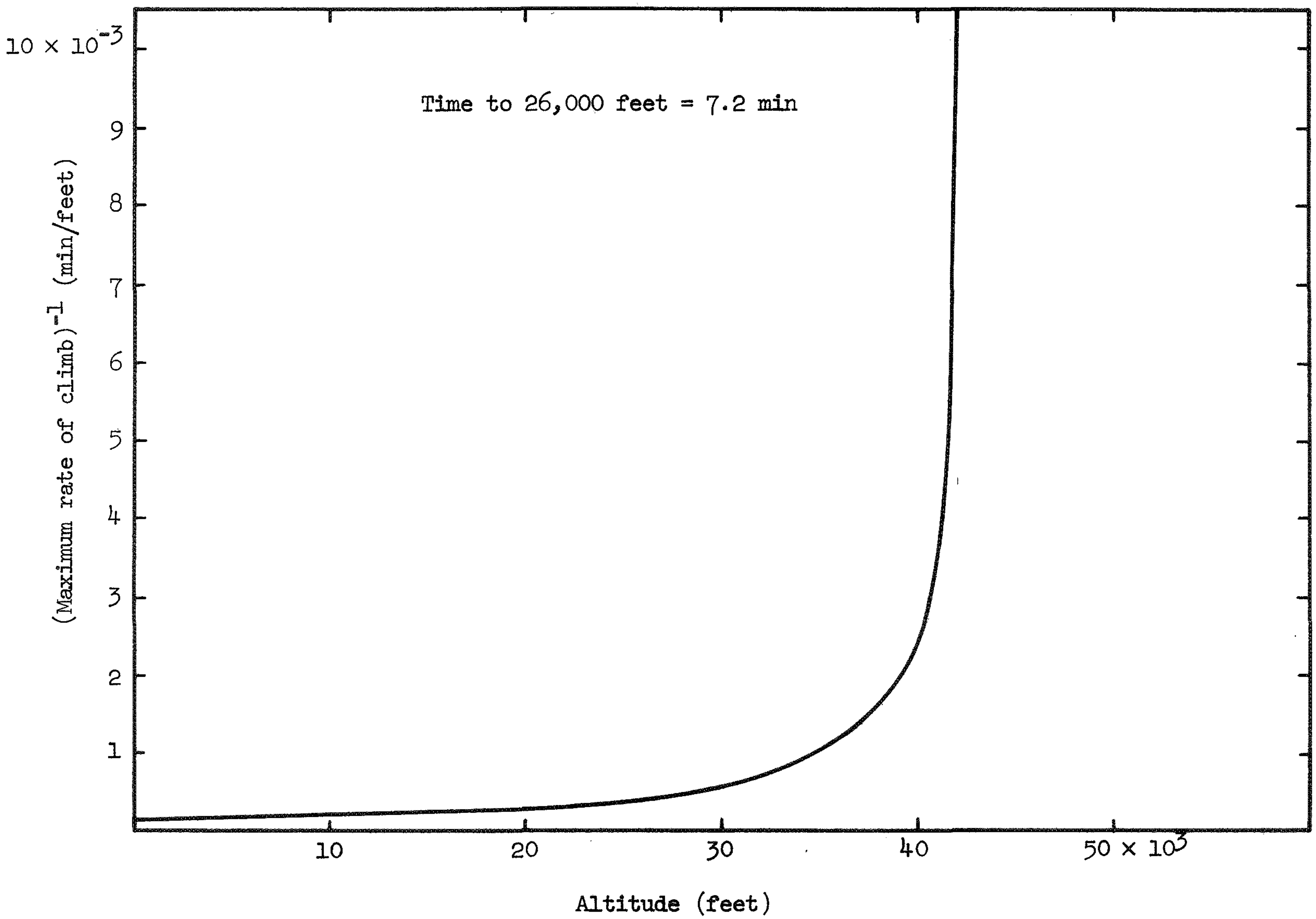

Figure 2.19.- Time to climb analysis.

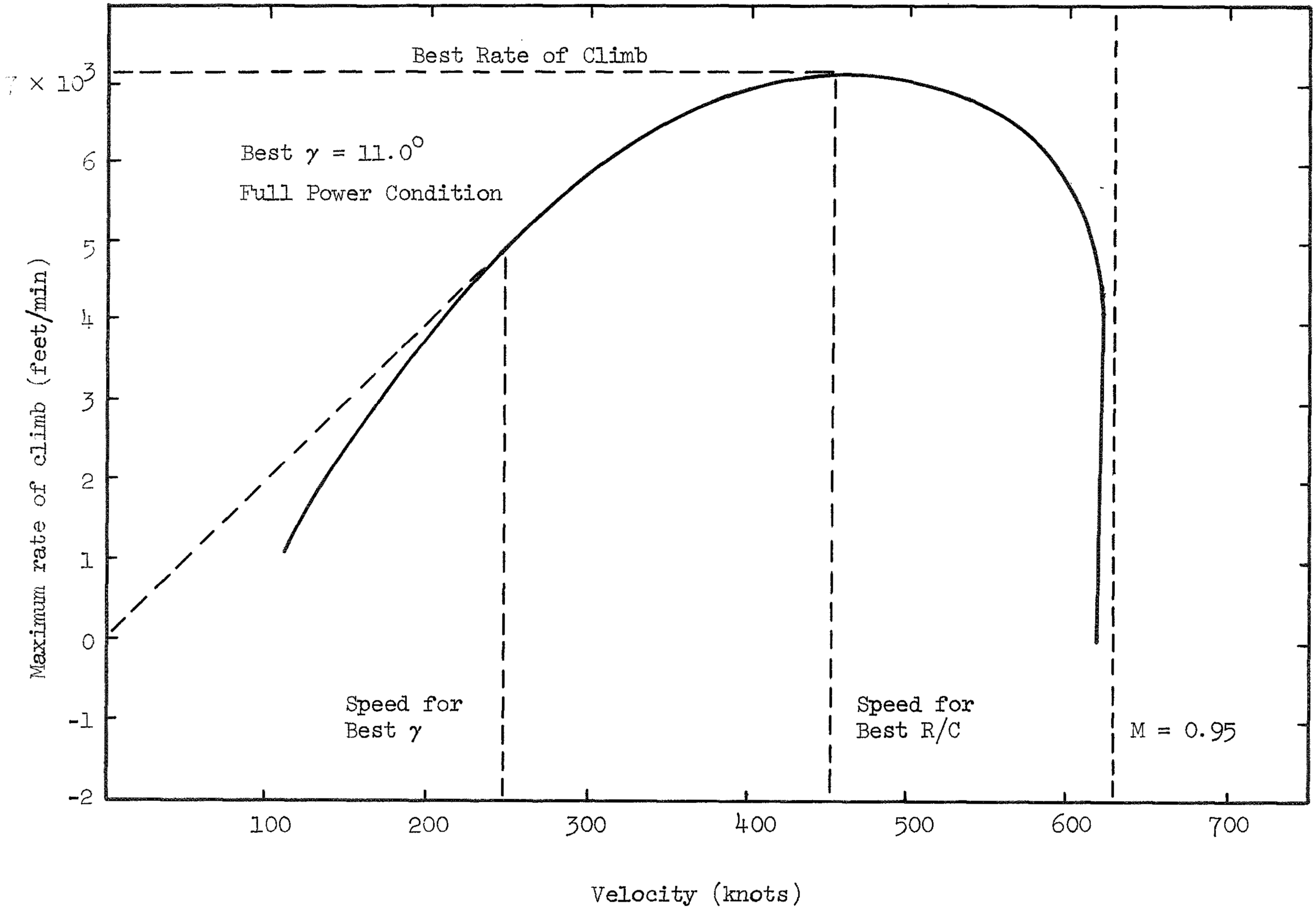

Figure 2.20.- Modified hodograph for TST at sea level.

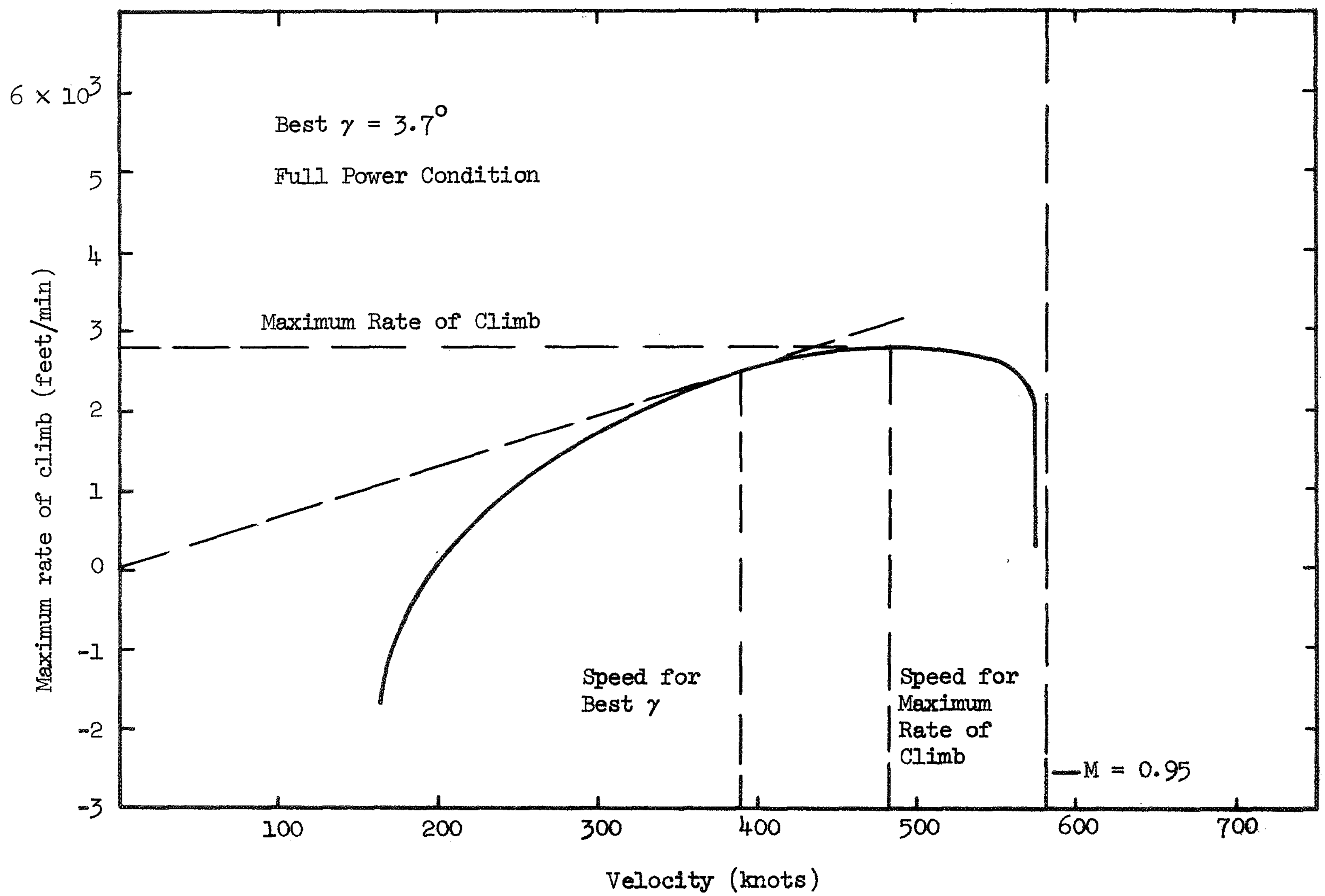

Figure 2.21.- Modified hodograph for TST at 26,000 feet.

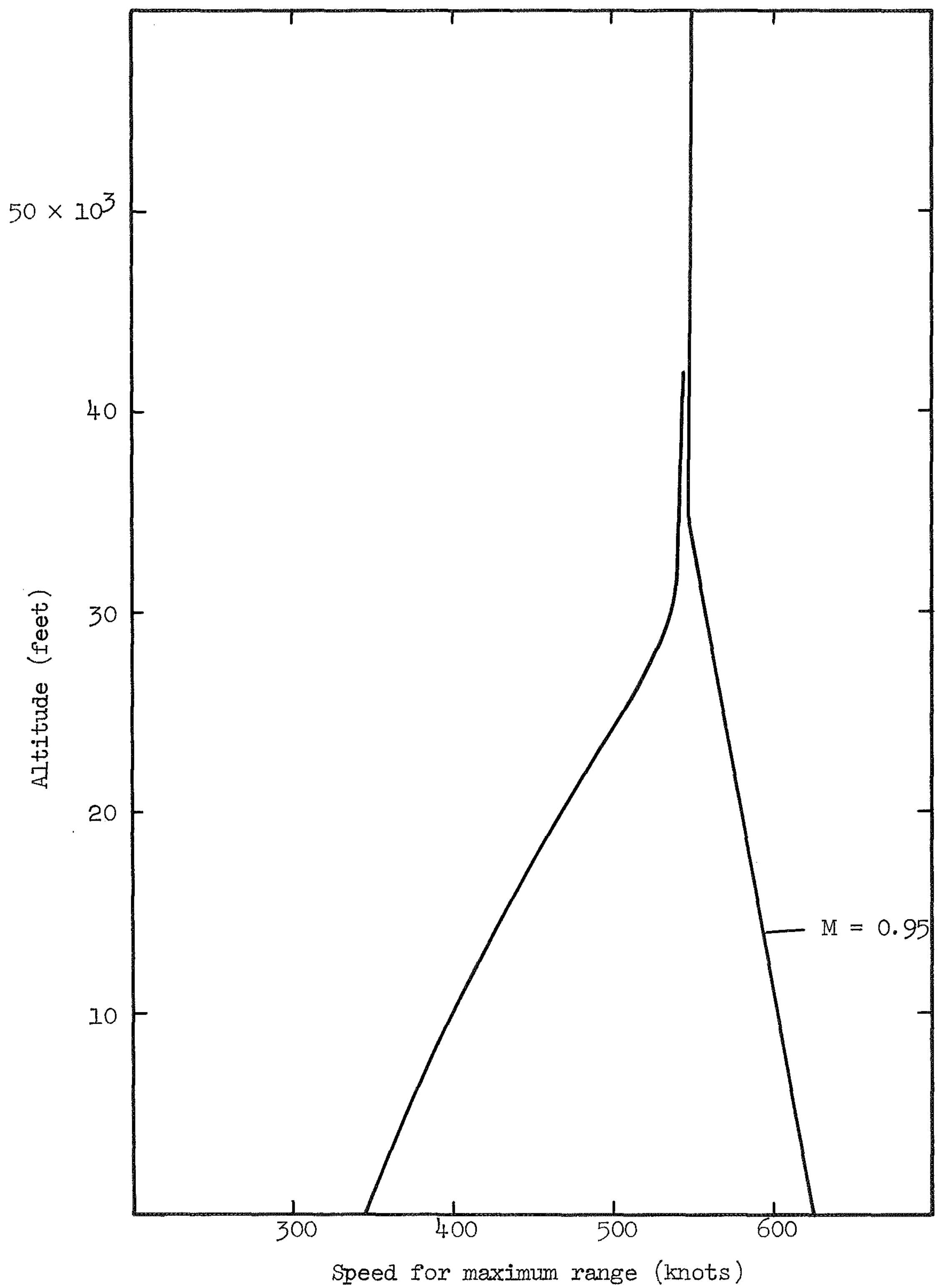

Figure 2.22.- Range performance profile.

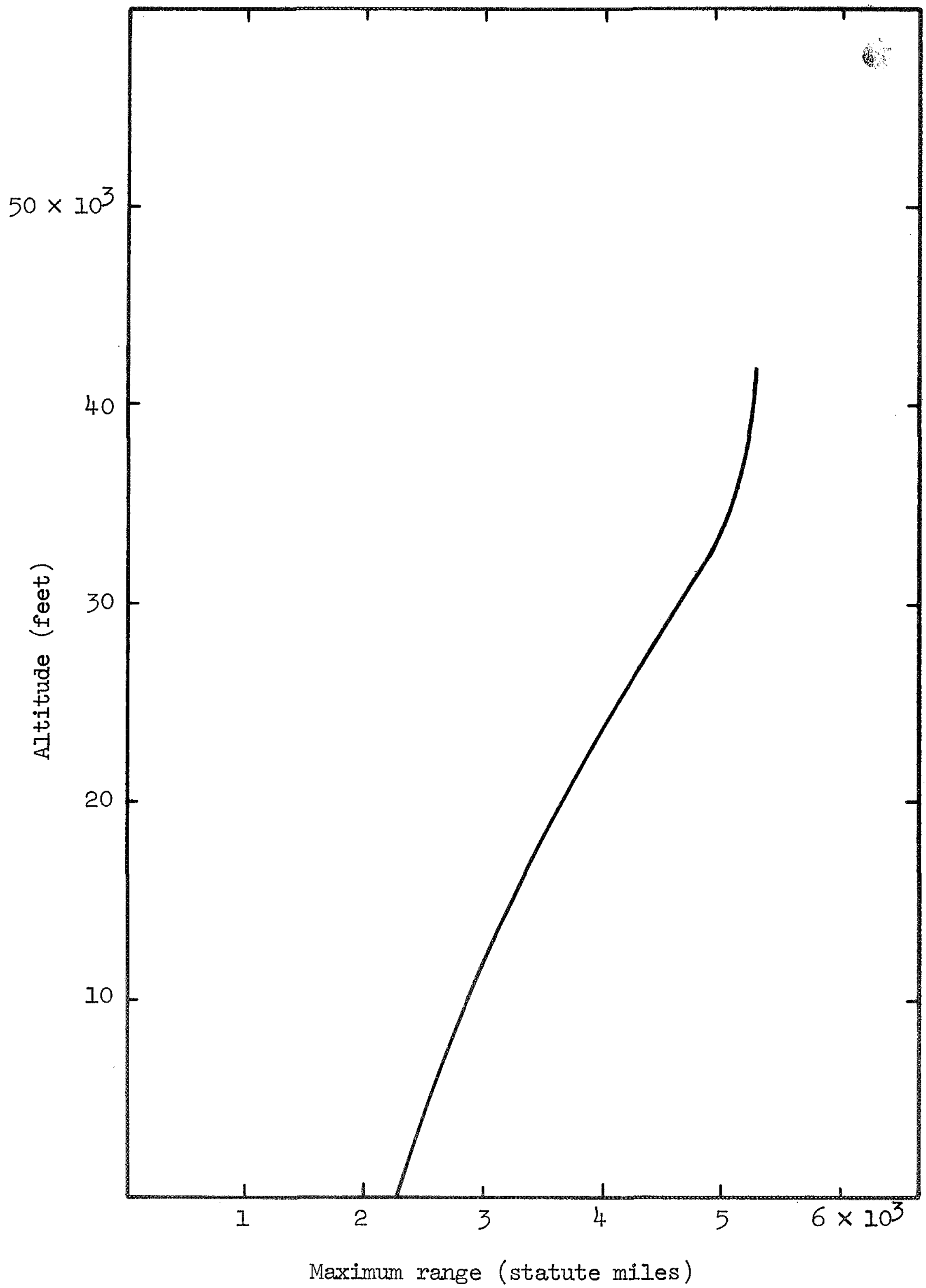

Figure 2.23.- Altitude performance.

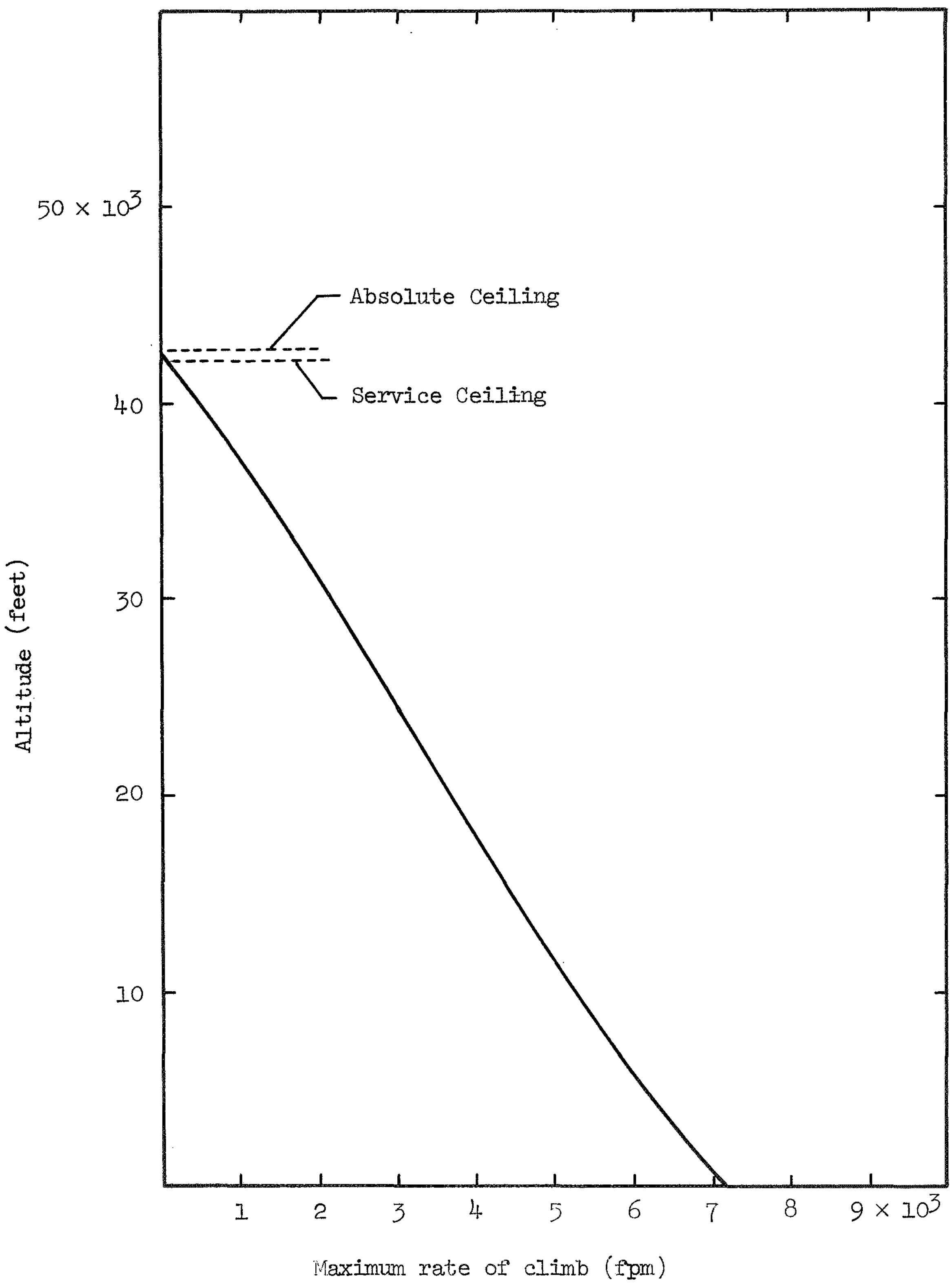

Figure 2.24.- TST climb profile.

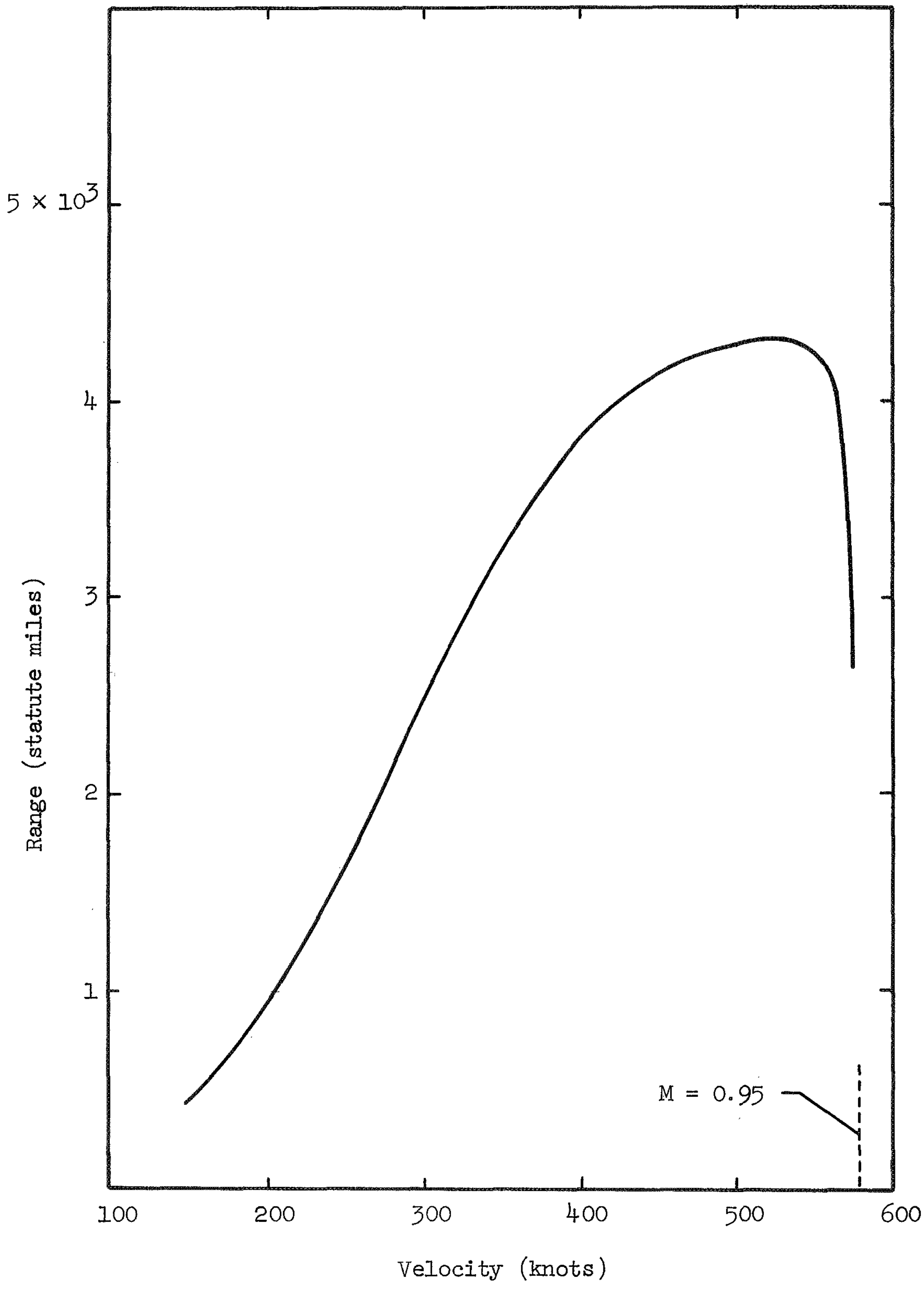

Figure 2.25.- Range performance at 26,000 feet.

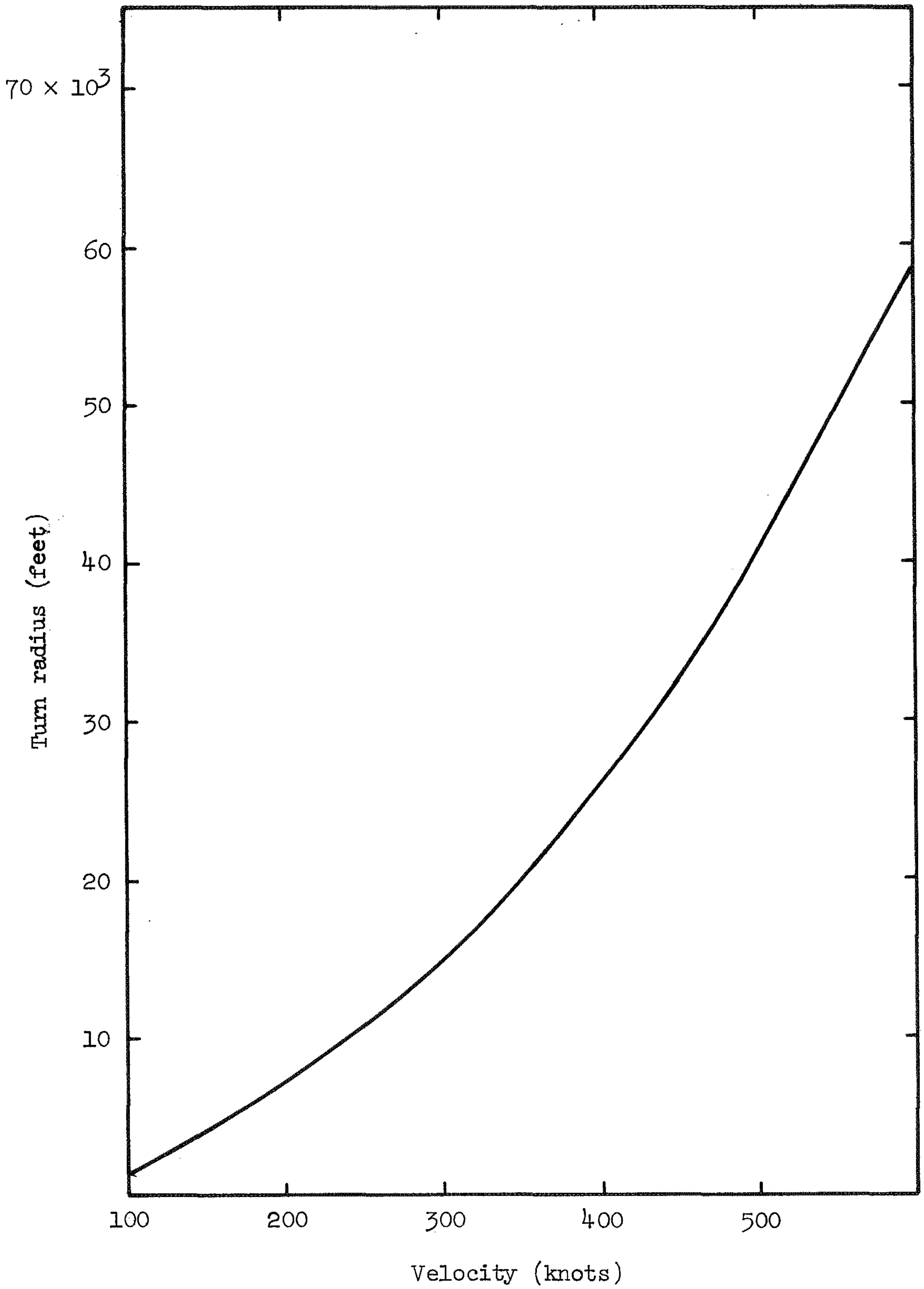

Figure 2.26.- Steady level turn performance for a 1.2g turn at sea level.

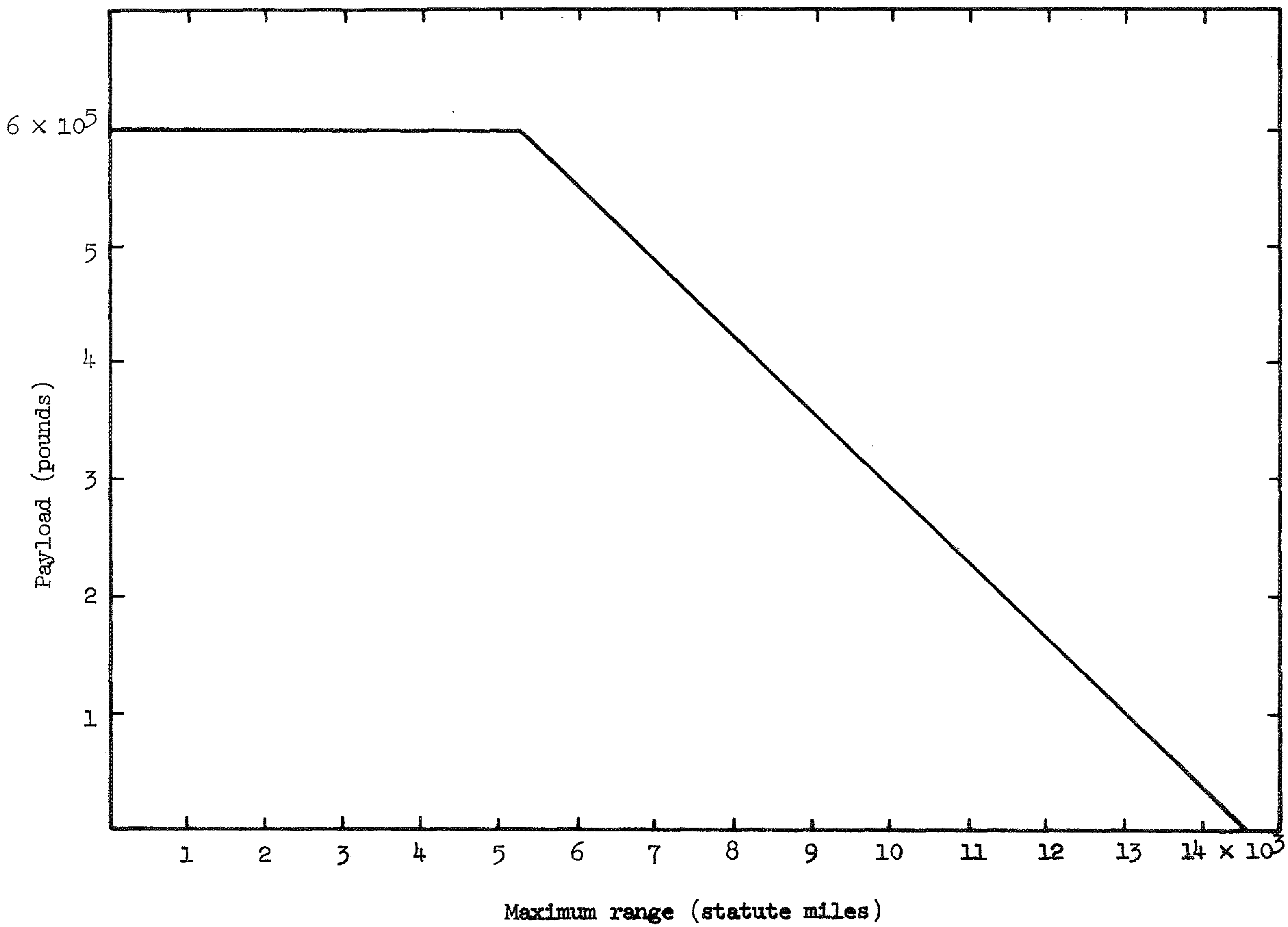

Figure 2.27.- Range-payload chart for TST.

Field Length Requirements:

Takeoff (SL)	3412 ft	___
Landing (SL)	6130 ft.	___

2.5 VORTEX ANALYSIS

A study of aircraft wake vortices was undertaken as part of this project on air traffic control since the separation of aircraft must be such that there is a very small probability of vortex induced upset of aircraft in the terminal area. Experience with transport aircraft has shown that aircraft can encounter mild upsets in the wakes of aircraft of similar weights. Such upsets can be very dangerous at low speeds close to the ground.

Description of Vortices

Aircraft trailing vortices are formed by the shedding of vortex sheets from lifting surfaces. These vortex sheets then roll up to form a pair of counter-rotating vortices behind the aircraft. After the rolling up, vortices appear as a vortex core surrounded by a potential flow field. This vortex system then undergoes decay by viscous diffusion from the core or by an unstable interaction induced by atmospheric turbulance, leading to the formation of vortex rings.

The flow field behind the wing is well understood qualitatively, but due to the three dimensional nature of the rolling-up process and due to the ill-defined role of viscosity in the process quantitative models are very inexact. These theoretical analysis of the process have been based on either unsteady two-dimensional flow or the equivalent three-dimensional steady flow. Several experiments to show contours of vorticity behind various wing planforms have been conducted but these results have apparently not been used to develop methods to study the rolling-up of the vortex sheet. Also, in these experiments little note was taken of axial (or longitudinal) flow in the formation process. Any studies in this region of the flow field must be based on numerical integration of the three-dimensional equations of motion using the vorticity distribution of the lifting surface as the initial (boundary) condition of the vortex sheet. Also, closed-form solutions must be based on the assumption of negligible longitudinal flows. This assumption leads to a reasonable representation of the sheet rollup, but is unlikely to give proper information on any axial pressure gradients in the vortex core.

In addition, the core of a tip vortex is usually turbulent; theoretical deterministic models will produce little more than qualitative information. Stochastic analyses of the decay of the vortex core have shown that the decay of a turbulent vortex may be predicted by using an empirical eddy viscosity (dependent on the initial vortex strength and Reynold's number) in the classical decay model used by many investigators. By the use of such an empirical approach, the downstream behavior of the vortices is smooth air can be well established. The effects of turbulence on the rolling up process are not known except for certain special cases.

The vortices on delta wings differ from those of vaguely rectangular planforms in that a vortex sheet is also shed from the leading edge of the wing. This vortex sheet forms a roughly laminar vortex over the wing. This vortex is responsible for the considerable vortex lift found on planforms with large leading edge sweep; as the vortex rolls up, the rotation of the core induces a very low static pressure along the axis of the vortex. In addition, the vortices on delta wings are observed to burst in the presence of an increasing axial pressure gradient (the vortex breakdown phenomenon) such as is encountered near the trailing edge of a delta platform. Whether this vortex bursting on a wing leads to a general turbulent motion or simply a turbulent vortex core is not clear. On very slender delta planforms, the vortices also develop an asymmetrical vertical interaction (the "vortex pop-up" phenomena), one vortex climbing over the other.

In the far downstream region, the behavior of vortices in smooth air is apparently well known. Here the vortices consist of two flow regions, an inner turbulent vortex core and an outer potential vortex. As discussed above, use of empirical constants in classical flows renders the downstream region quite tractable. Viscous diffusion is the usual mechanism of vortex dispersion in this region. In addition, an unstable interaction between the vortices based on their mutual induction has been shown to exist. Unfortunately for exactness, the time scales of vortex decay are similar to those of minor atmospheric movements. Thus, the persistance of a vortex in a particular air mass is still hard to predict.

Once the structure of the wake vortices is sufficiently well known, work can begin on the problem of vortex wake encounters by other aircraft. Although much work has been done on determining minimum separation for particular aircraft, such work must (for safety) be based on the most pessimistic circumstances and leads only to minimum separation distances, usually on the order of a few miles. In addition, flight tests have shown the vortices to be at full strength thirty seconds after the passage of large transports in landing configuration. This corresponds to a distance of over one mile. The vortex decays slowly from this intensity. Desired separation for the air traffic control procedures recommended in Chapter III was near this figure. Thus, it was decided to investigate the feasibility of vortex dispersion near the aircraft. While no explicit methods were worked out for breaking up vortices, qualitative ideas of the necessary prerequisites to this have been formulated.

Any work of this nature must start from a good knowledge of flow near the aircraft, i.e. from a model of the vortex sheet becoming a vortex core. Once the rolling up of the vortex sheet can be predicted, ways to break up the vortex can be examined. It is important to seek methods which can be applied to existing configurations with a minimum performance penalty; methods which require extensive modifications or incur substantial performance penalties will likely never be incorporated.

Vortex Dispersion

Once a reasonably exact model of the flow behind a wing has been developed, ways to break up the vortex can be investigated. There appear to be many possible ways to operate on the vortex formation and vortex flow to impede the formation of the vortex core or to dissipate the formed vortex core. Investigations of particular areas of the vortex formation process yield many possible schemes.

Operations on the circulation distribution about the wing, by wing-tip or planform geometry modifications, provide varying degrees of vortex strength reduction. Modifications such as tip tanks and end plates increase the two dimensionality of the flow and simply shift the vortex cores outward with little change in strength. Conversely, concentrating circulation and lift on inboard sections shifts the vortex cores closer together. Moving the vortices closer together should increase the instability due to mutual inductance mentioned earlier. Also circulation distributions giving more than two vortices (such as have been observed with partial-span flap deflections) may also increase the mutual inductance and accelerate vortex system instability. Many wingtip designs have been investigated in connection with helicopter rotor wake studies, but it seems doubtful that tip configuration alone can shown too much reduction in the vortices. In addition, experiments on the tip effects, unaided by a really good mathematical model of the flow behind the wing, will be essentially trial and error and will show results very slowly.

Operations on the vortex sheet, such as suction or blowing, could be devised to inhibit the rolling up of the vortex sheet. The introduction of swirling flows near the tip could decay the roll-up while the sheet undergoes a viscous diffusion. Experiments conducted using propellers at the wing tips have shown reductions in induced drag on the wings, implying a reduction in downwash near the wing; but no measurements of the vortices were taken, as that study was concerned with aircraft performance.

Another procedure suggested by the vortex breakdown phenomenon is to produce an adverse pressure gradient along the core. The effects of suction or blowing near the tip on the axial pressure gradient could be investigated were a proper knowledge of the axial flow characteristics of a vortex available. Also, the effects of periodic suction of blowing and periodic displacement of the vortex sheet (as a flapping surface) should be investigated. Such procedures might be able to produce further core instability.

Apparently the most promising of these approaches is the last. Even though the vortex has a different origin, i.e. from the leading edge, the fact that it bursts in the presence of a particular pressure field may be applied to other vortex flows. In fact, a conjugate-flow theory for vortex breakdown seems to apply well to vortex pipe flows. investigation of the axial flows in aircraft trailing vortices, possibly by wind tunnel or water tunnel tests, appears to be a necessary first step. After a consistent knowledge of this area is acquired, the affects of suction, blowing, and jet flaps on the vortex characteristics should be studied, preferably by analytical methods rather than experimental ones in order that good test areas can be defined. If a favorable pressure field can be generated without an unreasonable power expenditure, tests on aircraft could follow.

2.6 SUMMARY

Results and conclusions regarding future aircraft are the following:

1. Based on 2,013,700,000 projected passenger enplanements for the year 2000, a passenger fleet of 8179 aircraft is predicted.

2. Cargo demand in the year 2000 for the all-cargo fleet has been projected to be 601,082 millions of ton-miles, of which 434,600 millions are domestic air cargo. This cargo will be moved by a total of 3140 aircraft of which 1805 will be flying domestic routes.

3. General aviation aircraft in the year 2000 will number 700,000.

4. Due to the fact that higher wing loadings of future aircraft will compensate for advances in high lift technology, terminal area performance of future

conventional aircraft will be approximately the same as present aircraft performance.

5. Notable exceptions to conclusion four are that STOL and VTOL will have unique terminal area performance characteristics, and conventional aircraft will approach the runway at higher descent angles to help alleviate the noise problem.

6. Recommendation of aircraft separation distances based on vortex strength is only a stop-gap measure. Therefore, in order to significantly decrease aircraft separation distances, vortices must be dissipated. Further theoretical and experimental work will be required to determine methods for accomplishing this.

To fully appreciate the above aircraft projections, they must be compared with the present aircraft fleet (see Table 2.17).

A four fold increase in the total commercial fleet is estimated. Cargo aircraft will increase twelve times over its present fleet size and by the year 2000 the cargo fleet alone will be larger than the present total commercial fleet. This, combined with the projection of 700,000 general aviation aircraft, gives some indication of the urgent need for improvement in air traffic control equipment and procedures, especially when one considers that with the present fleet size, five of this country's major airports are now saturated.

TABLE 2.17 COMPARISON OF PRESENT AND PROJECTED AIRCRAFT FLEETS

Commercial Fleet	1969	Percent of Total	2000	Percent of Total	Increase
Passenger	2,327	90.0	8,179	72.3	3.51
Cargo	259	10.0	3,140	27.7	12.12
Total	2586	100.0	11,319	100.0	4.38
General Aviation	133,000		700,000		5.28

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CHAPTER III

AIR TRAFFIC CONTROL PROCEDURES AND HARDWARE

3.1 INTRODUCTION

The investigation of all ramifications of an air traffic control system is, at best, an arduous, time consuming task. Even more difficult, however, is the development of a future system to accomodate the anticipated growth of air traffic. Recognizing this fact, it was decided to focus attention on the technical aspects of a future system. The reader will, therefore, find little reference to the economic, social or political consequences of design proposals. These interactions, although not examined in depth, were considered in the systems design.

Every attempt was made to develop an optimal air traffic control system. An optimal system was considered to be an ideal or ultimate concept. No pretense was made, however, that this goal could be attained. A number of designs were proposed and each was examined in terms of its capabilities and limitations. The designs herein are those which are considered the most favorable.

Purpose

After gaining an appreciation of the problems associated with air traffic congestion, it was determined that the terminal area constituted the biggest bottleneck to the flow of traffic in the entire air traffic control system. As a result, the following statement of purpose was formulated:

> To develop air traffic control, approach, takeoff and landing, and air collision avoidance procedures and hardware to minimize terminal area operating time, safely and economically, through the year 2000.

Terminal area operating time is the key phrase in this statement. This time may be minimized by increasing airport capacity, the maximum number of operations per unit time with acceptable average delay, and/or by decreasing the time to landing, the time from entering the terminal area to touchdown.

Assumptions and Constraints

In an investigation or systems design study, it seems advisable to guide the working individuals through a set of coordinating assumptions. One drawback to such an approach may be to unduly restrict systems planning. In retrospect, this is properly a matter of concern but it is felt that joint activity requires effective direction through such measures. The more important assumptions and constraints which were considered for preliminary planning follow:

1. No order of magnitude advancement in aircraft power sources or lift generating systems was considered.

2. Concepts presently available in electronics, computer technology, and flight instrumentation would be employed with development and integration into a total system.

3. Aircraft would approach and depart in a single direction using dual lane runways.

4. System capabilities would include both segregated and mixed operations.

5. Initial design would be based on one airport with one runway at the center of an approximately 60 mile terminal area. Subsequent design would be expanded to include multiple runways and multiple airports in the terminal area.

6. System designs would accomodate mixed performance classes of aircraft under category II weather conditions.

7. Airspace within the terminal area would be segregated for controlled and uncontrolled aircraft.

Investigation Approach

Analysis of the sequence of events in current terminal areas prompted activity along four avenues of investigation:

1. Air Collision Avoidance--Procedures and hardware required to reduce air collision to the lowest practical level.

2. Landing and Takeoff--The transition from touchdown to ground taxi and from ground taxi to flight.

3. Final Approach--The precise transition from flight to touchdown.

4. Terminal Air Traffic Control--The transition from enroute flight to final approach.

Subsequent sections of this chapter describe the results of these investigations.

3.2 AIR COLLISION AVOIDANCE

The current problems concerning mid-air and near midair collisions have resulted in a number of devices and procedures to avert a collision situation. Recent developments have specified the first generation proposals.

The most developed system is the time-frequency[1], collision avoidance system (CAS). It is based upon a highly accurate cesium clock which is capable of segregating signals of all aircraft in an area, such that on board calculations of separation parameters are possible for as many as 2,000 aircraft every three seconds[2]. They system requires very accurate ground based clocks to neutralize the aircraft's time errors.

Below is listed the advantages and disadvantages of this system.

Advantages:

1. It is capable of handling multiple aircraft.

2. Range rate is accurately achieved.

3. Other navigational aids could be incorporated.

Disadvantages:

1. The cost of the system in prohibitive to general aviation. Minimum cost is estimated at about $4000 per unit.

2. The clock synchronous system may be difficult to implement due to its precise nature and extensive ground equipment.

3. The system still uses an exchange of heights based upon barometric measurements and its associated errors.

The cost of the above system has led to a different concept for general aviation. This system is based upon a Zenon beam of light warning the pilot of a small aircraft intruder within a certain area of this aircraft.[3] The relative merits of this system are listed below:

Advantages:

1. Multiple aircraft can be observed.

2. Cost of this system is less than the time frequency system ($1,500-2,000).

3. No signals in the commonly used radio frequencies are employed.

Disadvantages:

1. Only VFR traffic conditions are considered.

2. False and missed alarm rates are high due to inaccuracy of equipment.

The VFR constraint upon the system is the most serious. Those who advocate the system rely on past mid-air collision data which indicates that most collisions occur under VFR conditions.

A second generation system now on the drawing board at RCA incorporates collision avoidance with ground controller activities. The system, called SECANT-B[4] (Separation Control of Aircraft by Monsynchronous Techniques), allows multiple aircraft coverage by filtering all signals until the right frequency signal is received. This allows the same separate aircraft treatment as in the time-frequency system at much less cost. The versions of this system range from a $500 pilot warning system for general aviation to a $10,000 to $20,000 CAS for air-carriers and eventually to an on board traffic monitoring system coordinated with the ground control. A listing of its advantages and disadvantages follows:

Advantages:

1. Cost to general aviation is well below that of previously defined systems.

2. Multiple aircraft coverage is still possible.

3. All versions are compatible with one another.

Disadvantages:

1. System is still on paper and tested versions may still prove disappointing.

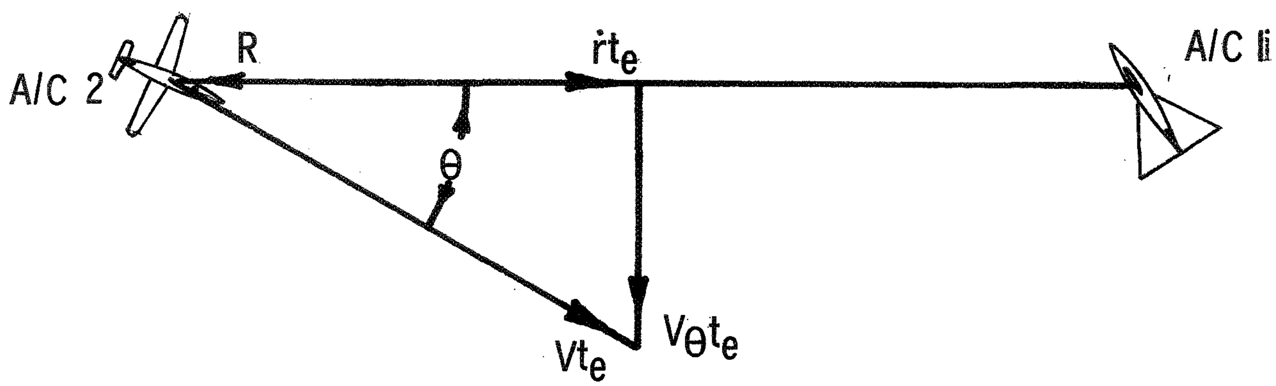
2. System may be too late to be employed as the solution to the immediate problem.

One basic method of hazard evaluation has evolved. This method must allow ample time for maneuvers after warning the pilot. It is felt that the relative range and velocities must allow a certain miss distance that must never be violated. Shown in Figure 3.1 is the geometry of the interaction among aircraft.

The mathematical expression for miss distance is:

$$(r + Vt \cos \theta)^2 + (Vt \sin \theta)^2 < x^2 \qquad (3.1)$$

The above equation holds when a hazard exists. Here x includes minimum miss distance, a term used to compensate for possible accelerations of



V = Velocity of A/C 2 relative to A/C 1

$\dot{r}$ = Range rate = $V\cos\theta$

$V_\theta = V\sin\theta$

R = Position of A/C 2 relative to A/C 1

Figure 3.1

Collision Alarm Geometry

aircraft and range rate error. Since range and range rate are the only measurements, the criterion for hazard becomes:

$$r + \dot{r}T < \frac{U}{2}(T^2 - Tc^2) + \text{Other Terms} \qquad (3.2)$$

where:

U = combined maximum allowed aircraft acceleration for both planes

T = Tau (time to collision).

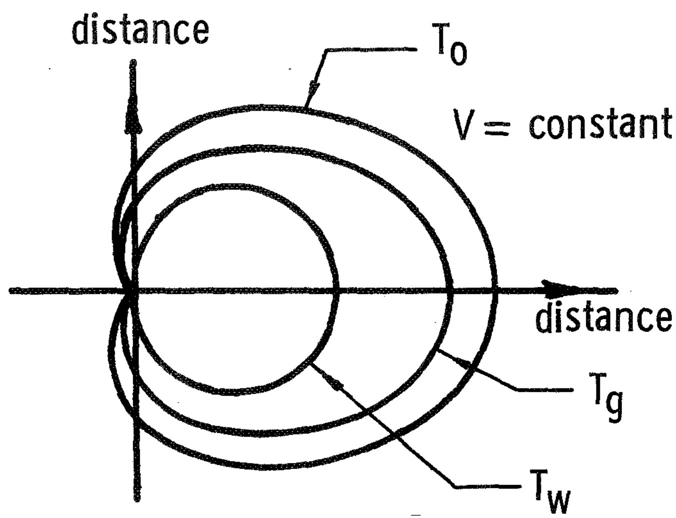
Tc = time due to data processing.

Other terms - include compensation for errors in measurements and the minimum miss distance.

This is called the modified tau criterion and can be represented graphically by a cardioid. A common system criterion is shown in Figure 3.2. The shortcoming with this method is that large areas about the aircraft are enclosed by the cardioid. This results in numerous alarms which do not represent a true hazard.

The future CAS systems will follow one of two solutions. The on-board systems described previously show the greatest amount of development. Another idea that shows promise for future use is a ground based evaluation system with alarm status being updated to each aircraft via data-link.

The advantage of a ground based system is that one can utilize the increased amount of data and accuracy of the ground measuring system. Future terminal area air traffic control using this tri-lateration system can determine accurately the position and velocity vector of each aircraft in the area. The addition of the V_θ component reduces the alarm region described by systems which use range and range rate alone. Figure 3.3 shows an example of a conflict situation being evaluated by both types of hazard region. The inner curve is the



$T = T_0$ is the initial alarm to level off.

T_0 = time to level off
+ time for A/C servo delay
+ time for data arrival
+ time due to r error
+ time for pilot to dive or climb

T T_g is the second alarm and requires a roll out

$T_g = T_0$
+ time to roll out
− time to level off

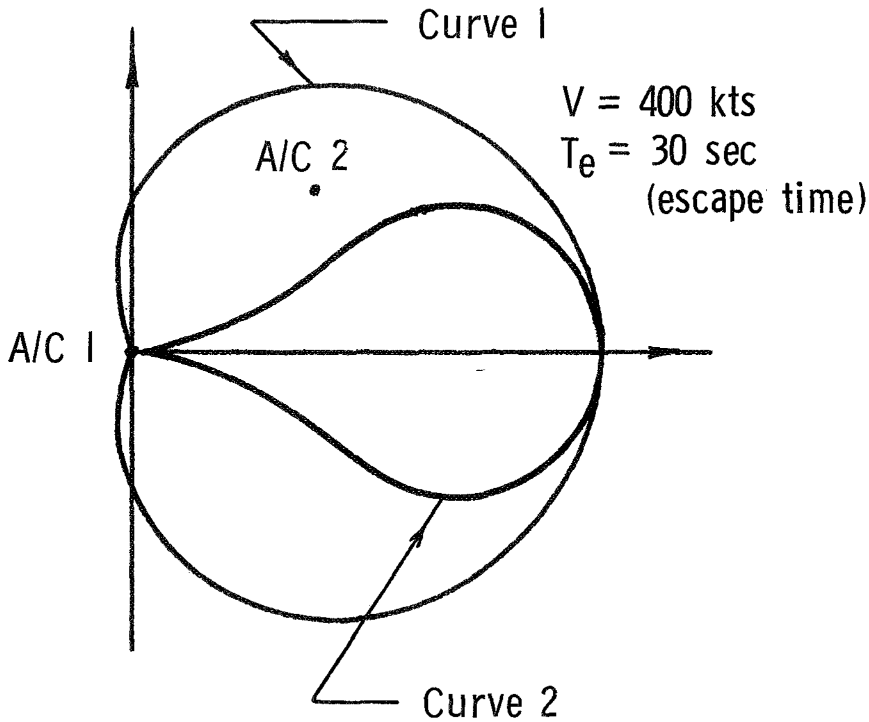
T T_w is the third alarm and requires a dive or climb

$T_w = T_g$
− time to roll out

Figure 3.2

Alarm Region Cardioid

Hazard Criterion Evaluation



Curve 1 Tau Cardioid
Range and range rate measured
Collision hazard alarm for

$$R + \dot{r}T_e \leq 1.54 \text{ nm}$$

Curve 2 Hazard Teardrop
Range and relative velocity measured
Collision hazard alarm for

$$(R + VT_e\cos\theta)^2 + (VT_e\sin\theta)^2 \leq (1.54)^2$$

Figure 3.3

conflict region for a set of aircraft in which the total velocity vectors are known.

One can still approximate V_θ using the on board equipment. This is done by differentiating the radial component $\dot{r}$ with respect to time. This yields $\ddot{r}$.[5] The normal velocity component is then calculated by:

$$V_\theta = \sqrt{r\ \ddot{r}} \quad (3.3)$$

The future of air collision avoidance is closely related to air traffic control procedures. It is safe to predict that automation and other improvements in the traffic control techniques will reduce the possibilities of separation violation in the controlled airspace. This places the recommended collision alarm and maneuver system into a back-up operation.

3.3 LANDING AND TAKEOFF

The approach used to study the aircraft-runway subsystem was to investigate the basic relationships of the subsystem, acknowledge the interface considerations, and construct a performance meodel. The performance capability of the system is measured as a function of identifiable physical parameters, the objective being to maximize the airport capacity by improving this capability.

The basic relationships of the subsystem are those between physical parameters of the system components, i.e., the aircraft and runway.

The Aircraft

Considering the wide spectrum of missions performed by aircraft, the performance characteristics vary widely. Those performance characteristics which directly affect the aircraft-runway subsystem are:

1. Landing Speed. The forward speed of the aircraft when it contacts the ground and begins the transition from an air vehicle to a ground vehicle.

2. Deceleration. The change in velocity from landing speed to turnoff speed.

3. Turnoff Speed. The forward speed of the aircraft when it leaves the landing surface and turns onto the taxiway. The turnoff speed depends upon the type of runway exits.

4. Distance Down the Runway to Landing. The distance from runway threshold to touchdown point. The threshold is defined for these purposes as that point where the aircraft is committed to land and from which a waveoff cannot be executed.

5. Entrance Speed. The forward speed of the aircraft when it enters the takeoff surface and aligns for beginning takeoff roll.

6. Takeoff Speed. The forward speed of the aircraft when it lifts off the runway.

7. Acceleration After Liftoff. The continued increase from takeoff speed during the climbout.

The Runway

The runway is internationally defined as "a (defined) rectangular area on a land aerodrome prepared for the landing and takeoff of aircraft along its length."

Functionally, the runway provides a channel through which the air-to-ground transition of traffic can be achieved. It is this single channel, one directional characteristic at which traffic converges and diverges that makes it a bottleneck even when it is operating below capacity.

The runway capacity largely dictates the size and nature of all other airport services provided.

The Landing Operation

In the landing operation, aircraft are accepted from the approach subsystem at the threshold of the runway, make contact some distance down the runway, decelerate, and exit to the taxiway/terminal subsystem.

The aircraft performance characteristics affecting subsystem capability in landing are:

1. Landing speed
2. Deceleration
3. Turnoff speed
4. Distance down the runway to landing

Deceleration on the runway is assumed to be constant, a good approximation if thrust reversal is not used. Thrust reversal represents an extra margin of performance.

The Runway Performance

The runway performance characteristics affecting subsystem capability in landing are:

1. Runway exit type
2. Exit location
3. Taxiway/terminal acceptance rate

Runway exit type characteristics include:

1. Angle of turnoff
2. Radius of curvature of the turnoff
3. Width

Exit location is optimized when exits are located for the highest possible turnoff speed at the ideal location.

If the aircraft performance characteristics are specified in terms of touchdown speed, deceleration, and turnoff speed, (a function of exit type) with the exits ideally located, the minimum runway occupancy time can be determined. This is illustrated in Figure 3.4.

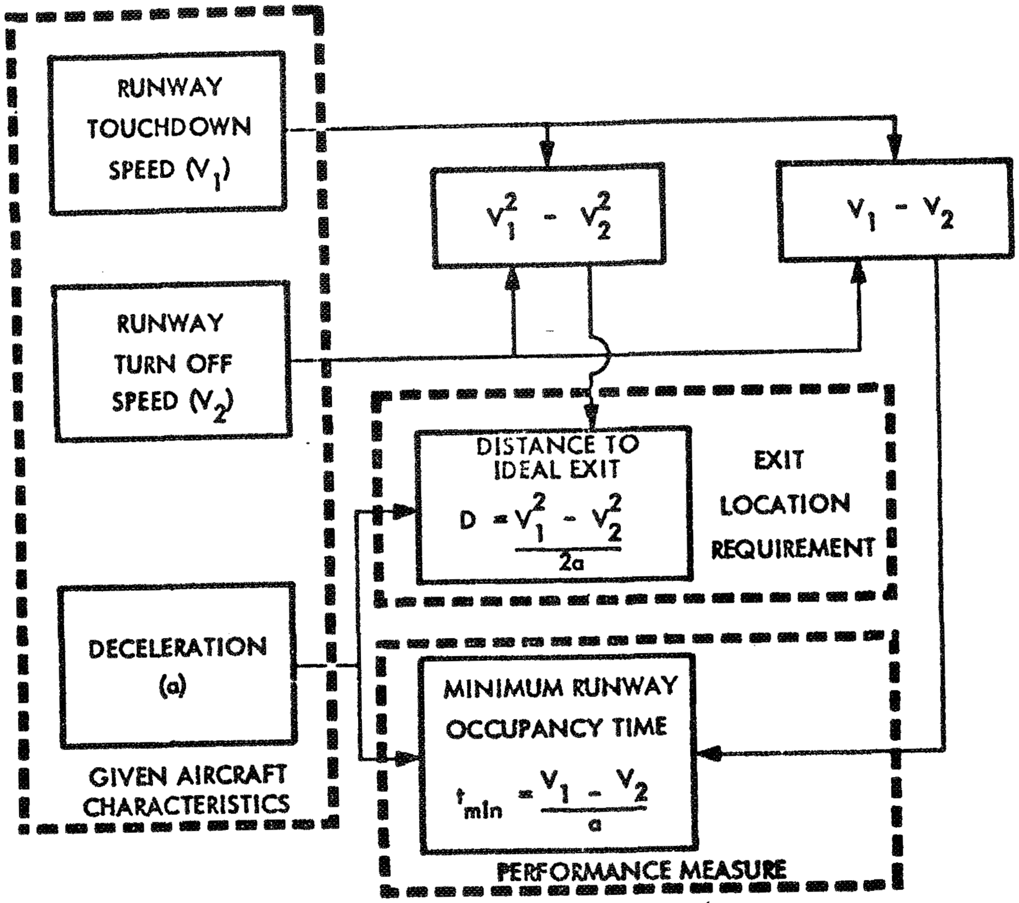


Figure 3.4 Aircraft Landing Characteristics, Given Exit Location and Type, and Runway Occupancy Time

If the aircraft performance characteristics are specified the effects of arbitrary exit location on minimum runway occupancy time can be determined. Figure 3.5 displays this procedure.

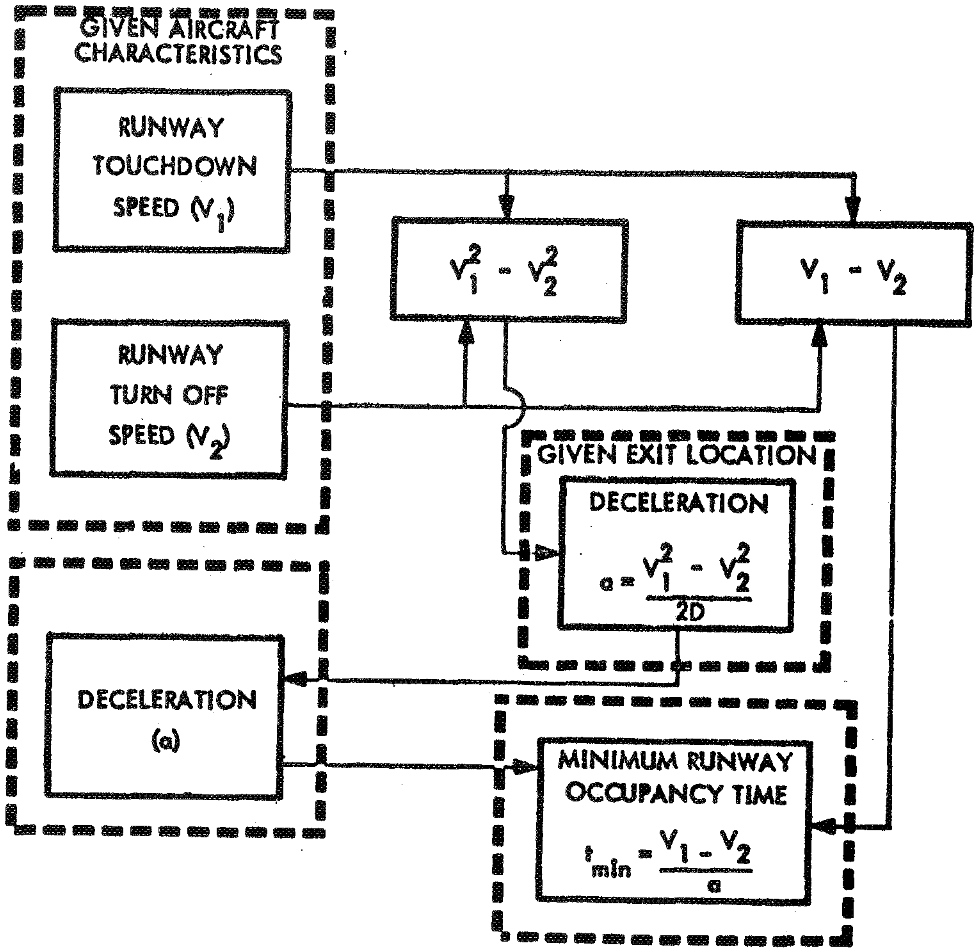


Figure 3.5 Aircraft Landing Characteristics, Ideal Exit Location For Given Exit Type and Minimum Runway Occupancy Time

The total runway occupancy time is the sum of the minimum runway occupancy time and the time required to fly from the threshold to touchdown. Time from threshold to touchdown is the distance from the runway to landing divided by touchdown speed which approximates approach speed.

Total Runway Occupancy Time

The maximum hourly capacity of the aircraft runway subsystem is defined as the ratio of time interval to mean runway occupancy time. Mean runway occupancy time is obtained by computing total runway occupancy times for each performance category of aircraft and computing a weighted average of occupancy times over the percentage distribution of aircraft performance category in the traffic. The following equation is obtained:

$$C_1 = \frac{60}{Ta} \qquad (3.4)$$

where:

C_1 = maximum hourly capacity of aircraft runway subsystem.

$T_a = t_{min} + k_1$

t_{min} = minimum time between touchdown and turnoff

k_1 = time over runway prior to touchdown (3.5)

Interface With Aircraft--Approach Subsystem

IFR rules governing the approach to the runway require:

1. A minimum separation distance between all aircraft in the approach corridor.

2. The position of the previous operation before another operation is accepted into the subsystem.

These rules reflect the accuracy of the control and navigation subsystems as well as aircraft-pilot and control-controller subsystem response.

Current specific IFR radar rules require:

1. Minimum separation distance of three miles

2. That a landed aircraft shall have turned off the runway before the approaching aircraft crosses the runway threshold.

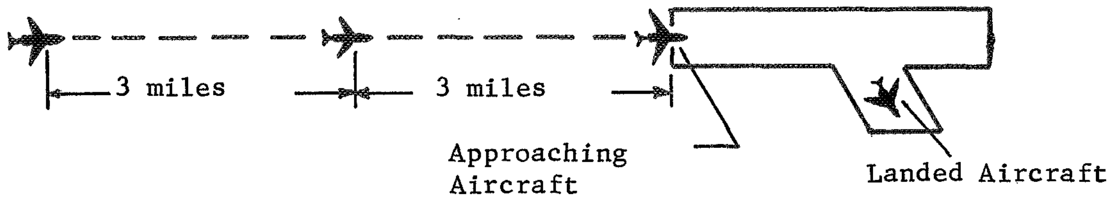


Figure 3.6 FAA Approach Control Rules (IFR) Single Runway

Interarrival time is a function of approach speed and separation distance. This relationship is illustrated below in Figure 3.7.

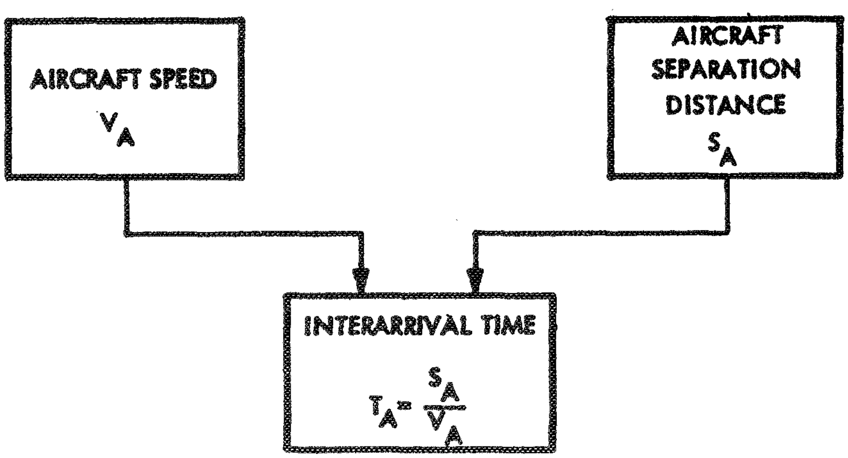


Figure 3.7 Airplance Characteristics And Approach Control

If all aircraft in the system have equal approach speeds the separation will be constant throughout the approach. If the approach speeds of succeeding aircraft are not equal, the separation distance will be either opening or closing during the approach introducing an additional time penalty when a slow aircraft follows a fast aircraft.

The mean interarrival time is a function of approach speed, separation distance, and frequency distribution of aircraft pairs with unlike approach speeds. The frequency of occurrence of unlike speeds can be taken as its natural frequency of occurrence or it can be modified by control measures such as segregating traffic into speed blocks.

The maximum hourly capacity of the aircraft-approach subsystem is defined in terms of the mean interarrival time. The following equation results:

$$C_2 = \frac{60}{T_a}$$

where: C_2 = maximum hourly capacity of aircraft approach subsystem

T_a = mean interarrival time (min.).

Subsystem Dependence

The basic subsystem dependence is the relationship of runway occupancy time and interarrival time. A comparison of the runway occupancy time and the interarrival time is made to ascertain whether the system is in balance. To illustrate the sensitivity of landing capacity to approach/landing speed, deceleration, and approach separation, the landing capacity of a runway for three mile approach spacing and a combination of exit design and aircraft capability permitting deceleration of 9 ft/sec.^{2} and exit velocity of 60 knots with ideal exit location is shown in Figure 3.8.

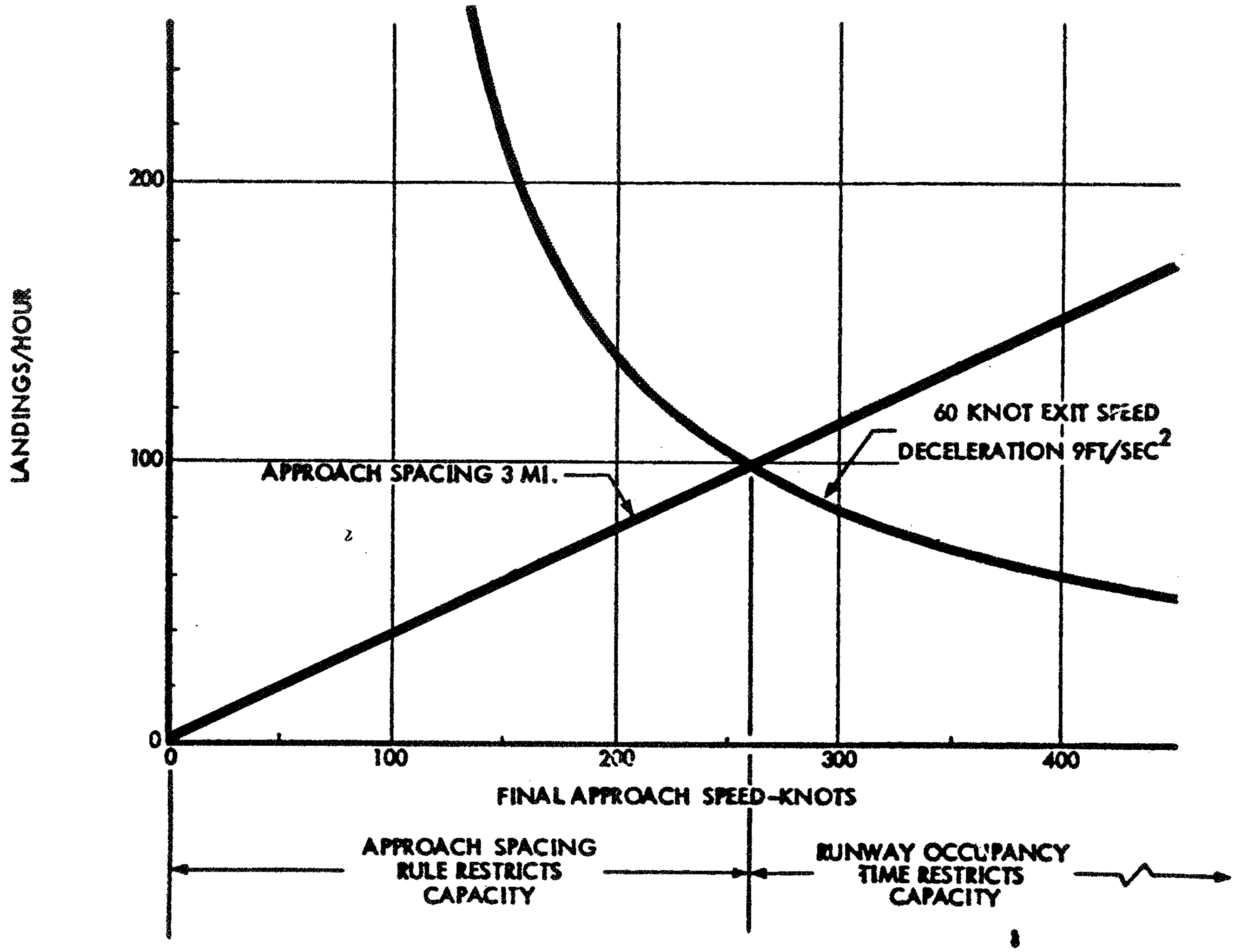


Figure 3.8 Landing Capacity Versus Approach/Landing Speed

The two curves define the upper limit of landing capacity. It can be seen that the approach spacing is restrictive for an approach speed below 260 knots and runway occupancy time is restrictive above.

By varying the approach spacing and deceleration the landing capacity can be changed. More important, the approach speed at which runway occupancy time becomes restrictive is decreased with decreased approach separation. The result is shown in Figure 3.9.

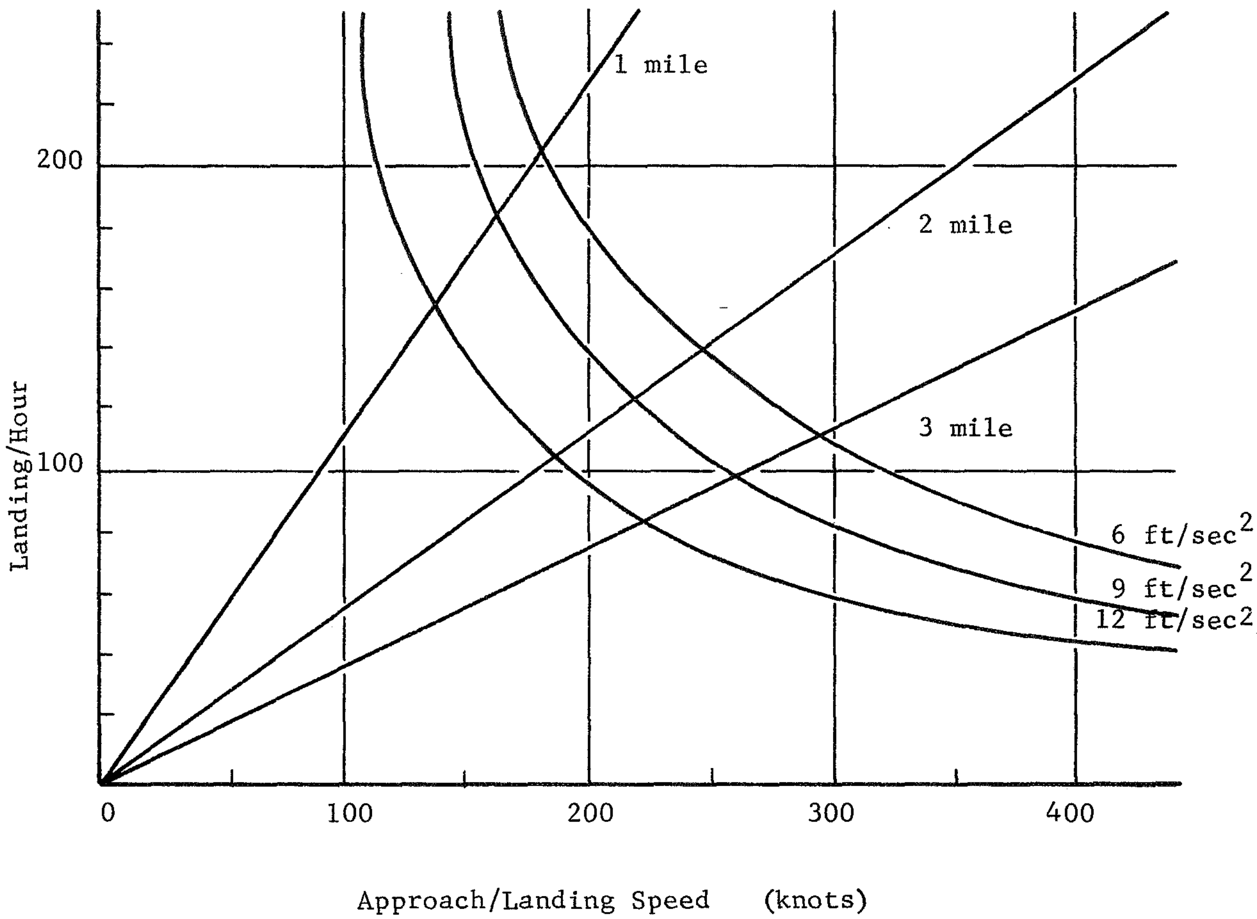


Figure 3.9 Landing Capacity vs. Approach/Landing Speed, 60 Knot Exit Speed

<u>The Takeoff Operation</u>

In the takeoff operation aircraft are accepted from the taxiway/terminal subsystem, accelerate in a ground roll, become airborne at takeoff speed, and accelerate airborne to enter the departure subsystem.

The aircraft performance characteristics affecting subsystem capability in takeoff are:

1. Entrance speed
2. Acceleration to liftoff
3. Takeoff speed
4. Acceleration after liftoff

The runway performance characteristics affecting subsystem capability in landing are runway entrance type and taxi-way/terminal deliverance rate. Runway entrance type characteristics include:

1. Angle of turn on
2. Radius of curvature of turn
3. Width

If the aircraft performance characteristics are specified in terms of acceleration and takeoff speed and runway entrances are such that the aircraft starts the takeoff roll at approximately zero speed, the minimum physical runway occupancy time as well as takeoff distance can be determined (See figure 3.10).

Interface With Aircraft-Departure Subsystem

IFR rules governing the departure of aircraft require:

1. A minimum separation distance between aircraft in the departure phase.
2. The position of the previous operation in the aircraft-runway subsystem before another operation is entered.

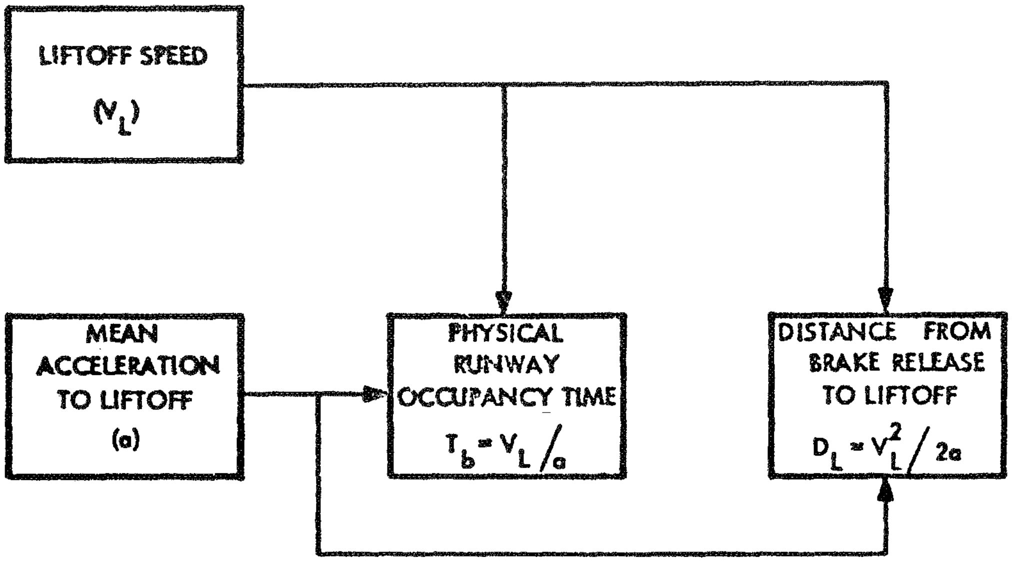


Figure 3.10 Aircraft Characteristics and Minimum Physical Runway Occupancy Time

Current specific IFR rules specify that:

1. An aircraft taking off shall have lifted off the runway before the following aircraft may begin takeoff roll.

2. A minimum distance, based on the size of aircraft involved, before the following aircraft may begin takeoff roll.

Because the separation distance of aircraft is generally less than the minimum separation distance, "effective" runway occupany time is generally greater than the actual runway occupancy time.

If the aircraft performance characteristics are specified and runway entrance are such that the aircraft starts the takeoff roll at approximately zero speed, the runway occupancy time for given separation distance can be determined by the method shown in Figure 3.11.

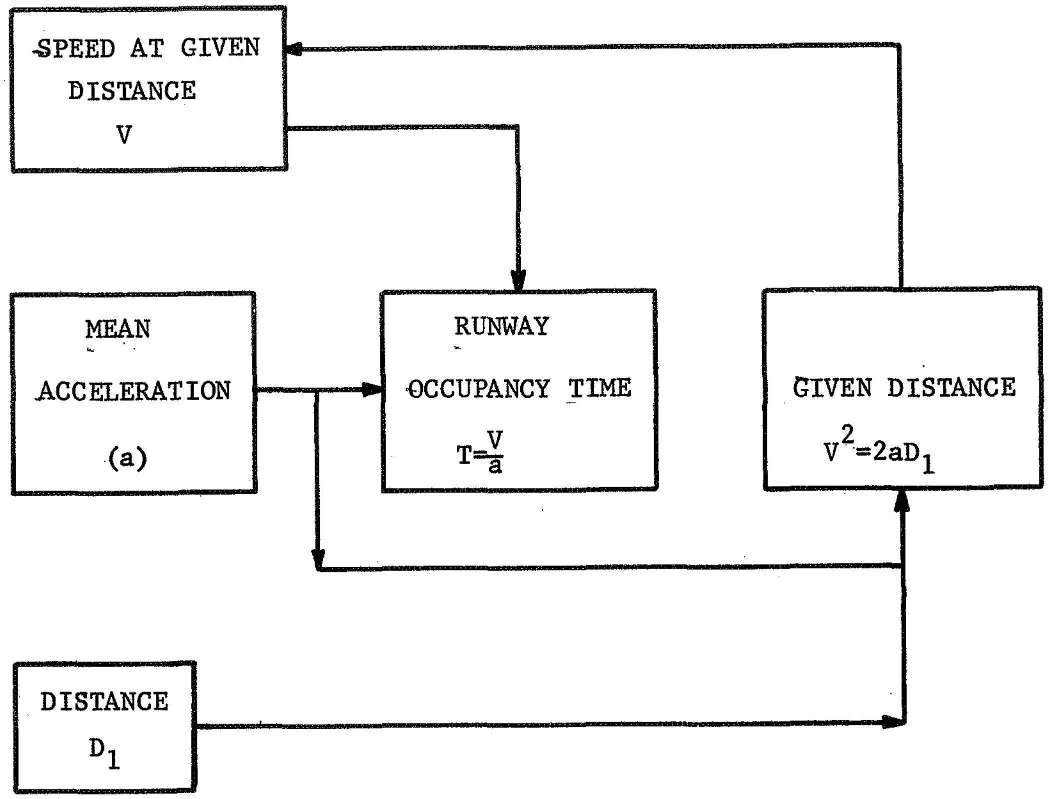


Figure 3.11 Aircraft Characteristics, Runway Occupancy Rule and Minimum Occupancy Time (Departure)

Mixed Operations On A Single Runway

When both landing and takeoff operations are executed from the same runway, the IFR rules interfacing the aircraft-runway subsystem are still applicable. They require:

1. A minimum separation distance between all aircraft in the approach corridor be maintained.
2. A minimum separation distance between aircraft in the departure phase be maintained.
3. The position of the previous aircraft in the subsystem be approved before another operation is entered.

To integrate mixed operations, the last rule specifies that a departing aircraft may not begin takeoff until the aircraft landing before it has exited the runway. Moreover, an arriving aircraft may not cross the runway threshold until the aircraft departing before it has lifted from the runway, resulting in a separation distance required for the insertion of a departure greater than that required for a series of arrivals. (See Figure 3.12)

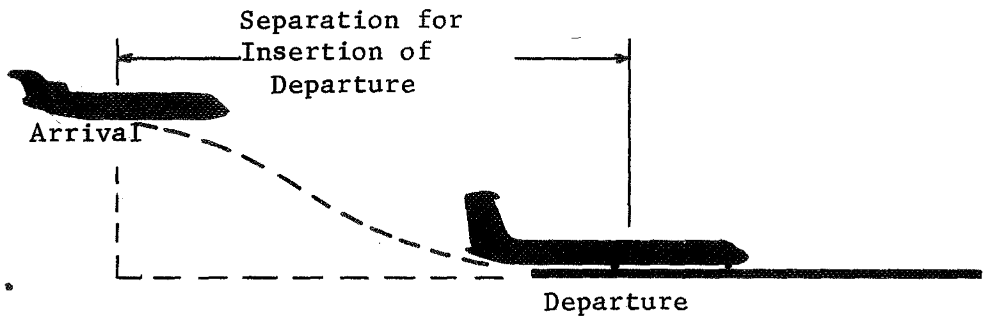


Figure 3.12 Mixed Operation Separation

Time-distance relations among arriving and departing aircraft using the same runway can be displayed by a distance versus time plot as shown in Figure 3.13. Aircraft speed is represented by the slope, and acceleration by the radius of curvature of the position plot. An arriving aircraft crosses the runway threshold at zero distance, shortly thereater makes contact with the runway, decelerates, and exits. After the arriving aircraft has exited the runway, a departing aircraft begins its takeoff roll, accelerates to takeoff speed, further accelerates, and exits the runway subsystem. Because a subsequent arrival may cross the threshold at the time that the preceding departure lifts off, there is an overlap of runway

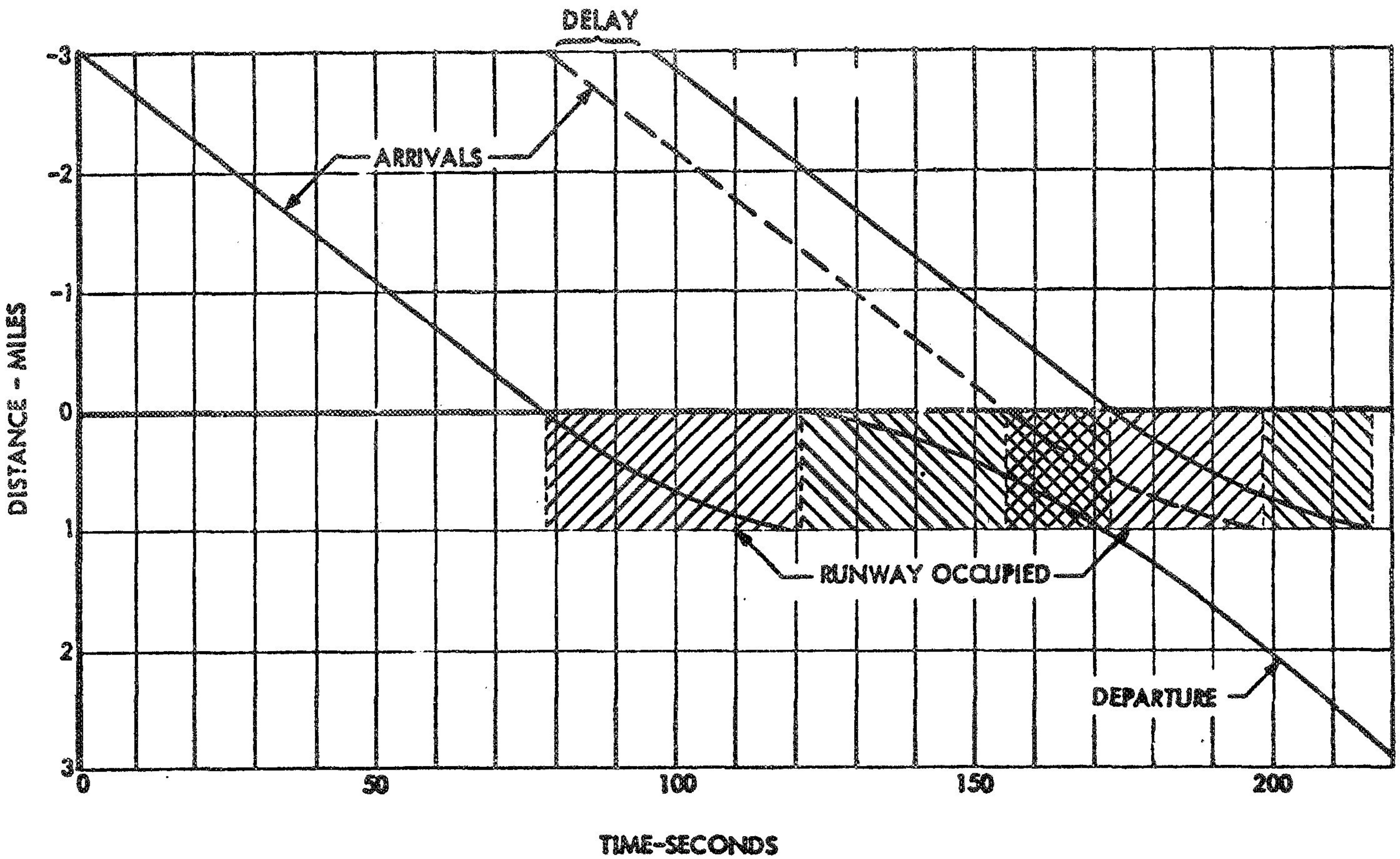


Figure 3.13 Time-Distance Relations Among Arriving And Departing Aircraft

occupancy times available. Any arrival that crosses the threshold at a time after the optimum represents a delay and such non-optimum arrivals decrease runway capacity.

Parallel And Dual Runways

From the distance versus time plot of aircraft positions in arriving and departing, it is evident that increases in runway capacity would be possible if an aircraft were released for takeoff immediately after an arriving aircraft has touched down on the runway. The departing aircraft could then accelerate to lift off speed on the runway while the preceding arriving aircraft is decelerating to exit speed.

Clearly, the requirement that only one aircraft occupy the runway at a time prohibits this scheme. The dual-lane runway circumvents this restriction on the runway by separating the arriving and departing aircraft on the runway, but not in the air. This configuration consists of two adjacent parallel runways that are interdependent in operation with arrivals and departures segregated. This configuration is shown in Figure 3.14.

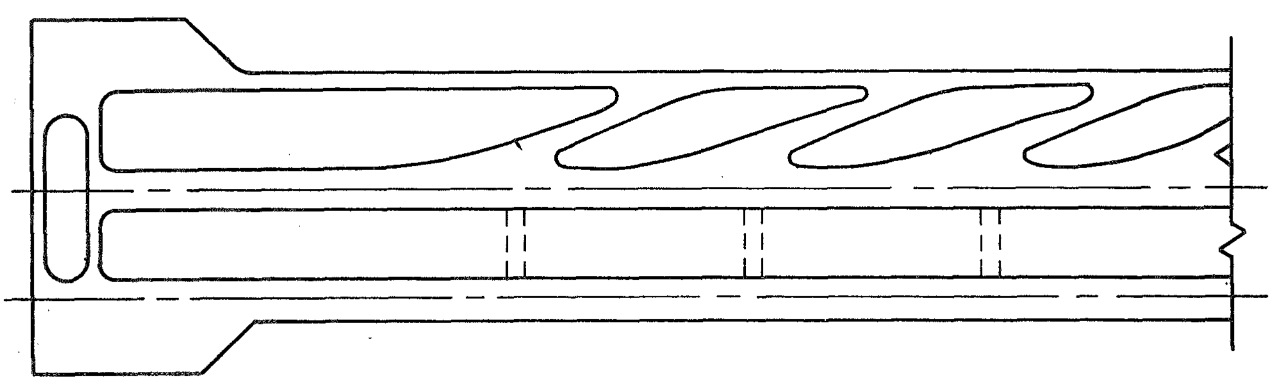


Figure 3.14 Configuration of Dual Lane Runways

If dual runways are separated laterally so that operations are no longer interdependent, a parallel runway configuration results. While operations are segregated in the dual system, mixed operations are conducted on the parallel system, resulting in two independent mixed operation runways located at the same facility. This system is displayed in Figure 3.15.

The amount of separation required for independent runway operations is a function of system capability to measure and display position and the pilot-aircraft ability to maintain position. The configuration which promises to provide the greatest capacity and flexibility is parallel arrangements of dual runway systems. This configuration has the simplicity of segregated operations to dependent runways with increased capacity gained from multiple runways.

Wake Vortices and Separation

The direct effect of wake vortices on runway capacity will now be considered. (For a more complete treatment of wake vortices, refer to section 2.5)

An analytical expression for vortex strength, Γ, is:

$$\Gamma = \frac{L'}{\rho V} \tag{3.7}$$

where:

$L' = \frac{W}{b}$ is the weight per unit span length of the aircraft,

ρ = air density,

V = velocity of the aircraft.

Clearly, for constant aircraft weight and configuration and air density, the vortex strength is inversely proportional to the aircraft velocity in flight.

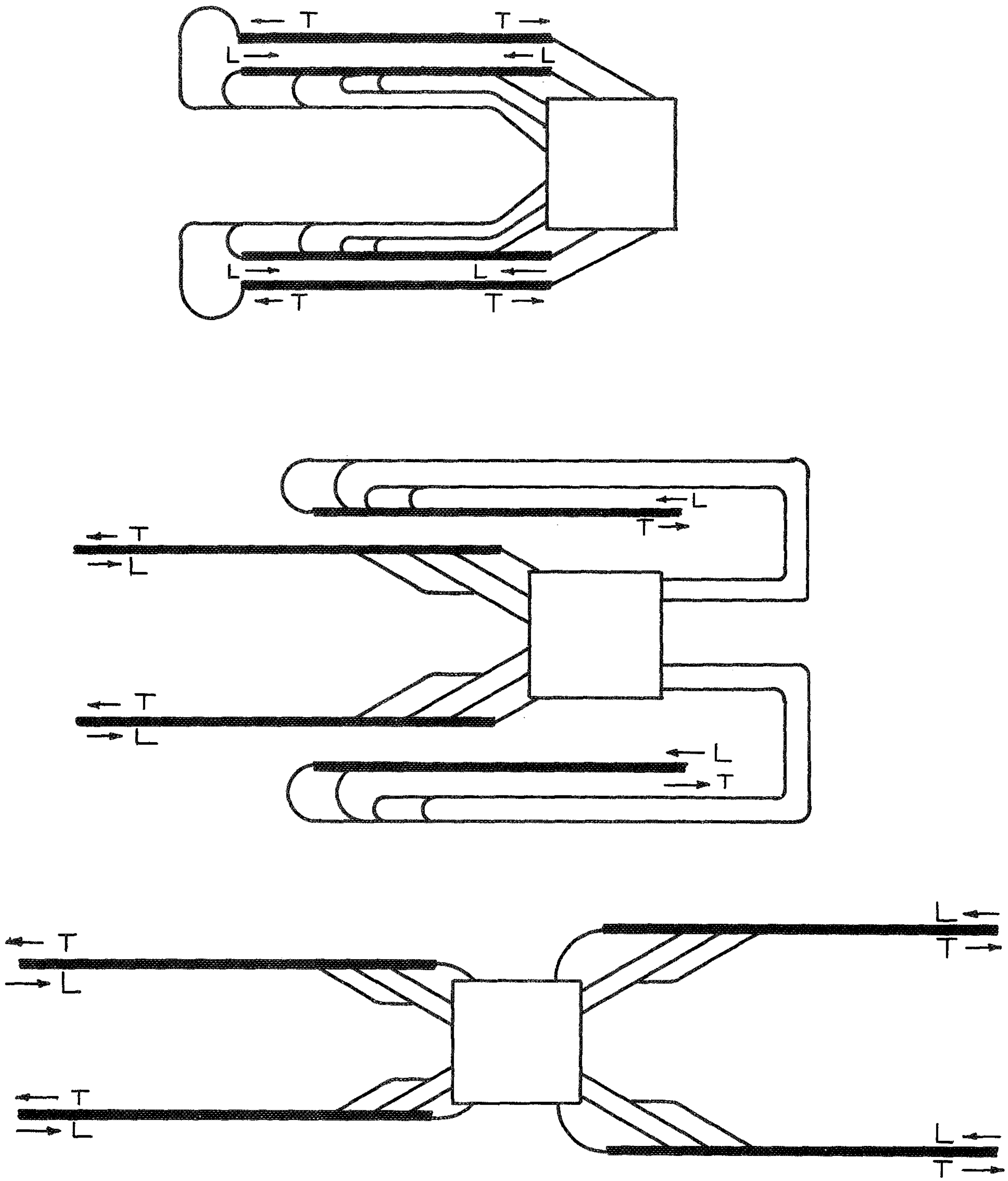


Figure 3.15 Parallel Dual Runway Configurations

In a takeoff or landing situation, however, where aircraft weight is partially supported by the gear on the runway, the lift is correspondingly smaller that aircraft weight. In takeoff, as the aircraft speed builds from zero to liftoff speed, the vortex generated builds from zero to a maximum at aircraft liftoff, then decreases slightly as the aircraft accelerates in departure. In the landing, the vortex strength will be maximum during the approach. Following touchdown, as the aircraft decelerates, the vortex strength decreases to a minimal level during high speed taxi.

The wake vortices generated by arriving aircraft are characterized by being some maximum strength throughout the approach and then rapidly decreasing at touchdown, just down the runway from the threshold; while the wake vortex generated by departing aircraft are characterized by building from zero near the threshold to a maximum at liftoff, well down the runway.

Thus, an arriving aircraft traverses in flight that portion of the runway where the wake vortex generated by a departing aircraft is a minimum, and traverses on landing rollout that portion where it is a maximum. Likewise, a departing aircraft traverses on takeoff roll that portion of the runway where the wake vortex generated by an arriving aircraft is a maximum and traverses in flight that portion where it is a minimum. Therefore, under conditions where aircraft separation in the arrival or departure phase is dictated by wake vortex strength considerations, this may be the limiting factor on runway capacity in segregated operations. In this case, runway capacity is increased by mixing operations on two independent runways, rather than by segregating operations.

Runway Exit Design

Runway exit type and exit location have been identified as performance characteristics affecting the subsystem capability for landing. Runway exit types are evaluated by the speed at which aircraft are capable of exiting. Factors affecting this speed are:

1. Angle of turnoff
2. Radius of curvature of the turn
3. Width [illegible]

Exits would ideally be located at a distance down the runway at which the aircraft reaches exit speed, using aircraft design deceleration.

The simplest runway exit design employs a single right angle exit taxiway at the upwind end of the runway, requiring all aircraft to rollout the full length of the runway before exiting. Only slightly improved are runways that employ a few right angle exits spaced periodically down the runway length. Although aircraft have the option of exiting prior to the end of the runway, the exit speed remains restrictively small.

To increase exit speed, the angle of the exit must be more nearly aligned with the runway centerline and the radius of curvature for the turn to the exit must be large. In all cases, the exit must be wide enough to accommodate an aircraft traveling at the design speed.

The requirements for multiple exit locations and angled exits have resulted in a design utilizing a continuous extension of the runway on one side which allows aircraft to "drift off" the landing surface at the highest exit speed, anywhere along the runway length. This "drift off: exit design will minimize the runway occupancy time by greatly increasing the exit speed and optimizing exit location.

Runway Entrance Design

Runway entrance type has been identified as a performance characteristic affecting the subsystem capability for takeoff. Runway entrance types are evaluated by the speed at which aircraft are capable of entering and using as an initial speed for takeoff roll. Factors affecting this speed are, as in runway exit design:

1. Angle of turn on
2. Radius of curvature of the turn
3. Width

The simplest runway entrance design employs a single right hand entrance taxiway at the downwind end of the runway, requiring all aircraft to enter at low speed and execute a large angle change before being aligned for takeoff roll. The aircraft is then able to begin the takeoff roll at a higher speed shortening the runway occupancy time. Illustrations of different types of runway entrances and exits follow.

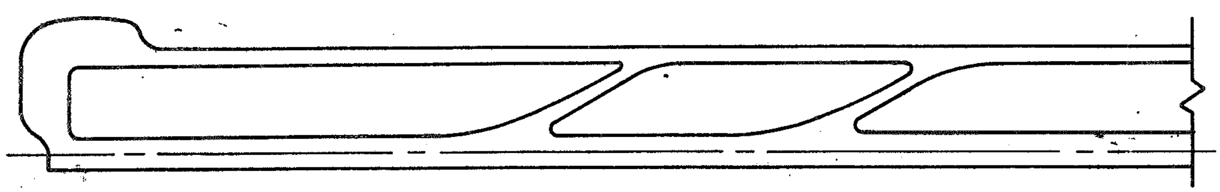


Figure 3.16 Runway With High Speed Turnoffs

Figure 3.16 depicts a conventional runway entrance/exit at the end of the runway requiring a ninety degree heading change and slow traverse speed. This runway also has periodic angled exits.

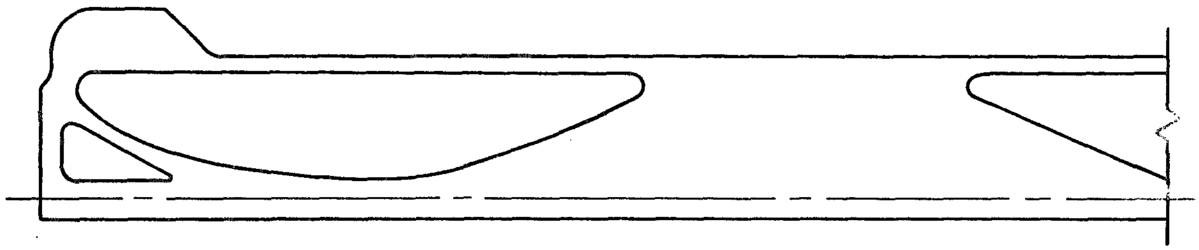


Figure 3.17 Drift-Off Runway

Figure 3.17 depicts a higher capacity runway with both angled and conventional entrances and a "drift off" exit. Both runways can be designed to allow the direction of operations to be reversed.

Crosswind Configurations

Each runway or set of dual or parallel runways inherently has a bi-directional character, so that by reversing the direction of traffic flow, operations may always be conducted with at least no tail wind. Crosswind runways are normally added to handle a small percentage of traffic when crosswind components of the runway exceed aircraft capability. When winds vary greatly in both direction and strength, another complete system of runways may be required with attendant duplication in other facilities. The need for a crosswind runway, to provide operational capability for all traffic using the airport, is apparent. The need to duplicate an entire system at a single site is not so apparent and should be approached as a trade-off to increased crosswind capability.

3.4 FINAL APPROACH PHASE

The next thirty years in air travel will show a great increase in the number of enplanements with the present day approach-to-landing system strained by increased landing demands. The system bottleneck is the antiquated Instrument Landing System (ILS).

A new system must satisfy certain needs and solve basic problems. The following is a list for ILS requirements that increase capacity and insure safety.[7, 8]

1. Increase vertical coverage to include the lower and higher approach angles necessary for new concepts in aircraft (i.e., V/STOL, SST, air carrier helicopters).

2. Eliminate the interference affect in the present day ILS due to ground object reflection.

3. Increase measurement accuracy to three dimensions for automated landing implementation and reduced approach area separation criteria. Eventually, this will be used to guide all-weather operations.

4. Include a scanning capability which will allow a variety of approaches to the runway. This will best utilize the immediate airspace by providing an extra separation direction, allowing trajectory optimization studies, and providing for noise abatement approaches.

The present air traffic control procedures in the terminal apprach area of an airport rely heavily upon the ability of a human controller to maintain an orderly and safe sequence of airplanes onto the runway. The accuracy of his equipment has led to certain separation criteria in the approach area.

The standard ILS serves IFR traffic with a one-dimensional (a straight line path) route to follow. A three mile separation is the standard rule for aircraft spacing. Problems arise when a faster aircraft preceeds a slower aircraft down the ILS course. The three mile separation distance being enforced along the entire course length constitutes a delay in the system. An example would be two aircraft separated by three miles at the outer gate. Let plane one have a speed of 180 knots and let plane two fly at 150 knots. When plane one touches down, the separation distance will have expanded to over 4½ miles. This represents a delay which is unavoidable with the present ILS. The case of the slower aircraft first results in a converging separation allowing the three mile separation to be achieved when the first plane touches down.

Another shortcoming of the present ILS is the requirement for large distances to be traversed by aircraft coming from the opposite landing direction in order to intercept the glide slope. A more versatile and broader ranged landing system would reduce these terminal delays.

One possible solution currently in the development state is the microwave scanning beam ILS (MILS). This system expands the terminal area coverage to three dimensions. This offers aircraft alternatives to lengthly flyout-and-back maneuvers to intercept the glide slope. Figure 3.18 illustrates this system. The scanning is done at prescribed frequency. Using modern control techniques which employ digital logic, many of the landing procedures can be automated.

Microwave ILS

The idea for a scanning microwave beam for approach guidance was first formally reported in the mid 1950's. These past 15 years have been devoted to flight tests of various modes of operation and equipment packages to evaluate the possibility of replacing the fixed beem ILS system. The analysis has produced a variety of systems. Table 3.1[1] shows a number of these.

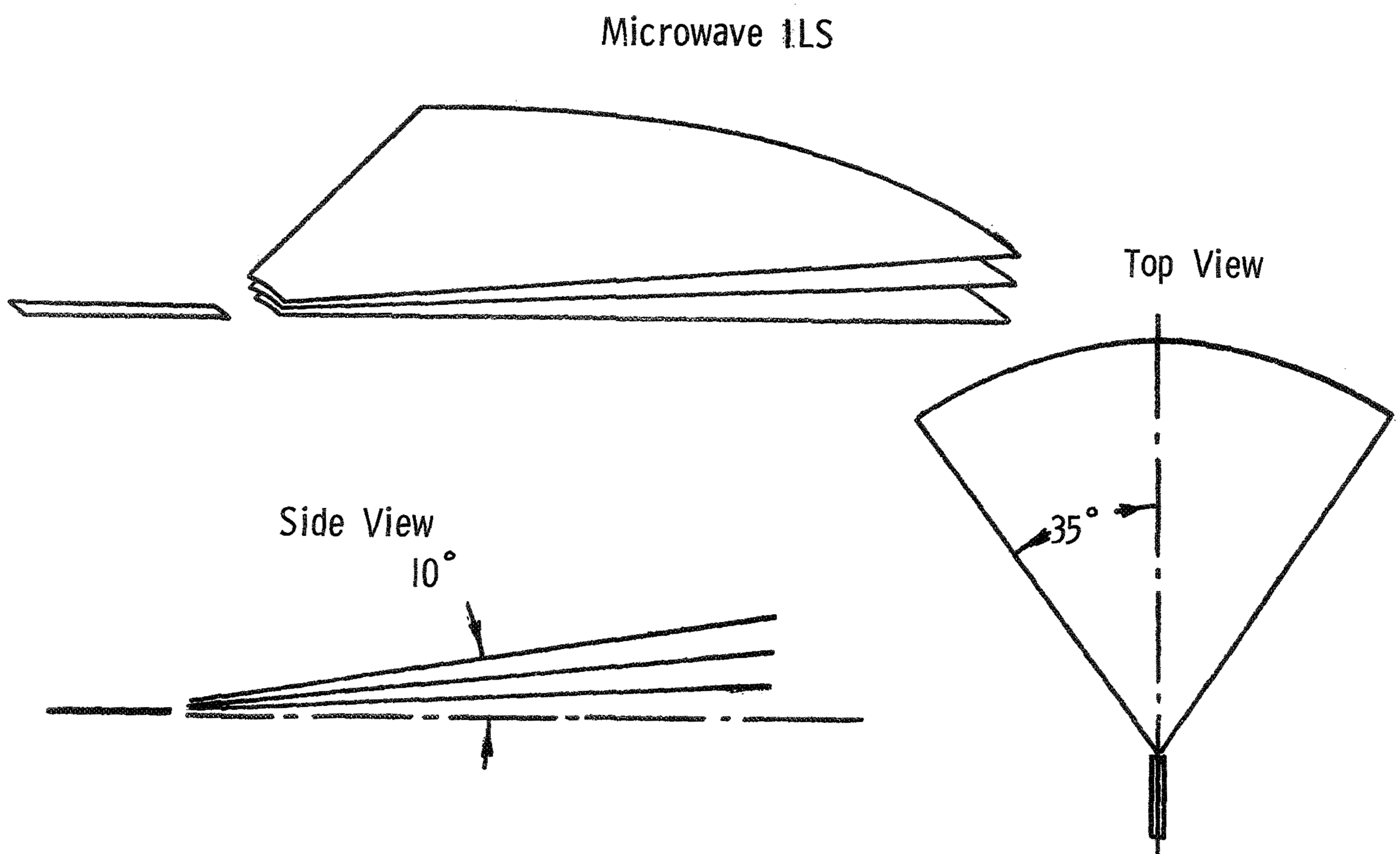


Figure 3.18

TABLE 3.1 CURRENT M-ILS CAPABILITIES

System	Azimuth Transmitter Angle Coverage (in degrees)	Elevation Transmitter Angle Coverage (in degrees)
AILS	±5 (±35 Clearance)	0 to 10
AN/SPN-41	±20	0 to 10
AN/TRN-28	±20	0 to 20
RSAFB/TILS	±20 (±35 Clearance)	0 to 10
A-SCAN	±60	5 to +45
RASCAL	±20	0 to 13.5
AN/TRN-18 Spec	±20	0 to 20

Three possible bands of transmission exist for the microwave system: C-band (3900-6200 MHZ), X-band (5200-10,900 MHZ), and Ku-band (15350-17250 MHZ). Looking at their implementation, there is not a C-band with enough antenna aperture to effectively guide fixed-wing aircraft on the final approach, the reason being that to eliminate ground reflection requires a tall antenna (~25') which makes guidance in flareout, touchdown, and rollout quite dubious. The X-band has a limitation in spectrum availability. Most successful tests have been made using the Ku-band, although some engineers think that under tropical rain conditions the range is insufficient[9].

Concerning the basic methods of beam scanning, the flat beam is the most flexible and easily interpretable. Other means, such as conical beams or phased array can be used also. The scanning rate of the flat beam can be either continuous or stepped, but it should be as low as possible, consistent with autopilot requirements, and should not exceed 5 HZ since a faster scan rate would reduce the dwell of the beam on the receiver antenna and thus reduce accuracy. Independent of the method, a granularity of .05 to .10 degree can be achieved.

The accuracy of the Ku-band system has been quite good. In terms of one standard deviation (σ), the beam has an accuracy of $\pm$ .03 degree in elevation, $\pm$ .05 degree in azimuth, and $\pm$ 100 feet in range, using precision distance measuring equipment (DME).

Altimetry

With the accuracies stated above, the MILS can be used as a tool in determining and retaining altitude separation in the terminal area.

At a slant range of ten miles, the accuracy of the MILS beam is:

$$\text{ERROR} = (\ 10\ \text{nm.}\ )(\sigma\ )$$
$$= (\ 10\ )(6016.1)\frac{(\pm.05)}{57.3} = \pm\ 53\ \text{ft.} \qquad (3.8)$$

This accuracy is valid up to a height of approximately 11,000 feet. This is achieved with the AILS made for the FAA and not the updated TRN-28 (refer to Table 3.1). This can be compared to another method of altimetry.

This method is the use of static pressure sensors. These devices record static pressure either with a static pressure port or a pilot static tube, both of which may differ from true ambient pressure because of location, Mach number, angle of attack, or configuration. Although manufacturers of this system claim an accuracy of 0'-65' at sea level and 100'-255' at 40,000 feet, flight tests have shown discrepancies of 50'-225' at sea level and between 225'-500 at 40,000 feet. Constant recalibration will allow an error determination within 50 feet at lower altitudes. Discounting an altitude of 40,000 feet in the terminal area, the MILS is more accurate at the lower altitude and does not have to be recalibrated.

With such positive factors, the MILS was incorporated into the final approach phase procedures developed in this chapter.

This scanning beam system provided new dimensions to arrange for more precise landings and approach paths. One attractive approach path idea employs the scanning capability to provide curved approaches from the outer radius onto the runway, tangent to the landing direction. The geometry involved is shown in Figure 3.19. The parameters are:

θ = azimuth of aircraft (θ_o = glideslope intercept azimuth)

α = centerline angle

V = aircraft velocity vector

r_c = radius of curvature

d = distance to touchdown
(d_o = initial scan radius)

Certain relationships can be derived.

$$\frac{r_c}{\sin\left(\frac{\pi}{2} - \alpha_o\right)} = \frac{d_o}{\sin(\pi - \theta_o)} \tag{3.9}$$

and

$$\theta = \pi + 2\alpha \tag{3.10}$$

Therefore:

$$\frac{r_c}{\cos \alpha_o} = \frac{d_o}{\sin 2\,\alpha_o} \tag{3.11}$$

and

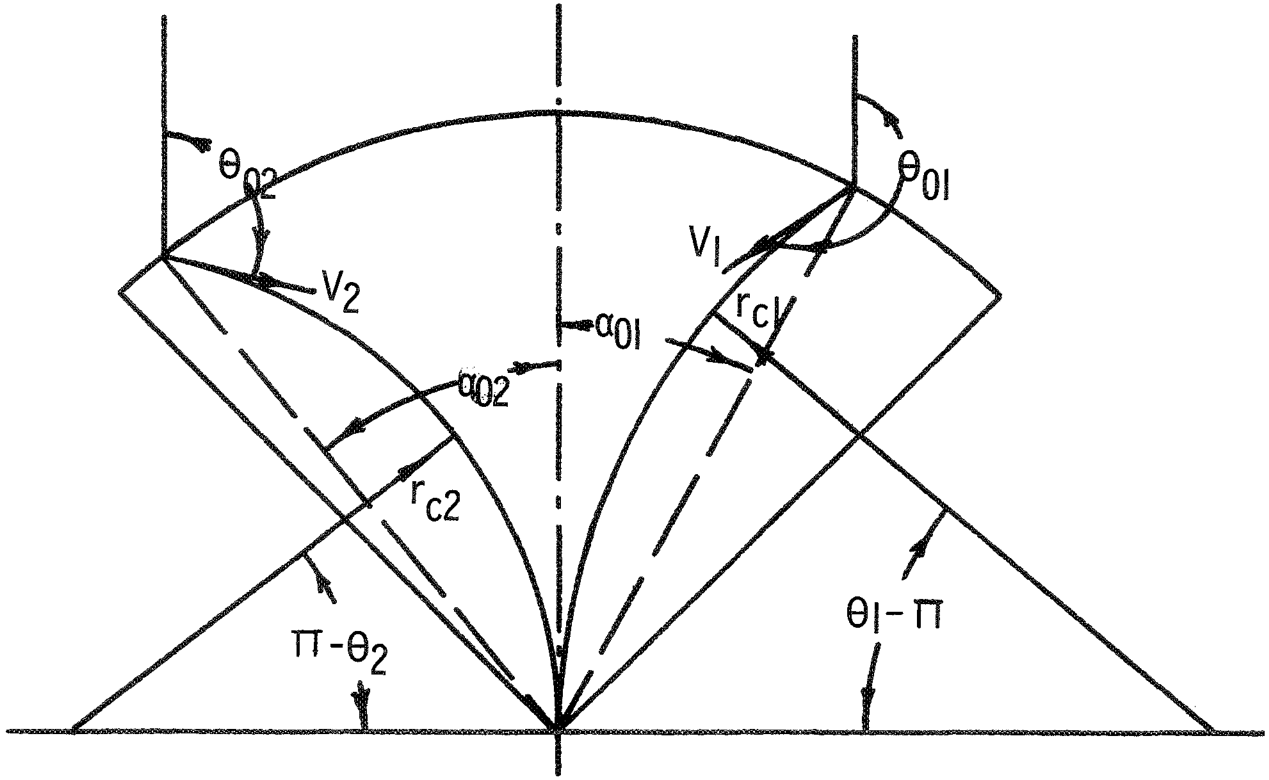
$$r_c = \frac{d_o}{(2 \sin \alpha_o)} \tag{3.12}$$

For a constant radius curve:

$$\frac{L}{d} = \frac{\alpha}{\sin \alpha} \tag{3.13}$$

where:

L = arc length of path with chord length d.



Curved Approach

Figure 3.19

The actual implementation of the system reveals many development problems. The curved paths represent a more difficult pilot task. Pilot workload in many cases is approaching its upper limit; therefore, ease in flying these paths is of great concern. Pilots have found flight directors to be of great assistance and it is believed that similar equipment employed here would best fit the pilot into the control loop.

Flight Director

The above final approach system assumes that the aircraft will be able to precisely follow the prescribed path. This can be accomplished in two ways. First, a display for the pilot to follow or second, an autopilot. Either method would use radar information supplied by the MILS. This information would be processed by an onboard digital computer. It was decided to use the first method--a good display for the pilot to follow. There were several reasons for this choice. First, it was felt that the pilot should still be in command of the plane even in the year 2000. Also, the design considered only category II operations: that is not completely "0--0" weather conditions. An autopilot will have to be used for category III operations.

The work in this area concerned determining exactly how accurately a pilot following a display could hold a prescribed path. It was assumed the path was known exactly--or at least to the accuracy of the MILS system which is $\pm$100 feet. A literature search revealed that a similar study was carried on by NASA Ames Research Center concerning flight profiles for noise abatement.[1] In that study, pilots were required to fly two segment straight approaches--one at six degrees followed by one at three degrees. The pilots used the flight director system shown in Figure 3.20.

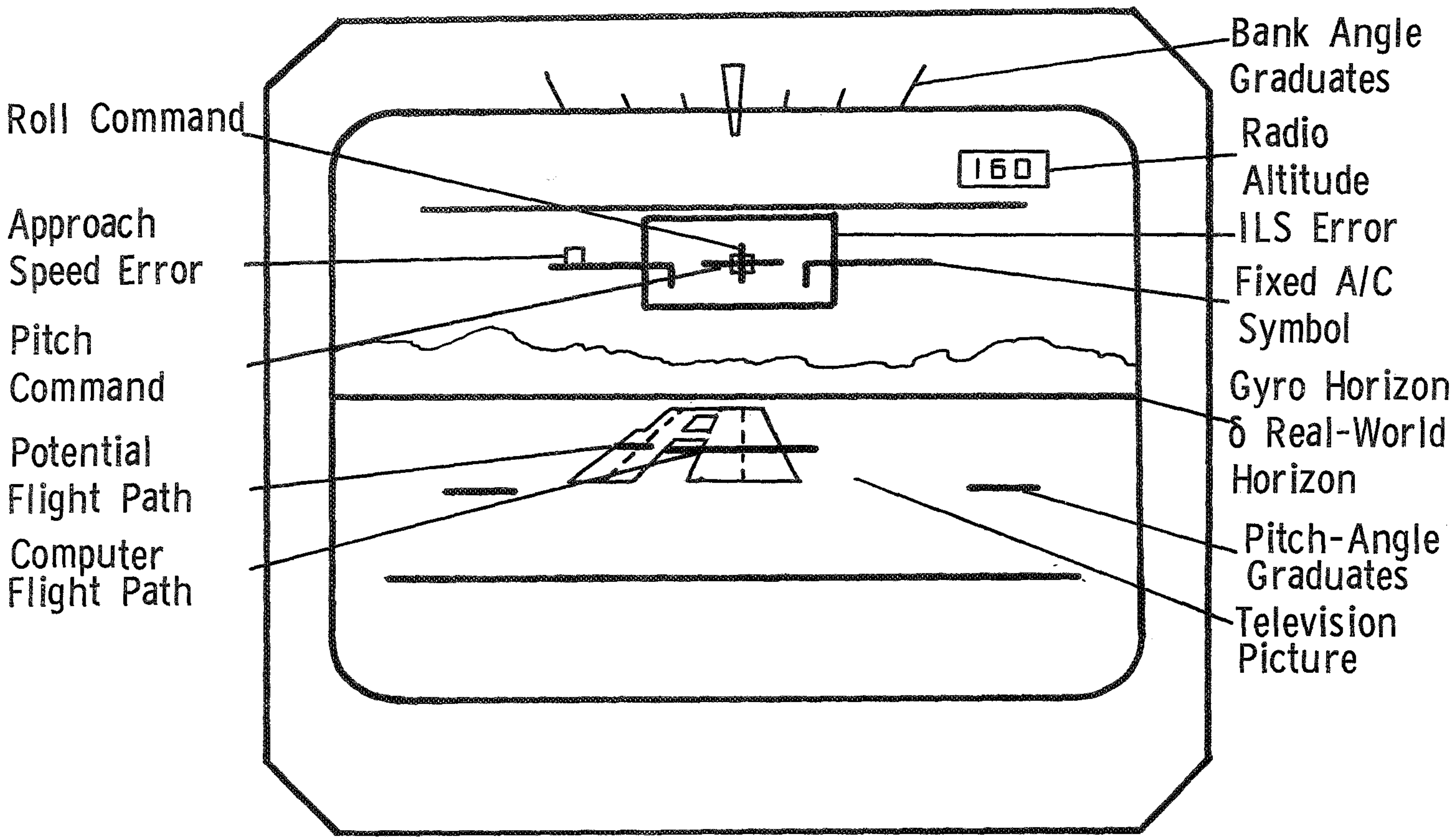


Figure 3.20

Flight Director

In those tests, pilots were able to stay within 100 feet of the prescribed path laterally and within 50 feet vertically.

Using this as background, it was predicted that future pilots could follow the curved approach paths to within these same accuracies. Thus it was determined that the future system would have at most a 200 foot lateral error--100 feet from the microwave ILS error and 100 feet from the pilot-display error. The pilot-display errors are not the limitation of the system. It may be noted that these errors were included in the point simulation of the final approach and caused no false alarms to the air collision avoidance equipment.

The question of time delay due to separation maintenance is another problem area that should be investigated.

The microwave system can reduce the delay time caused by the faster-plane-first situation. This is illustration in Figure 3.19. The lateral separation of the two interacting airplanes allows the minimum separation distance point to be delayed until some time before the first, faster aircraft lands. The closer one can bring the minimum separation point to the time when the first aircraft touches down, the shorter this excess delay will be. Figure 3.21 illustrates this improvement. X_{save} represents a distance savings acquired by the microwave ILS.

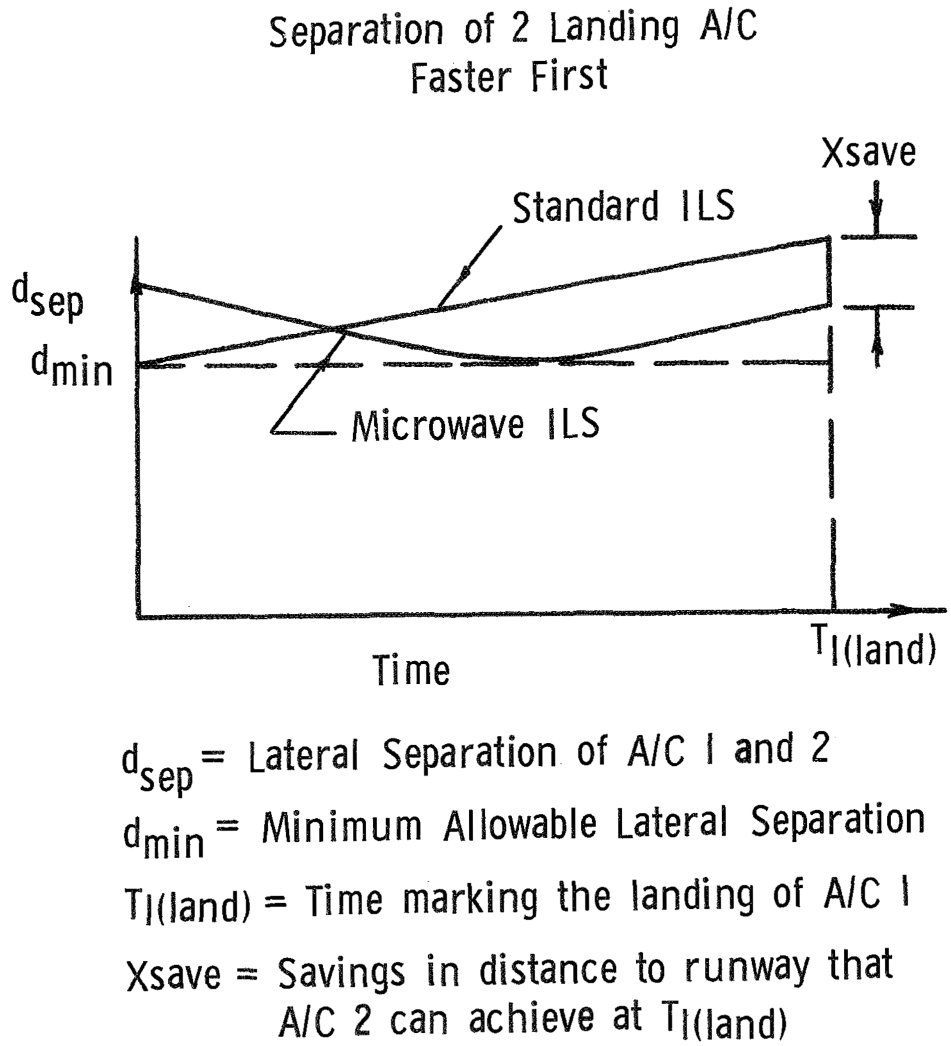
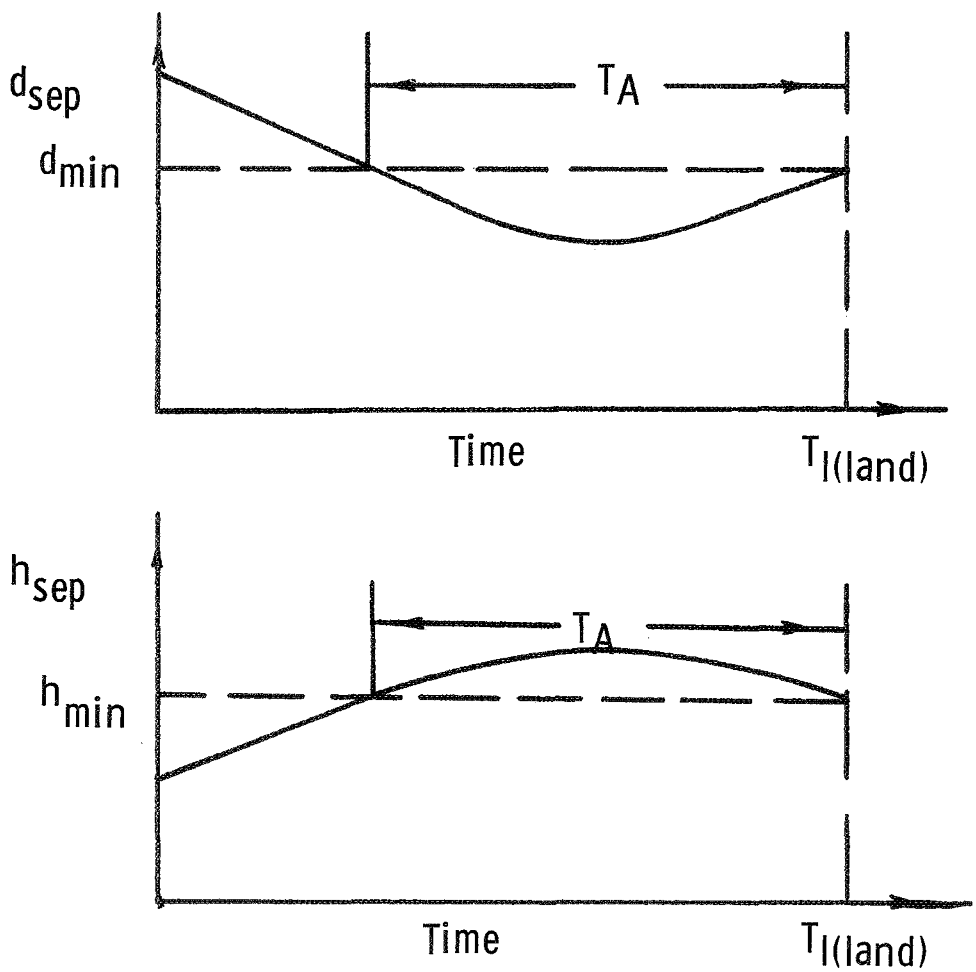


Figure 3.21 Separation of Two Land Aircraft Faster First

Another technique employs the addition of the height dimension into the separation criterion. Using an altitude separation during certain portions of the approach phase allows the lateral separation limit to be relased. Figure 3.22 illustrates some possible interaction of the two criteria. Notice that whenever the lateral separation is

Separation of 2 A/C Using An Altitude Criterion



h_{sep} = Altitude separation of A/C 1 and 2

h_{min} = Minimum allowable altitude separation

T_A = Time interval for altitude separation standard

Figure 3.22

not observed the altitude separation is maintained and vice-versa. This allows the minimum lateral separation to be achieved when plane one touches the runway. This results in an optimal landing rate for a prescribed separation distance.

An analytical investigation can be performed to test the feasibility of using altitude separation in the final approach. Consider two aircraft flying in the same vertical plane as in Figure 3.23. The vertical separation can be expressed by the following equation.

$$h_{sep} = [d_{min} + V_2(t_2-t)]\sin\gamma_2 - [V_1(t_2-t)\sin\gamma_1] \tag{3.14}$$

By examining the time derivative

$$\frac{d(h_{sep})}{dt} = V_1\sin\gamma_1 - V_2\sin\gamma_2 \tag{3.15}$$

One finds that there are three ways to insure a minimum altitude separation.

1. When plane one touches down

$$h_2 \geq h_{min} \tag{3.16}$$

and,

$$\frac{d\,h_{sep}}{dt} = V_1\sin\gamma_1 - V_2\sin\gamma_2 \leq 0 \tag{3.17}$$

2. When plane two intercepts the glide slope

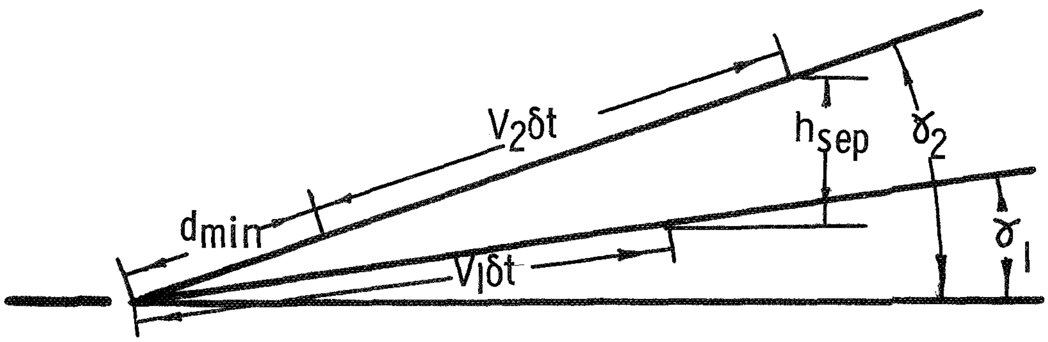
$$\Delta h_{sep} \geq \Delta h_{min} \tag{3.18}$$

and,

$$\frac{d\,h_{sep}}{dt} = V_1\sin\gamma_1 - V_2\sin\gamma_2 \geq 0 \tag{3.19}$$

3. At any time in which two planes are within the final approach boundaries

$$\Delta h_{sep} \geq \Delta h_{min} \tag{3.20}$$



V_1 = Velocity of A/C 1

V_2 = Velocity of A/C 2

γ_1 = Elevation angle of A/C 1 (not to scale)

γ_2 = Elevation angle of A/C 2 (not to scale)

$\delta t = t_2 - t$ (t_2 is time A/C 2 hits entry marker)

h_{sep} = Vertical separation of the two A/C at time t

d_{min} = Minimum allowable lateral separation

Vertical Plane Geometry
Figure 3.23

and

$$\frac{d\, h_{sep}}{dt} = V_1 \sin \gamma_1 - V_2 \sin \gamma_2 = 0 \qquad (3.21)$$

or

$$\sin \gamma_2 = (V_1/V_2) \sin \gamma_1 \qquad (3.22)$$

The curved paths do not allow a strict application of the above equations. They are used as separation guidelines to allow for separation rules to be obtained for each particular aircraft interaction.

ILS Comparison Study

This section is a numerical study which compares a standard ILS with the scanning beam ILS using vertical separation. The constraints for the example are IFR traffic, three miles lateral separation, and 1000 feet altitude minimum separation.

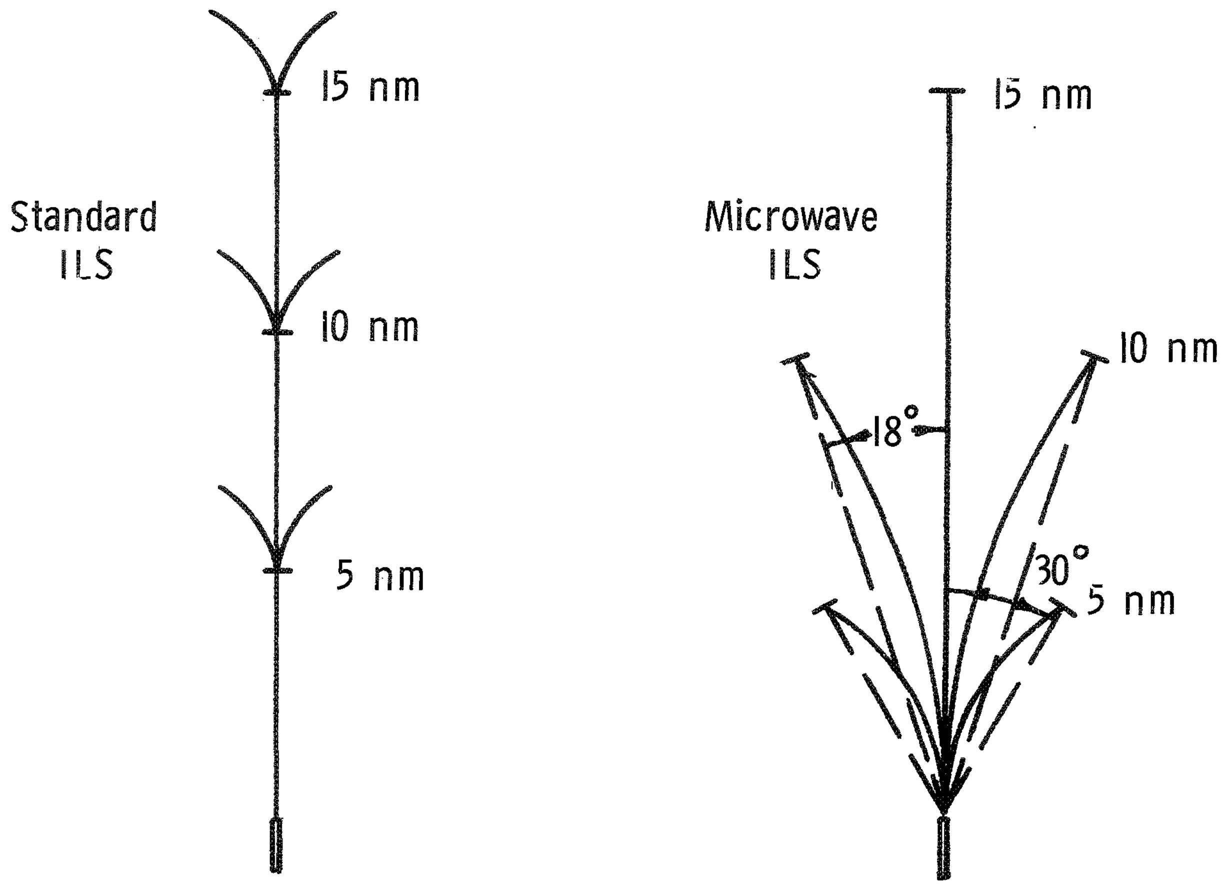
1. The Standard ILS is shown in Figure 3.24. It is capable of accepting aircraft at any of three gates as shown.

2. The Micro-wave ILS is also shown in Figure 3.24. Composed of five entry gates, the attempt here is to conserve airspace by making the wider approach paths shorter. A possible speed segregation could be as in Table 3.2.

TABLE 3.2. SPEED SEGREGATION AT MILS APPROACH GATES

Approach Gate	Terminal Speed
0° Gate	150-200 knots
18° Gate	110-160 knots
30° Gate	80-120 knots

The particular example examined here is to optimally land the following aircraft in the specified order as shown in Table 3.3.



ILS Comparison
Figure 3.24

TABLE 3.3 AIRCRAFT LANDING ORDER

Sequence No.	A/C Type	Final Speed
1	SST	165 kts.
2	707	150 kts.
3	DC-6	110 kts.
4	Bonanza	80 kts.

The order is chosen as an example of decreasing speeds to produce an arrival delay for the standard ILS and to generate some numbers for the scanning beam system which would help evaluate the feasibility of the ideas involved.

The following equations were used in the study:

T_{im} = time for i^{th} aircraft to reach the glideslope marker

T_{iL} = time for i^{th} aircraft to land

α_i = runway bearing for i^{th} aircraft (α_{im} initially)

γ_i = elevation angle for i^{th} aircraft (γ_{im} initially)

θ = heading azimuth for i^{th} aircraft (θ_{im} initially)

The calculation of the parameters (t_{im}, t_{iL}, θ_{LM}, im d_{im}) associated with the i^{th} aircraft are based upon the preceding aircraft.

The following equations are used to determine these times:

$$T_{iL} = T_{(i-1)L} + \frac{dmin}{Vi}\left[\frac{\alpha isep}{\sin(\alpha isep)}\right] \quad (3.23)$$

$$Tim = T_{ii} - \frac{dim}{Vi}\left[\frac{\alpha im}{\sin(\alpha_{im})}\right] \quad (3.24)$$

$$h_{im} = \Delta h_{sep} + V_{(i-1)}\left[T_{(i-1)L} - T_{im}\right]\sin(\gamma_{i-1}) \quad (3.25)$$

$$\gamma_i = \sin^{-1}\left[\frac{h_{im}}{d_{im}\cos\alpha_{im}}\right] \quad (3.26)$$

Some initial value calculations differ from the above.

T_{1m} = To initial reference time

α_1 = Chosen independent of other A/C

$\gamma 1$ = Assumed

$$\gamma 2 = \sin^{-1}\left[\frac{\Delta h_{min}}{d_{min}}\right] \qquad (3.27)$$

(method 1)

Standard ILS calculation equations were used:

$$T_{im} = T_{(i-1)m} + \frac{d_{min}}{Vi} \qquad (3.28)$$

$$TiL = T_{im} + \frac{d_{im}}{Vi} \qquad (3.29)$$

The following table, Table 3.4 resulted from using the aircraft of Table 3.3 and the above equations.

TABLE 3.4 RESULTS OF COMPARISON BETWEEN STANDARD ILS AND MICROWAVE ILS

	i^{th} A/C	1	2	3	4
Standard ILS					
	T_{im}	0	3.02	4.82	10.07
	T_{iL}	5.45	7.02	10.82	13.82
	d_{im}	15	10	10	5
Micro-wave ILS	T_{im}	0	2.61	2.39	6.74
	T_{iL}	5.45	6.65	8.45	10.7
	θ_{im}	180°	216°	144°	240°
	α_{im}	0	18°	-18°	30°
	d_{im}	15	10	10	5
	V_i	165 kts	150 kts	100 kts	80 kts
	γi	2°	3.1°	4.43°	5.10°
	h_{im}	3,180'	3,110'	4,480'	2,340'

The table shows that the four aircraft were brought down in less total time by the microwave system.

$$\text{percent decrease} = \frac{13.82 - 10.7}{13.82} = 22.6 \text{ percent}$$

Considerations and Constraints

1. The three mile and 1,000 foot separation criterion will be reduced in the coming years, but this will only change the numbers used in the calculations. The implementation of the accuracy will greatly reduce the separation constraint.

2. The altitude separation approach lends itself to on-the-spot computer calculations of final approach fixes because each aircraft's parameters depend upon the previous aircraft's status.

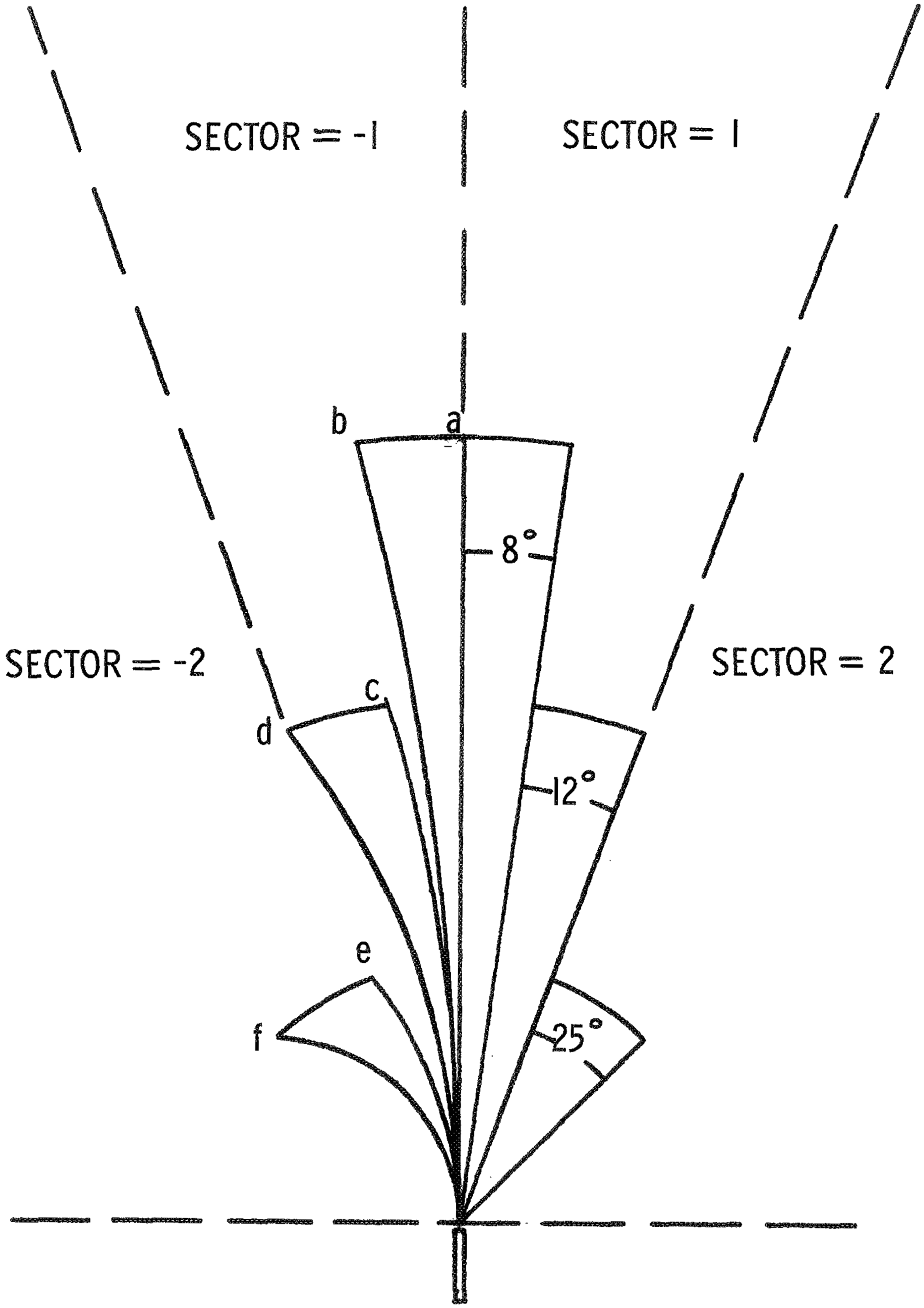
3. The landing capacity constraint for the future will gradually shift to the runway itself and will produce a large time separation. This will permit more altitude-lateral separation tradeoffs.

One-Runway System

The micro-wave system being evaluated here also permits increased accuracy in determining aircraft position and velocity. Using this system for terminal survelliance, the separation distances can be reduced extensively. The three mile lateral separation can now be modified to less than one-half mile. This places the landing interval constraint on the runway.

It has been estimated that for future air travel the landing interval will be reduced to 40 seconds between aircraft. This figure reflects the minimum time necessary to allow all types of aircraft to land and clear the runway.

The previously defined micro-wave ILS can now be altered to be more compatible with these separation standards. Figure 3.25 depicts a set of curved paths that allow maximum integration of aircraft types with



I Runway System

Figure 3.25

assured separation and 40 second landing intervals. The aircraft in a future terminal system must maintain a two mile[10] separation at the outer approach gates. The lateral separation at any point may be substituted by a 500 foot[10] altitude separation standard.

The aircraft that enter the system are broken down into the categories specified in Chapter 2. Table 3.5 shows a projection of the types and percentages of the aircraft that will be properly equipped to fly into this runway system. Other aircraft may not use this runway because they would not be properly equipped to integrate into the landing pattern. The data excludes a large percentage of the total aircraft fleet, that of general aviation.

General aviation will be relegated to smaller airports away from the positively controlled airways. The desired safety and efficiency of future air operations will not allow ill-equipped aircraft to fly in controlled airspace within the terminal area.

Combining the aircraft types in Table 3.5 with the approach possibilities of Figure 3.26 one can derive computer logic to prescribe the MILS entry point which best fits the necessary separation maintenance with a minimal enroute flight distance for each aircraft. Figure 3.25 is a flowchart that could serve as a program used by the traffic controller that properly places the aircraft on its final approach entry point.

N_i is the aircraft's category number as shown in Table 3.4. This specifices the ILS approach distance. The algorithm evaluates the aircraft's relation with the previous aircraft in the landing system. Care must be taken to prevent a slower aircraft from using the same approach path as the faster aircraft which immediately precedes it.

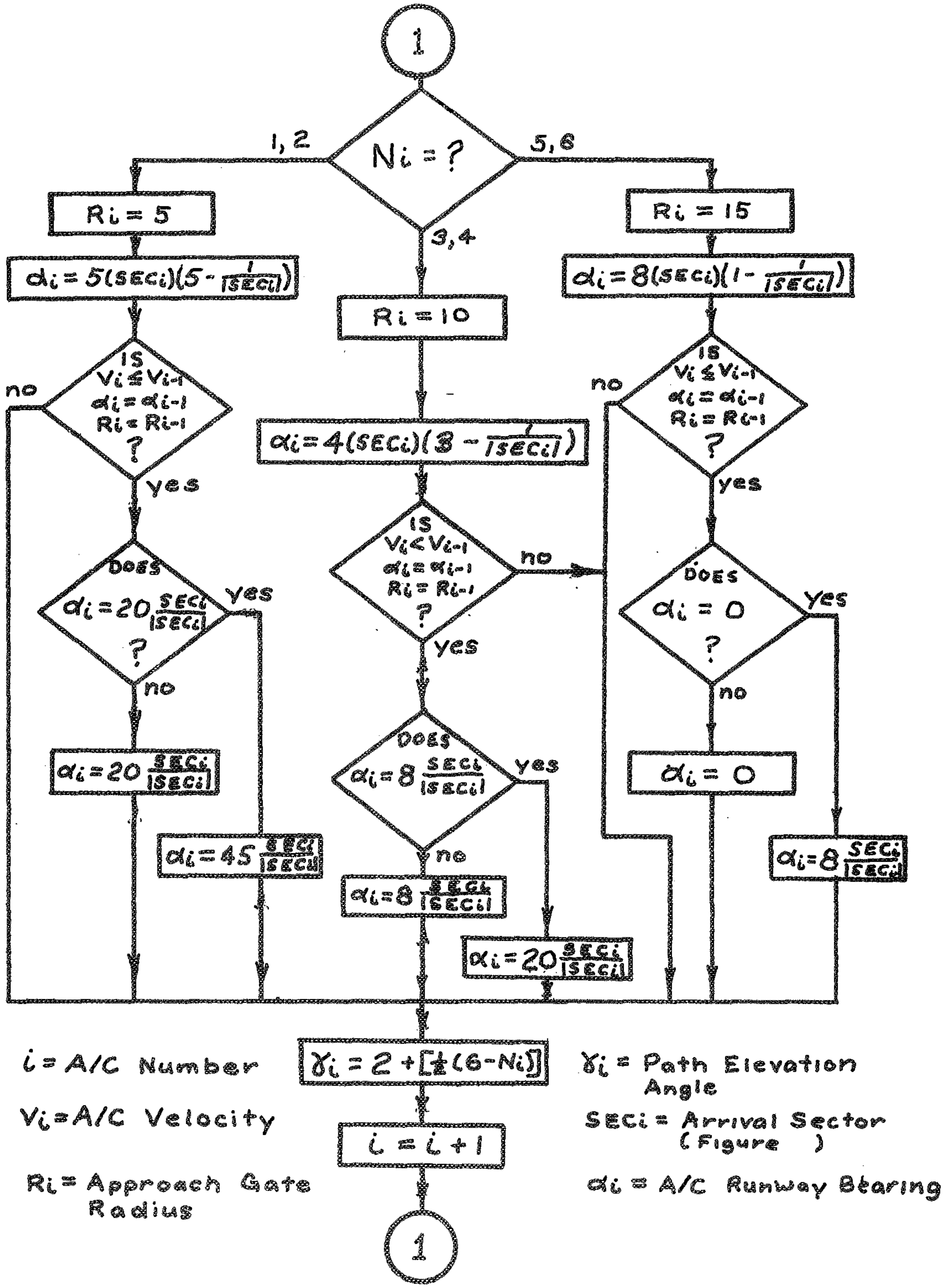
Aircraft Type	Number	Final Speed	Elevation Angle	% of Total Operations	M-ILS Gate
STOL	1	85 kts	6°	24.8	±20°-45° r=5 nm
General Aviation	2	115 kts	4°	10.0	±20°-45° r=5 nm
Short & Medium Haul	3	135 kts	3.5°	16.8	±8°-20° r=10nm
Jumbo Transport	4	140 kts	3°	19.3	±8°-20° r=10nm
Transonic Transport	5	140 kts	2.5°	26.1	±0°-8° r=15nm
Supersonic Transport	6	165 kts	2°	3.0	±0°-8° r=15nm

Table 3.5

Terminal Area Aircraft

Figure 3.26

Entry Gate Flowchart



Flight Path Simulation

A computer simulation was devised to check for separation maintenance along the ILS paths.

The program input was a sequence of aircraft chosen at random from the distribution presented in Table 3.5. No optimal sequencing was done, therefore, the study represents the capabilities of the landing geometry. The input includes a factor as to which of the four sectors (Figure 3.25) the aircraft used when entering.

The program details are located in Appendix D. The results verify the entry logic as all cases of random input for 1000 aircraft into the total system showed that minimum separation standards were maintained.

Multi-Runway System

The landing system under study cannot be accepted unless as investigation is performed to evaluate its performance in a large airport environment with many runways.

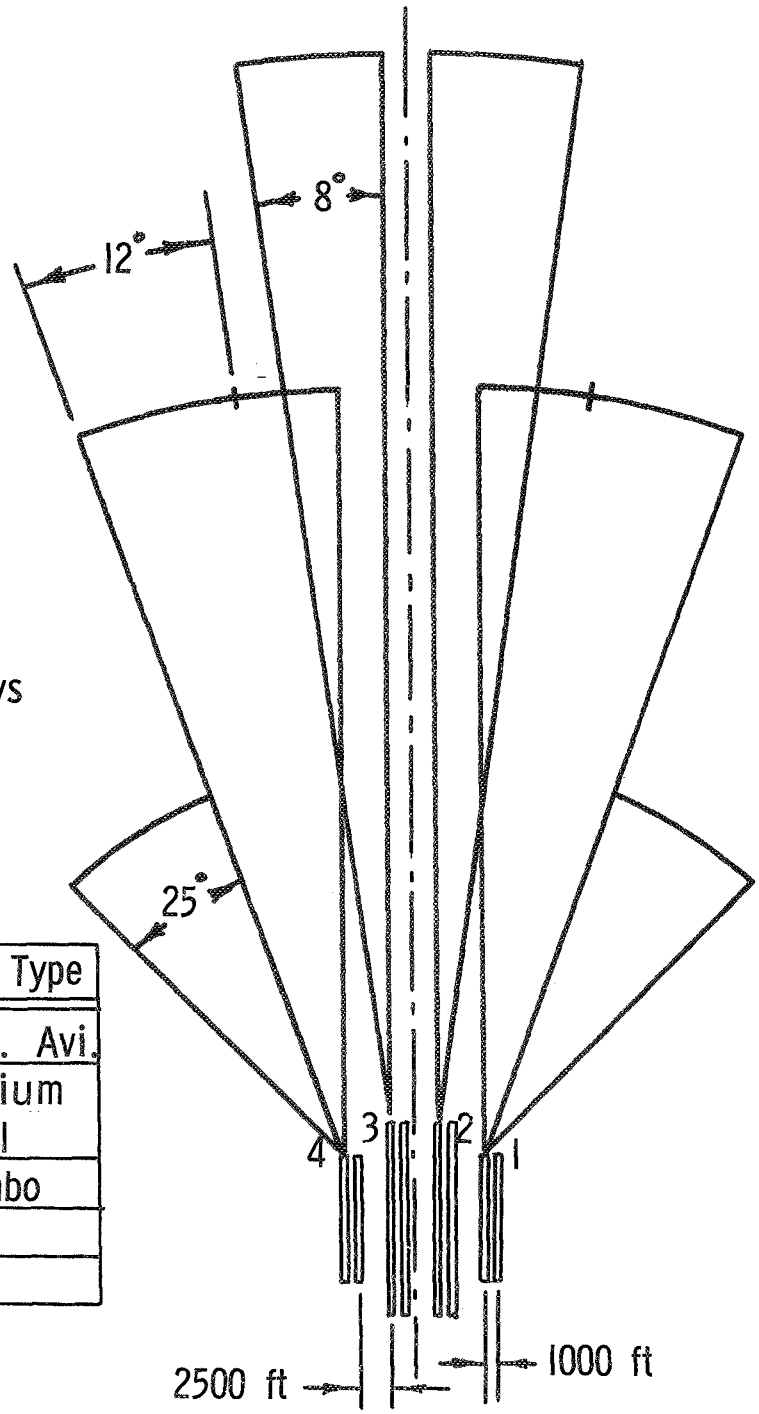
The basic requirements for a multi-runway system are:

1. Parallel independent runway systems with minimum land usage.
2. Proper integration of takeoffs and landings to acheive maximum number of operations per hour.
3. Procedures giving each aircraft a distinct waveoff or escape path for a missed approach.

The accuracy of the micro-wave system will allow a reduction of the parallel runway spacing to 2500 feet. Figure 3.27 shows a four runway configuration that employs four parallel independent dual lane runways. Each can accept the maximum specified capacity of 90 aircraft per hour (40 second interval). The fifth runway is a STOL landing strip. This runway achieves a greater number of approach possibilities because of

Figure 3.27

Multirunway System



Four Runways

Independant Operations

Runway	A/C Type
1 & 4	Gen. Avi.
1 & 4	Medium Haul
1 & 4	Jumbo
2 & 3	TST
2 & 3	SST

the higher descent angle capability of the STOL aircraft. The figure shows a normal operational breakdown of aircraft category into each runway. This breakdown represents a peak operation condition which accepts inputs distributed similarly to those in Table 3.5. The location of the STOL strip is not specified here but the consideration for its placement would be: first, one allowing the maximum scan angle which doesn't interfere with the paths of the other runways; secondly, the runway operation must not interefere with abort paths of the four main runways; and thirdly, the runway must still be close to the other runways for minimum use of land space.

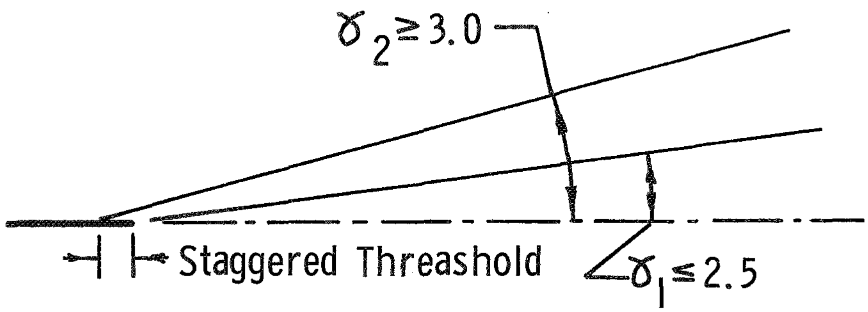
When the system operates below a saturated level, aircraft can be sorted into different runways depending upon the individual MILS occupancy and the overall advantages to be gained by switching runways.

The dual lanes shown in Figure 3.14 provide the capability for an aircraft to take off as another lands on the other lane. This retains the arriving plane's abort route clearance and allows an equal number of departures and arrivals to occur.

The runways are basically speed segregated. The SST, however, flies the same approach pattern as the TST. Runways 2 and 3 allow an eight degree path scan to allow for glide slope passing. Runways land 4 are for slower aircraft as shown in the table with Figure 3.27.

The elevation drawing, Figure 3.28, shows the altitude separation obtained between runways caused by differing approach angles, staggering approach angles, and staggering the runway threshold.

The net result of a runway-approach combination like this will be 720 mixed operations per hour at capacity. The automation needed to handle this vast increase is a large design problem in itself.



Multirunway Elevation
(not to scale)
Figure 3.28

Air Collision Avoidance in Final Approach

The air collision avoidance procedures discussed in section 3.2 can now be modified and refined for the final approach system.

An independent system must serve as the automatic landing abort indicator for IFR conditions. The use of the scanning beam in the system to increase airport capacity requires greater safety assurance because of reduced separation standards.

Various modifications of the general air collision avoidance procedures already presented can now be examined.

Maneuver restrictions in the final approach area allow the maximum acceleration parameter to be reduced from the enroute value of ½ g per aircraft to a smaller and safer 1/10 g maximum.[1]

The system chosen to evaluate the collision hazard must be as independent from the landing system as possible. This will allow the

CAS to serve in a back-up separation assurance roll. Two future terminal area systems look promising for this job.

The first is an advanced version of the onboard system discussed earlier. The main requirement is more accuracy in measuring range and velocity. The confidence level needed is one which allows normal curved approaches to proceed free of collision alarms. The CAS would serve to specify the abort route should the microwave system fail or the aircraft's path following control malfunction. At present, the onboard CAS systems being tested do not have sufficiently accurate measurements to achieve the desired terminal approach alarm status.

A second system is envisioned which could provide the needed service to the final approach system. Using the terminal tri-lateration navigation equipment the ground based collision hazard criterion can effectively warn aircraft of collision possibilities without interfering with normal curved approach landing runs. The numerical characteristics are in Table 3.6.

TABLE 3.6 FUTURE TERMINAL CAS USING TRILATERATION

Parameter	Values
Data Interval Time	1 sec.
Delay Time	9 sec.
Total Escape Time	28 sec.
Range and Velocity Error	.30 n.m.
Minimum Separation Distance	.10 n.m.
1/10 g Freedom	.23 n.m.
Alarm Region Half-width	.63 n.m.

The flight director allows each aircraft to deviate 100 feet laterally from its path. This condition may be simulated by expanding the alarm half-width.

$$HW = .63 + (2x\ 100/6080) = .67 \text{ nautical miles} \tag{3.30}$$

The path simulator program included a collision avoidance algorithm. Figure 3.29 shows the logic flowchart used to evaluate the ability of the one-runway system approaches to proceed free of collision alarms. As mentioned before, the minimum separation standards were maintained for 720 landing aircraft under saturation conditions. It is desired, therefore, to allow the aircraft to proceed down the prescribed path without being bothered by a false CAS alarm.

The flow chart shows the height standard set at 600 feet. This is a combination of the 500 foot minimum standard for separation and the two aircraft flight director errors of 50 feet each.

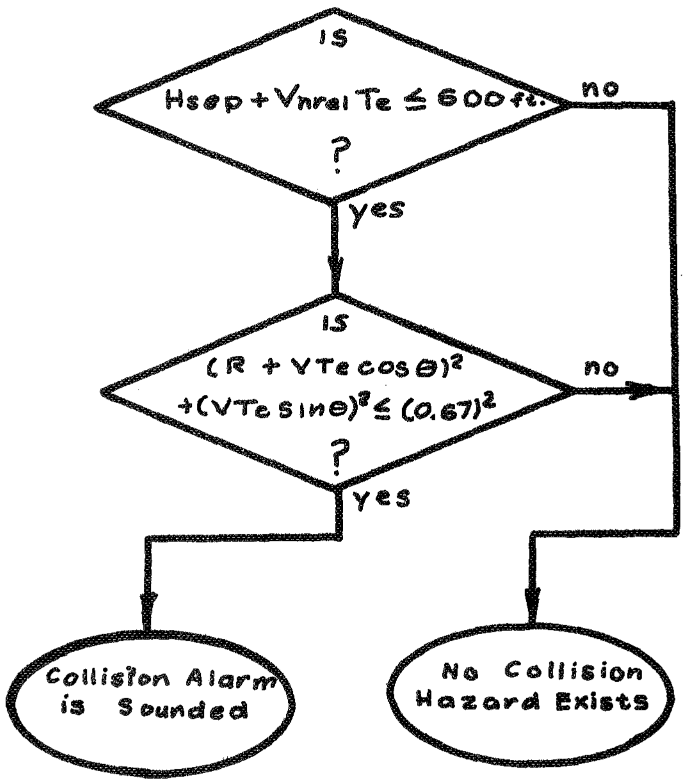
The number of alarms observed for the 1000 aircraft was two. The conclusion is that had the aircraft involved been flying at the maximum error points along the curves, the alarm would serve to direct the pilot back onto the course.

No simulation was done on the possibility of entering an intruder into the landing pattern. It is believed, however, that the alarms would have noticed the intrusion and escape maneuvers as described in the collision avoidance section would have been employed.

3.5 TERMINAL AIR TRAFFIC CONTROL SYSTEM

This segment attempts to define a future terminal area air traffic control system. The system is designed to sequence and to direct arrivals and departures in order to achieve the maximum runway-approach system capacity with minimum delay to aircraft.

The terminal area system interfaces with the enroute air traffic control (ATC) and the runway-approach system. Terminal ATC accepts



V = Relative velocity measured between the two A/C
R = Relative range measured between the two A/C
T_e = Time needed to avoid a collision
θ = Angle measured between the velocity and range vectors
V_{hrel} = Vertical Component of relative velocity vector

Collision Hazard Flowchart
Figure 3.29

arrivals from enroute ATC sixty nautical miles from the airport and delivers them properly sequenced to the speed segregated gates of the scanning beam ILS.

The system is designed within four primary constraints:

1. The initial configuration is a single airport with a single dual lane runway. Later configurations include multiple runways and multiple airports.

2. The system is based on the avionic, navigational, computer, and aircraft capabilities forecast between now and the year 2000, assuming no order-of-magnitude increase in aircraft performance during that time.

3. The system is designed considering the arrival problem only since departure handling is not as crucial as the problem of sequencing and directing aircraft to the ILS gates within a few seconds standard deviation of their scheduled time. Also arrivals and departures can be treated independently because the dual lane runway makes it possible to release departures as soon as arrivals touch down, eliminating the need to include departure gaps in the landing sequence.

4. The system is designed for Instrument Flight Rules traffic only. Thus positive control is assumed.

It was felt that the system should be compatible with four desirable aspects of a terminal ATC system.

1. The system must have a time management capability of delaying aircraft that are ahead of schedule and of expediting aircraft that are behind schedule.

2. The system should minimize airspace usage. This implies that aircraft should be assigned specific terminal area paths or corridors to fly. The paths should be speed segregated to ease the difficulty in handling a mix of aircraft types with altitude and lateral separation for safety. They should be close to the airport and as direct as possible to minimize aircraft flight time. And they should be arranged for ease in changing the active runway in case of a wind shift.

3. The system should be strategic in that the responsibility for managing the overall sequencing, vectoring, and safety of aircraft in the terminal area should lie with a computer on the ground. It was felt that this centralization of responsibility is consistent with the philosophy of centralized national scheduling of IFR flights.

4. The system should direct aircraft to fly optimum descent-deceleration profiles so as to minimize their flight time within the terminal area.

Terminal Surveilliance And Control Equipment Capabilities

Control of aircraft in a high density terminal area with proper sequencing and spacing requires an accurate position and velocity sensor system. This system must also have a rapid track update rate to relay control information to and from the aircraft.

The present day ATC system with its standard radar and ILS does not provide the accuracy and data rates that would be required for this control. Listed below are some of the data acquisition capabilities that may be required for a computer controlled terminal system:

1. Three-dimensional search and track functions
2. Rapid track update capability (1 second or greater).
3. Maximum positional error of $\pm$ 400 ft. at the outer terminal perimeter with the error decreasing to $\pm$ 100 ft. at 20 nm. from touchdown.
4. Two way data link capability.

Four systems were studied to determine the capabilities of a control system in the period 1970 to 2000 and they are listed below.

I. Radar

A. Rotating Antenna (Improved)
   1. Range error $\pm$ 370 ft. Az .25^{o}
   2. Track update rate limited to rotation
   3. Altitude through transponder $\pm$ 250 ft
   4. Greater accuracies requiring large antenna

B. Phase Array
   1. Position error $\pm$ 360 ft. (3-Dimensional)
   2. Track while scan capability (100 A/C)
   3. Data link capability
   4. Rapid update information for control
   5. Transponder for altitude (2-Dimensional)
   6. Position error $\pm$ 100 ft. at 20 nm

II. Radio Beacon (Trilateration Systems)

A. Ground Based (discrete coded)
   1. Position error ± 300 ft. up to 150 miles
   2. Interrogate 8000 A/C up to 5/sec.
   3. Data link
   4. Could be phased in with present day ATCRBS

B. Satellite Based
   1. Position error
   2. Velocity error 1 ft./sec.
   3. Data link for limited terminal control
   4. System still on the drawing board.

A brief description of each system follows.

Air Traffic Control Radar Beacon System (ATCRBS)

The improved ATC radar beacon system will meet most of the requirements stated previously (with a transponder equipped for altitude information) except for the track update capability. Track update capability in the terminal area is an important factor in the proposed terminal model since speed changes and path delays are used in sequencing and spacing. In this system, with a mechanically rotating antenna, data rates affect tracking accuracy. For this reason, the rotating radar beacon system, even with improvements, seems lacking for precise terminal control. Data transmission to aircraft is limited by the amount of time the system can spend on target. System capabilities include:

1. Range accuracy ± 370 ft.
2. Azimuth accuracy .25 degree (center marking)
3. Range resolution -- 350 ft.
4. Azimuth resolution 4^o--5^o
5. Elevation via transponder ± 250 ft.

Phased Array Radar

Various studies indicate that phased array radar is favored in the near future for surveillance and control in the terminal area. The phased array radar offers a tracking capability along with the possibility of providing a data link capability. Presented below are some of the expected advantages:

1. Three-dimensional capability without transponders
2. Maximum range error at 60 nm. could be less than 360 ft.
3. Track while scan (up to 100 targets)
4. Rapid update rate of track information
5. Interrogator capability
6. Data link capability in the track mode
7. Intruder surveillance

The system's disadvantages include the following:

1. Expensive, thus possibly limiting use to high density terminal areas.
2. Untested working prototype
3. Requires digital control of beams steering
4. Frequency not the same as conventional radar. (Aircraft will require a new transponder)

The Alexander Report recommends phased array interrogators. Moreover the system does meet the requirements for a automatic type control in the terminal area. With more improvements, the capabilities may be extended to approach control.

Discrete Code Range-Ordered Trilateration System

A range-ordered trilateration system offers many unique features essential to the successful implementation and operation of air traffic control systems. These features include:

1. Ability to interrogate over 8000 aircraft in an air traffic control area at rates up to five times per second.

2. Positional accuracies of 300 feet at ranges up to 150 miles

3. Positional accuracies at close range commensurate with blind landing system requirement.

4. Capability for working with radar systems

5. ICAO-compatible

6. Ability to handle orderly phaseout of existing equipment

7. Inherent two-way link capability

8. Minimal airborne equipment

9. Ready compatibility with ground collision avoidance system

This system was used in the Los Angeles study and has the accuracy and data link capability that is required in a terminal area. The system is also technologically and economically feasible.

The apparent disadvantages are the number of sites required in a control area and a line of sight requirement from three stations to the aircraft.

TABLE 3.7 PARAMETERS OF CONTROL FOR THE LOG ANGELES AIR TRAFFIC CONTROL AREA (400 NM by 800 NM)

Item	Number	Interrogation period-seconds	Maximum Position error (ft)
Interrogated aircraft	8,000		
Final approach aircraft	300	1/5	25
Terminal aircraft	1,400	1	100
High density en route	425	1	100
En route and VFR aircraft	5,875	3	600
Number of radar in area:			
Enroute	8		
Terminal	5		
Number of aircraft seen by one en route radar	2,500		
Noise reports	250		
Number of aircraft seen by one terminal radar	1,000		
Noise reports	100		
Number of failing transceivers (percent)	0.1		

TABLE 3.8 MINIMUM COST OF GENERAL AVIATION CONTROL EQUIPMENT

Item	Cost
Basic transponder	$1,700
Altitude encoder	200
Antennas (2)	100
Adaptive antenna selection	600
Display	250
	$2,850

Satellite System

Although this system lends itself to area navigation the predicted accuracy of the system forces a consideration of usage near the terminal area. Using three satellites with highest elevation angles from a five-satellite constellation, accuracies can be obtained in position error of 100 ft. and velocity errors of 1ft./sec. (important inflow control) anywhere in the continental United States. The system also has data link capabilities. The system would require an active transponder at cost equivalent to the present radar transponder. The system has yet to be designed and tested. The cost of satellites, system deployment, and cost of airborne equipment for navigation information is a prohibitive factor at this time.

Conclusion

It is generally agreed that the track data update in the terminal area should be one second or greater. Of the systems investigated the phased array type radar best satisfies the accuracy required plus the track data update capability. The phased array radar can take on two basic forms, either the two-dimensional phased array is less expensive but relies on a transponder for altitude information. The three-dimensional system is more versatile in a high density terminal area since knowledge of the altitude of intruders and aircraft with non-operational transponders is known and the system's accuracies could be incorporated into approach control. The ground based trilateration system and the satellite system also meet the requirements of control in a terminal area.

A possible development by the 1980's for high density terminals would be phased array radar as a primary control system with ground based trilateration sites near the terminal as back up, yielding the expected accuracies and capabilities of:

1. Terminal position accuracy ± 360 ft. at 60 nm.
2. Terminal position accuracy ± 100 ft. at 20 nm.
3. Data Rate (tracking and control) 1/sec.
4. Tracking capability (control) 100 targets at high data rates.

Future developments in the post 1980 period may prove that the satellite or the ground trilateration system is more capable of handling aircraft in a high density terminal area as the primary system with the phased array radar used as a system backup. A system of this type could yield advantages such as:

1. Position accuracy (continental) ± 100 ft.
2. Data rates of 1/sec. or greater
3. Command guidance for 10,000 aircraft in the U.S. at high data rates.
4. Approach guidance to multiple runways (using the phased array radar.
5. Velocity accuracy of 1 ft./sec.

The Time Frequency system was not considered in this study because of the high cost of an accurate clock prohibits its use in small aircraft, and more important the system relies on cockpit management rather than ground control.

No mention has been made about the computer or the program needed to accomplish the control function, but reports on this subject indicate that the computer technology is or will be available to handle the problem by 1980.

Aircraft Flow into the Terminal Area

A terminal area will have an upper limit of landings that it will handle in a specified time based on some limiting factor such as trailing vortices or spacing limitations of aircraft at each runway.

To land aircraft at the maximum acceptance rate the aircraft would have to be delivered to the landing threshold including delivery error and potential waveoffs at less than or equal to this rate. In order to eliminate extensive maneuvering delays in the terminal area and still meet the maximum acceptance rate, aircraft must be metered into a terminal system in some orderly fashion which allows for an error that can be corrected in a small area. With a metered type flow control into the terminal area it is not so important that arrivals meet on original scheduled time slot. The important point is that they meet an open time slot that can be dynamically scheduled during the enroute phase. The metering system suggested in this report is similar to that suggested by the Air Traffic Control Advisory Committee with primary emphasis placed on the metering of aircraft from the enroute phase to the terminal phase. The purpose is to deliver aircraft to the terminal in a specified time slot with an error less than or equal to a runway acceptance time interval. The system would use a central control for scheduling and control of all aircraft in flight to high density terminals. The following procedures could be used for metering aircraft into a high density terminal to meet this time interval.

1. A flight plan similar to present day is filed. A clearance is given based on an open time slot ($\pm$ one minute nominally at the destination airport runway.

2. Enroute monitoring at flight route control points is conducted to compare actual position versus the predicted schedule's position.

3. If minor deviations exist in the Estimated Time of Arrival (ETA), corrections are made in flight to compensate them.

4. If aircraft meets flight conditions that do not allow meeting scheduled arrival time, the central control searches for another time slot that can be met.

5. If a new time slot is not available a check is made to see if another flight or flights to the airport can be modified to open an available time slot. Since a high density airport may have multiple runways a check is also made of all runway time slots at the airport.

6. Under the extreme condition that a time slot cannot be met, the aircraft will be held at the outer terminal radius (approximately 60 nm.) until an opening occurs.

7. Errors up to a minute are corrected in the preapproach phase.

These basic procedures would require computer control for flow regulation and a more strategic type navigation than used at present. Primary sequencing would then be done while the aircraft is in the enroute phase. Secondary sequencing would be done in the terminal area to compensate for the error in delivery. A system of this type is feasable since for a flight of 90 minutes or less a precise departure and arrival time can be met. Longer flights may require an exact arrival time to be assigned at midflight.[12]

Using accurate area navigation, aircraft could be handed off from the enroute to terminal system at the terminal acceptance rate with delivery errors not exceeding one runway time slot (i.e. if one runway can land one plane per minute the projected error in delivery to the runway would be no greater than one minute of schedules time to land under normal contitions). A delivery of this type would facilitate sequencing in the terminal area since under the worst case a cluster of three aircraft would be competing for the same landing threshold time. Normally in the terminal area the maneuvering space is limited and the model introduced in this report can compensate for an error of approximately one minute in delivery (using a maneuver area with a five mile radius before approach).

Airspace Structure

The airspace structure is a synthesis of many arrangements that have been advanced. Each arrangement takes advantage of a slightly different set of air traffic control procedures, and because few simulations of advanced concepts have been conducted, the rational for an airspace structure rests with how well it serves the system and philosophy of which it is designed to be a part. For the single airport, single runway configuration of Figure 3.30 has been selected as being consistent with the constraints of the study and containing the desirable aspects previously mentioned.

Since the structure is designed around the ILS system, there is a high speed approach path feeding aircraft to the high speed ILS course, with medium speed and low speed approach paths feeding the medium and low speed ILS courses, respectively. The high, medium, and low speed approach paths are laterally separated by two nautical miles[13] with the high speed farthest from the airport, and the low speed nearest.

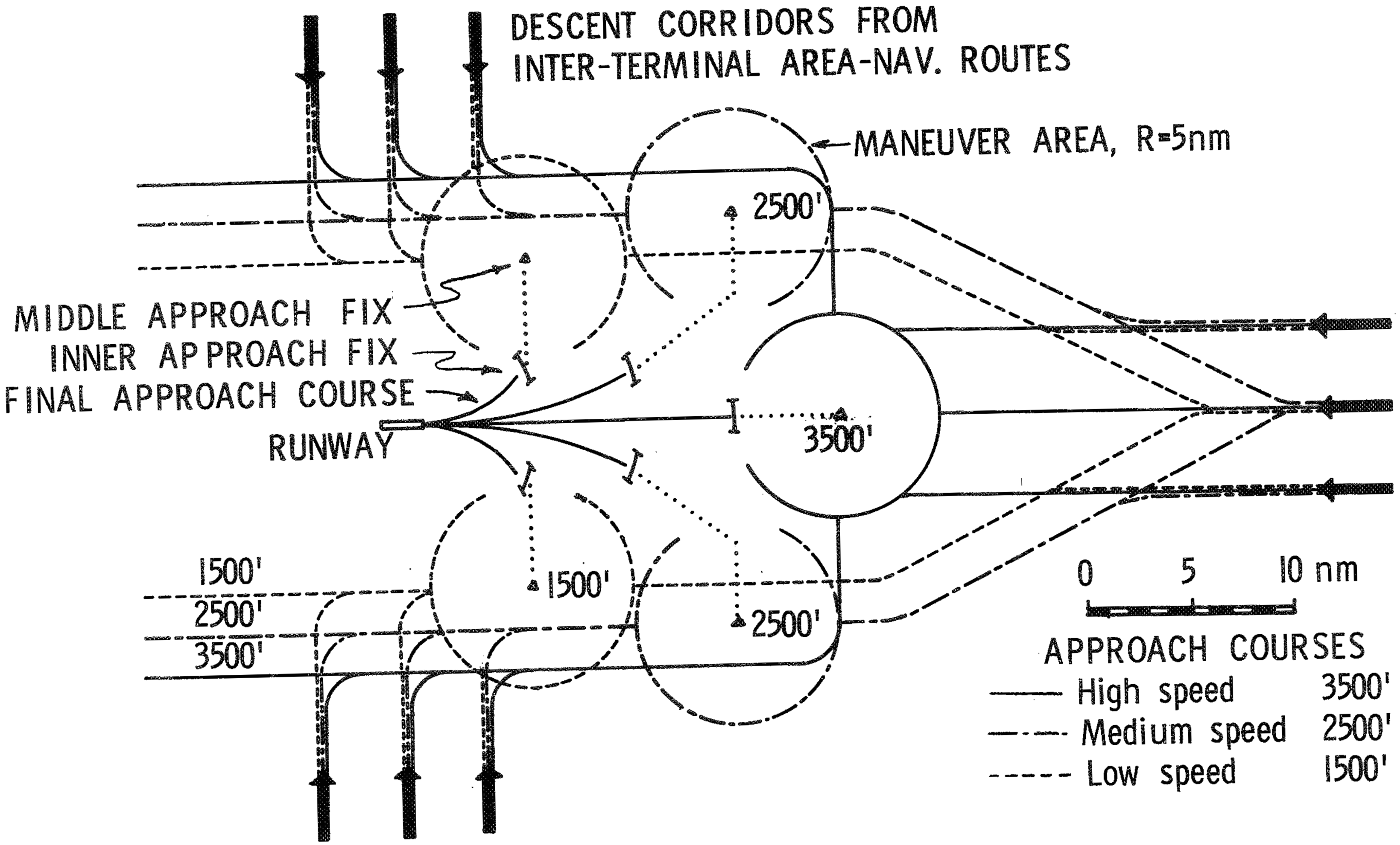

DESCENT CORRIDORS FROM
INTER-TERMINAL AREA-NAV. ROUTES
MANEUVER AREA, R=5nm
2500'
MIDDLE APPROACH FIX
INNER APPROACH FIX
FINAL APPROACH COURSE
RUNWAY
3500'
1500'
1500'
2500'
3500'
2500'
0 5 10 nm
APPROACH COURSES
High speed 3500'
Medium speed 2500'
Low speed 1500'

Figure 3.30

This is desirable for four reasons. Longer paths take less time for high speed aircraft to fly than low speed aircraft. The high speed ILS gate is farthest from the airport and must be fed from further out. High speed aircraft have larger turning radii requiring more room for maneuvers. And, the specific arrangement allows for a convenient fit of the paths into the airspace. The approach courses are altitude separated by 1000 feet with the high speed at 3500 feet, the medium speed at 2500 feet, and the low speed at 1500 feet. This is reasonable because it is desirable to keep the high intensity noise at higher altitudes. Also, since high performance aircraft generally operate at higher altitudes, descent to high approach paths is desirable from a separation-for-safety standpoint. The distances the paths lie from the airport compare favorably with the distances used in the FASA and MAT/TAS simulations, the New York Metroplex arrangement, and the arrangements discussed in the references.

The number and geometric arrangement of descent corridors feeding into the approach paths are determined by the most direct international routes used by the area navigation system. However, near the airport, descent corridors that intersect the approach paths on headings parallel and perpendicular to the runway heading are advantageous because the symmetry allows the active runway to be changed without changing the descent corridors. The descent corridors are laterally separated by four nautical miles in accord with the views of reference 13.

The approach fix arrangement was chosen in conjunction with the procedures for computerized handling of terminal area traffic. In general, fixes on the higher speed approach courses are farther from the airport.

ATC Procedures and Sequencing Logic

The procedures and logic of the system are taken from the Federal Aviation Administration's FASA and MST/TAS[14] simulation studies with two important differences. First, the FASA, MAT/TAS studies use computerized sequencing as an aid to the air traffic controller, who retains vectoring and decision making responsibility. Although the pilot will remain responsible for the safe operation of his aircraft the controller will assume a supervisory capacity overseeing the computer's handling of aircraft, the reasons being that the expected high density of traffic in the terminal area will make sophisticated decision making necessary and the continuous updating of scheduleing and maneuvering to optimize operations will preclude the controller as a communications link. Secondly, current sequencing logics ascertain the deviation in the aircraft's arrival time at the delivery point and correct the error with a count-down turn to final approach.[15] It is felt that the projected improvement in terminal surveillance and control equipment will enable a future terminal air traffic control computer to continuously correct deviations from schedule. The following is a description of the operating logic and procedures envisioned in the future air traffic control system. (See Figure 3.31.)

1. Acceptance. The aircraft arrives at the outer perimeter of the terminal area within some error of its schedule time of arrival. Terminal air traffic control begins tracking the aircraft and knowledges the aircraft's entrance into the terminal area.

2. Tentative Scheduling. The terminal air traffic control computer has the aircraft's performance profile in memory and computes its Direct Course of Touchdown, DCTT, via the various approach courses by adding the aircraft's fastest time to fly the descent and transition approach to its time to fly the final approach in the ILS, at the aircraft's optimum final approach

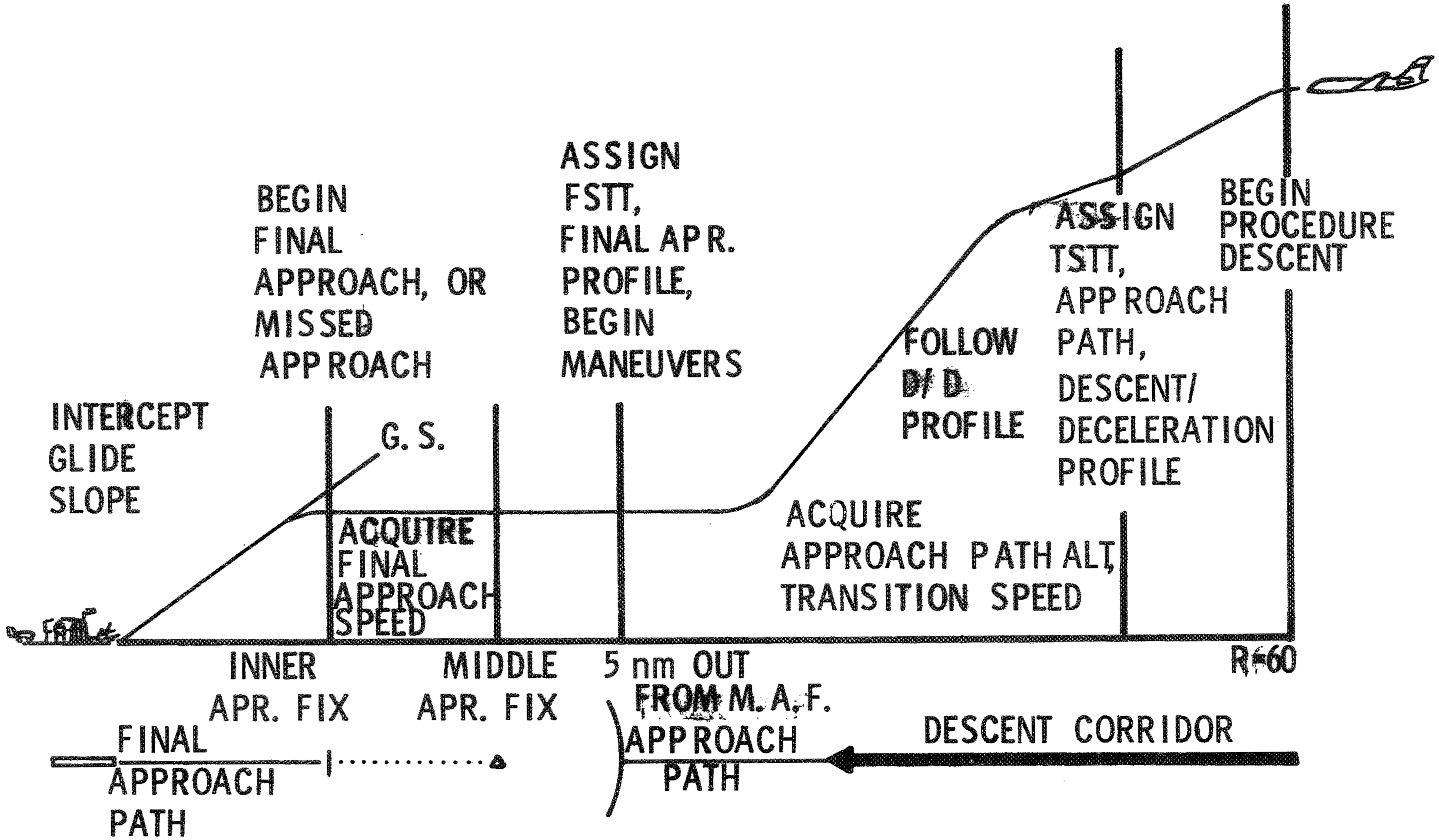


Figure 3.31: Vertical Airspace and Flight Plan Profile

speed. The computer then searches the tentative landing sequences for an optimum Tentatively Scheduled Time of Touchdown, TSTT, by comparing the aircraft's DCTT with the TSTT's of already tentatively scheduled aircraft, looking for the best fit for all aircraft on the basis of the following:

a. If the aircraft is heavily arrival weighted, i.e. preferred, it is assigned a TSTT as close to its DCTT as possible, perhaps stepping into the sequence ahead of already tentatively scheduled aircraft.

b. The TSTT should place the aircraft in a sequence that will land it the minimum allowable time or distance behind the aircraft preceeding it in the sequence. Alternating right and left side approaches are desirable.

c. No aircraft may be scheduled so as to incur more than the maximum delay the system is capable of absorbing. If this is not possible, the aircraft is stacked at the outer perimeter.

3. Standard Descent. If the aircraft can be scheduled, it is cleared for a 5-10 nautical mile standard descent in one of the descent corridors. The computer uses this time to scan other arrivals and recalculate the landing sequence for all tentatively scheduled aircraft, looking for the best fit. As aircraft in the standard descent phase have not yet been assigned a descent/deceleration profile, changes in the sequence at this stage can be made without having to alter the aircraft's flight profile.

4. Tentative Schedule Assignment. After penetrating 5-10 nautical miles, the aircraft is assigned the computer's current optimum TSTT and is given an approach path to fly. The computer then calculates a Tentative Arrival Time at the Inner Approach Fix, TAT-IAF, and assigns a descent/deceleration profile that will deliver the aircraft to the IAF on schedule.

5. Descent/Deceleration. As the aircraft is assigned a tentative schedule, it is given a higher priority so that it is less likely that it will be slipped back in the sequence, requiring an undesirable midcourse alteration of the descent/deceleration profile. The computer, however, is continuously updating the landing sequence and may alter the schedules and descent/deceleration profiles of any or all tentatively scheduled aircraft if it finds a more advantageous sequence. The descent/deceleration profile is tailored to the aircraft's performance capability and brings the aircraft to its appropriate transition speed and approach path altitude at least five nautical miles out from the first Middle Approach Fix, MAF, the aircraft encounters.

6. Firm Schedule Assignment. At five nautical miles from the MAF, the computer firmly schedules the aircraft. The aircraft's current TSTT is adopted if no priority slip in the sequence has occurred. Or, the computer assigns an updated Firm Scheduled Time or touchdown, FSTT, if the aircraft has accured an error in his schedule that the computer has not been able to correct by ordering speed change maneuvers in the descent stage. If, at this time, a different approach path would be more advantageous, the computer may order a "last chance" divert to another approach path. The landing sequence cannot be altered once the aircraft is firmly scheduled. The computer then assigns a Time of Arrival at the IAF, TA-IAF, and a final approach profile as described in the Final Approach section.

7. Fine Maneuvering. The computer now indicates lateral and speed change maneuvers to the aircraft which will deliver it to the IAF at its assigned time, at its final approach speed.

8. Final Approach. If the aircraft arrives at the IAF within allowable standard deviation limits of its assigned time, it is released for a final approach according to its final approach profile. If the aircraft cannot arrive within acceptable limits, it must declare a missed approach.

Time Management Capability

System logic must be supported on a sound mathematical foundation. A mathematical analysis is necessary to demonstrate system performance with the constraints imposed on the system. By system performance is meant the ability to accommodate air traffic at the airport acceptance rate with a specified separation maintained between aircraft. This section describes the assuption; constraints, and geometry used in support of the design model from the terminal boundary to the initiation of final approach. A study was performed to determine the time management capability in the system or ability to compensate for inherent timing errors. An error of $\pm$ 5 seconds at the inner approach fix was considered acceptable.

A simple geometry is desirable for two primary reasons:

1. The time required by a computer to solve the resulting mathematical expression is minimized. As has been indicated previously, all aircraft positional information and directions will be processed through a ground based computer facility. It is advantageous to reduce computation time as far as possible in order to improve traffic handling capabilities.

2. Flight path geometry is easy to negotiate by pilot personnel. Prior to landing the pilot follows prescribed procedures which require considerable effort and attention. Therefore, in order to reduce pilot fatigue and the probability of aircraft position error, a minimum number of inflight maneuvers should be designed into the system.

In these reasons and in consideration of air collision avoidance the following restraints were imposed in the time management analysis:

1. All turn maneuvers will be accomplished at a half standard rate or 1.5 degrees per second.

2. Final turning maneuvers will be performed within a five nautical mile radius of the middle approach fix.

Terminal Boundary

As has been indicated in section 3.5, terminal control and surveillance equipment are expected to meet a position error of ± 360 feet at the terminal boundary. However, it is not unreasonable to assume that larger errors could develop due to faulty equipment or pilot error. The system should be designed to respond, therefore, to the largest anticipated error while considering its probability of occurrence. For planning purposes, it was decided to consider a system capable of responding to arrival time errors of ± 1 minute (16,230 feet at 180 knots).

Since a super saturated condition will never be permitted to develop, the aircraft arrival rate must be less than or equal to the airport landing capability. It was considered reasonable to use 90 aircraft per hour (interarrival time of 40 seconds) as airport capacity. This figure represents a substantial improvement over percent landing capabilities. Providing some cushion for inflight emergencies and go-arounds, the aircraft arrival rate at the terminal boundary was limited to 86 aircraft per hour.

Upon entering the terminal boundary from any quandrant aircraft are directed to follow one of three air corridors to the middle approach fix. The spacing between aircraft along a given corridor will not be allowed to fall short of 40 seconds. In most cases spacing will be considerably greater because with multiple corridors available to arriving aircraft, there is a low probability that one aircraft will be required to follow immediately behind another along a common path. During this period aircraft decelerate to transition speed and decend to a specified altitude while attempting to correct position error. Upon reaching a point five nautical miles from the middle approach fix, however, some position error may still be present.

Time Maneuver Area

In order to achieve accuracy of $\pm$ 5 seconds at the inner approach fix the system incorporates five maneuver areas, one for each ILS gate. Aircraft within these areas maintain a constant altitude and decelerate from transition to approach speeds. A simplifying assumption of constant speed terms was made, however, for the analysis. Also, wind effects were neglected. By directing the aircraft to follow a specified flight path within the maneuver areas, the computer is able to correct aircraft position errors. The reader is directed to the system schematic Figure 3.32. It can be seen that four maneiver configurations are

MANEUVER CONFIGURATIONS

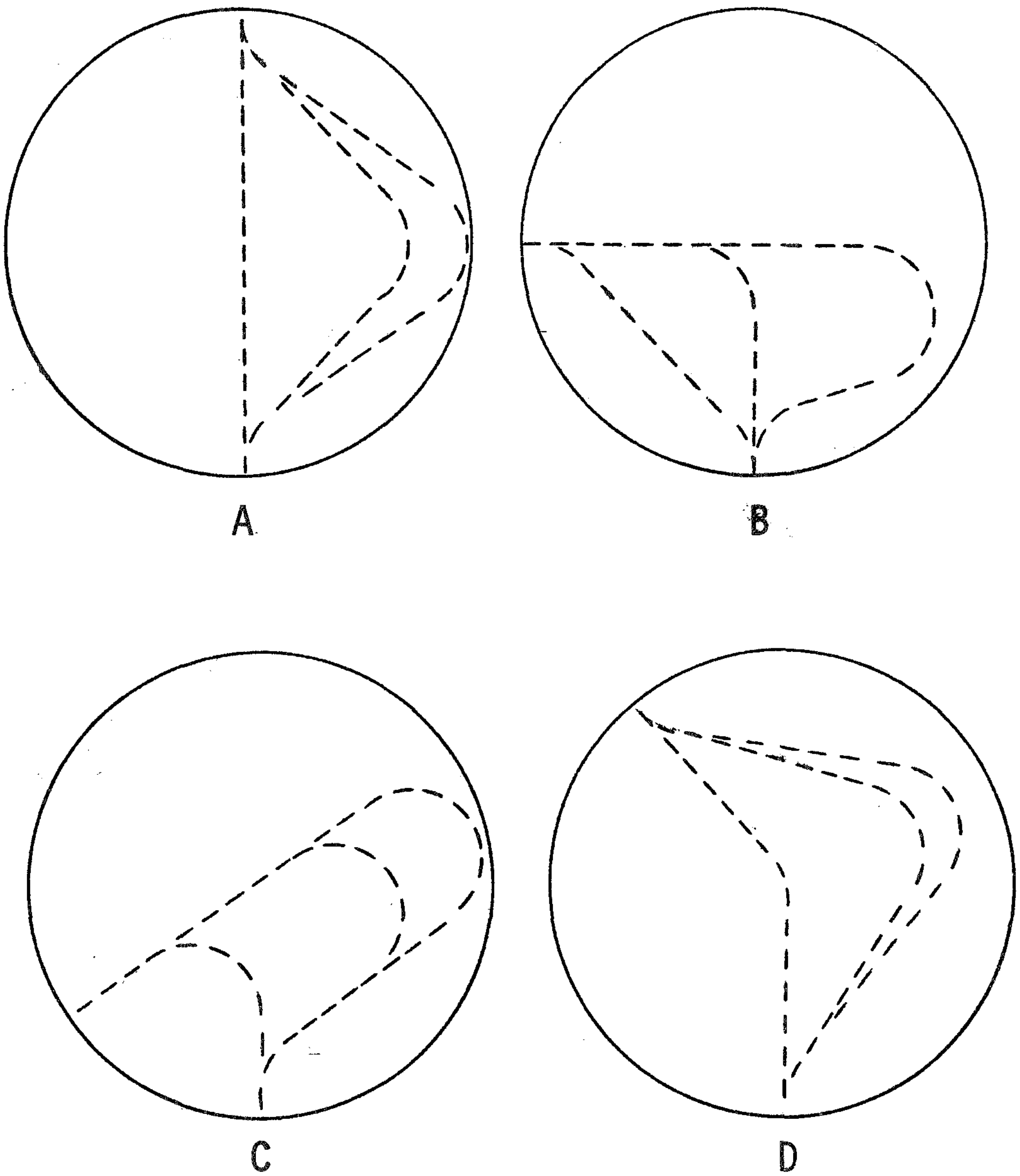


Figure 3.32: Approach Configurations

depicted for this typical system. An analysis of each maneuver configuration with its appropriate mathematical expression follows. The expressions relate the error compensation to the parameter which is varied during the maneuver.

The expressions are written in the following terms:

R-maneuver area radius in nautical miles

r-radius of curvature in nautical miles determined by the expression

$r = \frac{d}{\theta_r}$ where d is the arc length

θ - angle of turn in degrees

θ_r - angle of turn in radians

V - aircraft velocity in nautical miles per minute

D - total flight path distance in nautical miles

$\emptyset$ - angle between the maneuver area entry point (EP) and the inner approach fix.

Configuration A

This configuration is appropriate when the entry point (EP), the middle approach fix, and the inner approach fix lie along a common straight line. (Refer to Figure 3.33)

Three possible flight paths are shown for the maneuver configuration. The straight line path is, of course the shortest route to the IAF, aircraft incurring the earliest allowable arrival error would be directed to follow this path. Longer, curved paths would be followed by aircraft incurring smaller early arrival errors, on time, or late arrival errors. The curved path is symmetrical. By monitoring the aircraft airspeed and time of arrival at the PE, the computer is able to specify the appropriate flight path using the following mathematical expression which relates flight path distance to angle of turn:

$$D = ((R - r\tan\theta/2)\sec\theta - r(\tan\theta + \tan\theta/2) + V\theta/45) \qquad (3.31)$$

Thus, by specifying the angle in which the turns are performed, the time required to fly from Er to IAF may be specified. The following table indicates the flight time-angle of turn relationship for typcial airspeeds. Flight times are expressed in minutes:

TABLE 3.9 FLIGHT TIME-ANGLE OF TURN RELATIONSHIP FOR TYPICAL AIRSPEED

Angle of turn	Airspeed (knots)				
	85	115	135	140	165
0^o	7.06	5.22	4.44	4.28	3.64
15^o	7.30	5.39	4.59	4.42	3.75
30^o	8.02	5.89	5.00	4.82	4.06
45^o	9.44	6.83	5.74	5.51	4.59
59^o*	11.34	8.05	6.66	6.37	5.45

*Limiting angle for 165 knots to remain within the 5 nm maneuver area using the relationship:

$$(R - r\tan\theta/2)\tan\theta - r(\sec\theta - 1) \leq R \qquad (3.32)$$

By observation, this configuration provides a maximum of 1.81 minutes ($\pm$ 55 seconds) for arrival error correction at 165 knots, the highest anticipated approach speed. Greater error correction, therefore, are possible at slower approach speeds.

Configuration B

This configuration (Figure 3.34) is applicable when the angle between the PE, MAF and IAF is 90^o. All aircraft would follow a curved

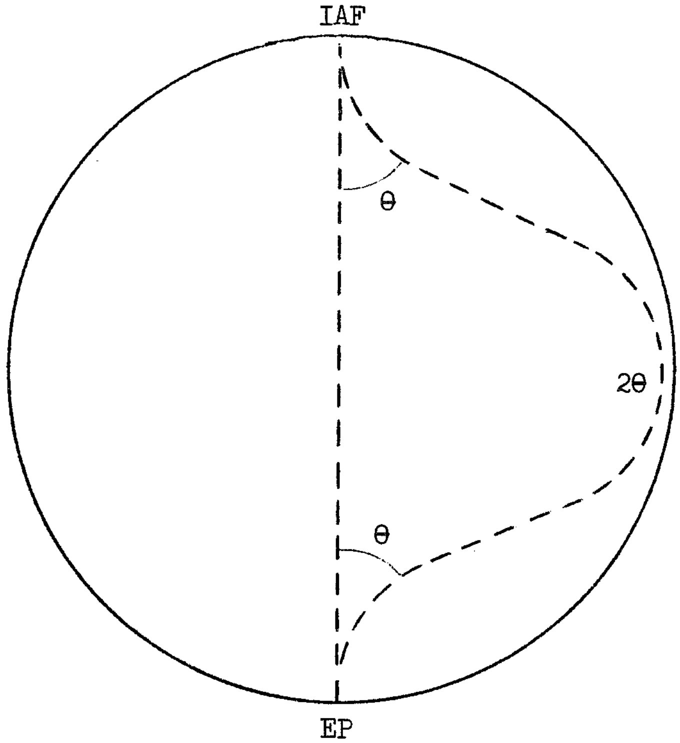


Figure 3.33: Configuration A

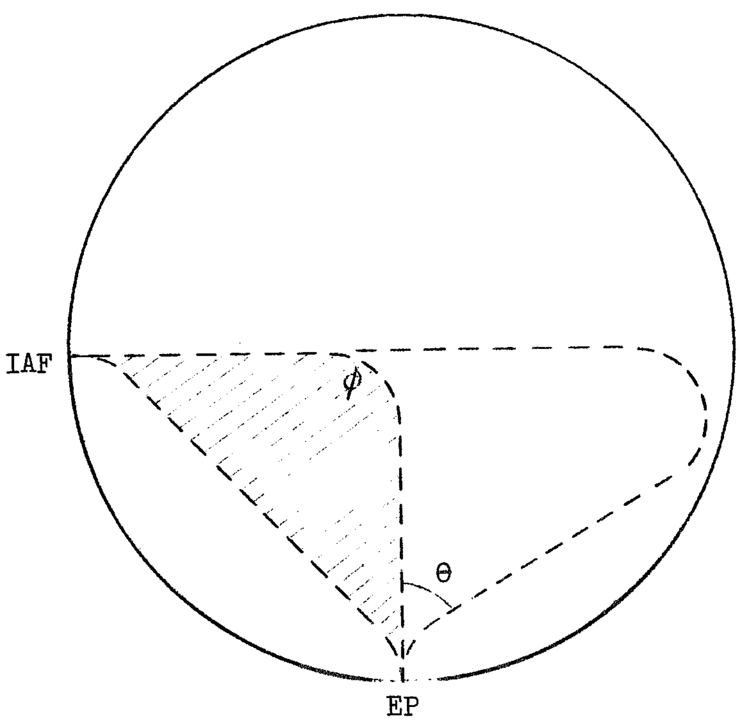


Figure 3.34: Configuration B

path from PE to IAF. Two mathematical expressions are appropriate:

1.

$$D = 2x + r\,\phi_r + \sqrt{(R - x - r\tan\phi/4)^2 2(1 - \cos\phi - 2r\tan\phi/4)} \qquad (3.34)$$

where $\phi = 90^o$. The expression reduces to

$$D = 1.414 + 0.586x + 0.1556r$$

This expression is applicable to flight paths within the shaded area (Figure 3.34) where the parameter X, the distance flown prior to the initial turn, is varied to provide the required error correction. This parameter varies from zero to R - r.

For longer flight paths the initial turn is made away from the IAF with angle of turn specified using the following expression:

2.

$$D = 2r\,\theta_r + R\sec\theta + R\tan\theta - 2r\sin\theta/2 - 2r\tan((90^o + \theta)/2) + r\,\pi/2 + R \qquad (3.35)$$

where angle θ is limited to the expression

$$(R - r\tan\theta)\mathrm{ctn}(90^o - \theta) - r\,\mathrm{ctn}(90^o - \theta) + r \qquad (3.36)$$

Minimum and maximum flight times (minutes) for this maneuver configuration are listed below:

Table 3.10 Maximum and minimum flight times for configuration B

	Expression 1					Expression 2				
Airspeed (knots)	85	115	135	140	165	85	115	135	140	165
Minimum	5.18	3.87	3.32	3.21	2.75	6.79	4.95	4.17	4.01	3.36
Maximum	6.79	4.95	4.17	4.01	3.36	10.49	7.35	6.02	5.75	4.64

It should be noted that the maximum flight times by expression 1 are equal to the minimum flight times by expression 2. Error correction varies from 5.31 minutes ($\pm$ 160 seconds) at 85 knots to 1.89 minutes ($\pm$ 56 seconds) at 165 knots.

Configuration C

When the angle between the EP and IAF is less than 90°, maneuver configuration C (Figure 3.35) is used. The distance, X, between the first and second turns is varied to acheive the densired error correction using the following expression:

$$D = 2R + \pi r + \theta r - 2r \csc \theta - r \tan \theta/2 + 2X$$

The parameter X may be veried from 0 to R-r. A table of minimum and maximum flight time values (minutes) is depicted for typical approach speeds and a θ value of 30°.

TABLE 3.11 MAXIMUM AND MINIMUM
FLIGHT TIMES FOR CONFIGURATION C

Airspeed (knots)	85	115	135	140	165
Minimum	6.68	4.84	4.06	3.91	3.25
Maximum	12.46	8.79	7.23	6.93	5.61

Error corrections of 5.78 minutes ($\pm$ 173 seconds) at 85 knots to 2.36 minutes ($\pm$ 71 seconds) at 165 knots may, therefore be obtained using this maneuver configuration.

Configuration D

The final configuration (Figure 3.36) is used when the angle between the EP and the IAF is greater than 90° but less than 180°. The expression

$$D = 2((R - r\tan \theta/2)\cos \theta + (R - r\tan \theta/2)\sin \theta \operatorname{ctn} \phi/2 - r\tan \theta/2 - r\operatorname{ctn} \phi/2) + 2r\theta + r(180^{\circ} - \phi) \quad (3.37)$$

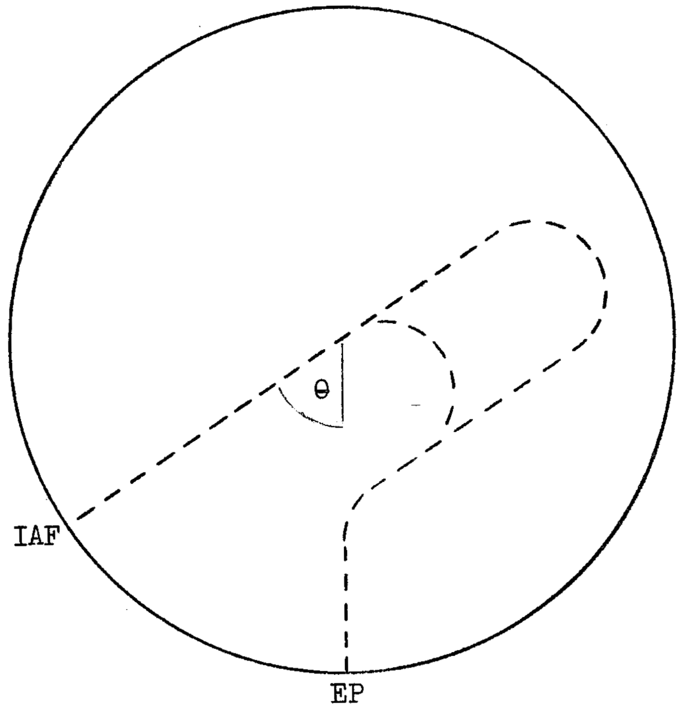


Figure 3.35: Configuration C

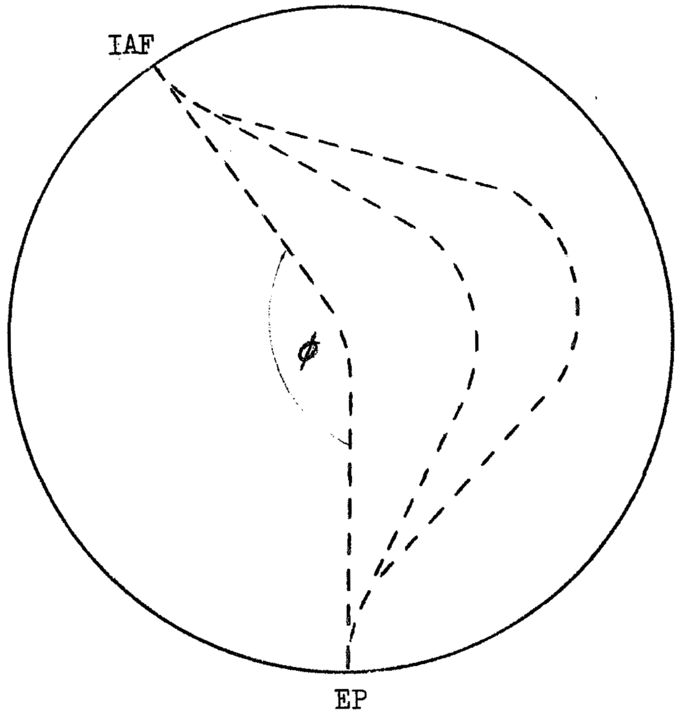


Figure 3.36: Configuration D

relates the flight path distance to the angle 'of turn θ. This angle is limited by the expression

$$((R - r\tan\theta/2)\sin\theta - r)\csc\phi/2 + r \leq R \tag{3.38}$$

which designates flight paths in the maneuver area. Typical flight times (minutes) using this configuration with $\phi = 150^{\circ}$ are shown in Table 3.12.

TABLE 3.12 MAXIMUM AND MINIMUM FLIGHT TIMES FOR CONFIGURATION D

Airspeed (knots)	85	115	135	140	165
Minimum	7.05	5.21	4.44	4.28	3.63
Maximum	11.42	8.46	7.31	7.01	6.42

Multiple Runway Airports

Additional runways in the airport layout alter the Final Approach System, but do not appreciably effect the terminal air traffic control airspace configuration or sequencing logic. The speed segregated approach path arrangement used for one runway is immediately adaptable to the final approach system adopted for the four runway airport. The only significant change is the addition of another high speed approach course. Figure 3.37 depicts such an airspace structure with the high speed approaches feeding the outer runways. The landing sequence can be optimized on the outer runways. The landing sequence can be optimized on the outer runways which have multiple gates, but aircraft on the inner runway approaches will have to be lined up on final approach in much the

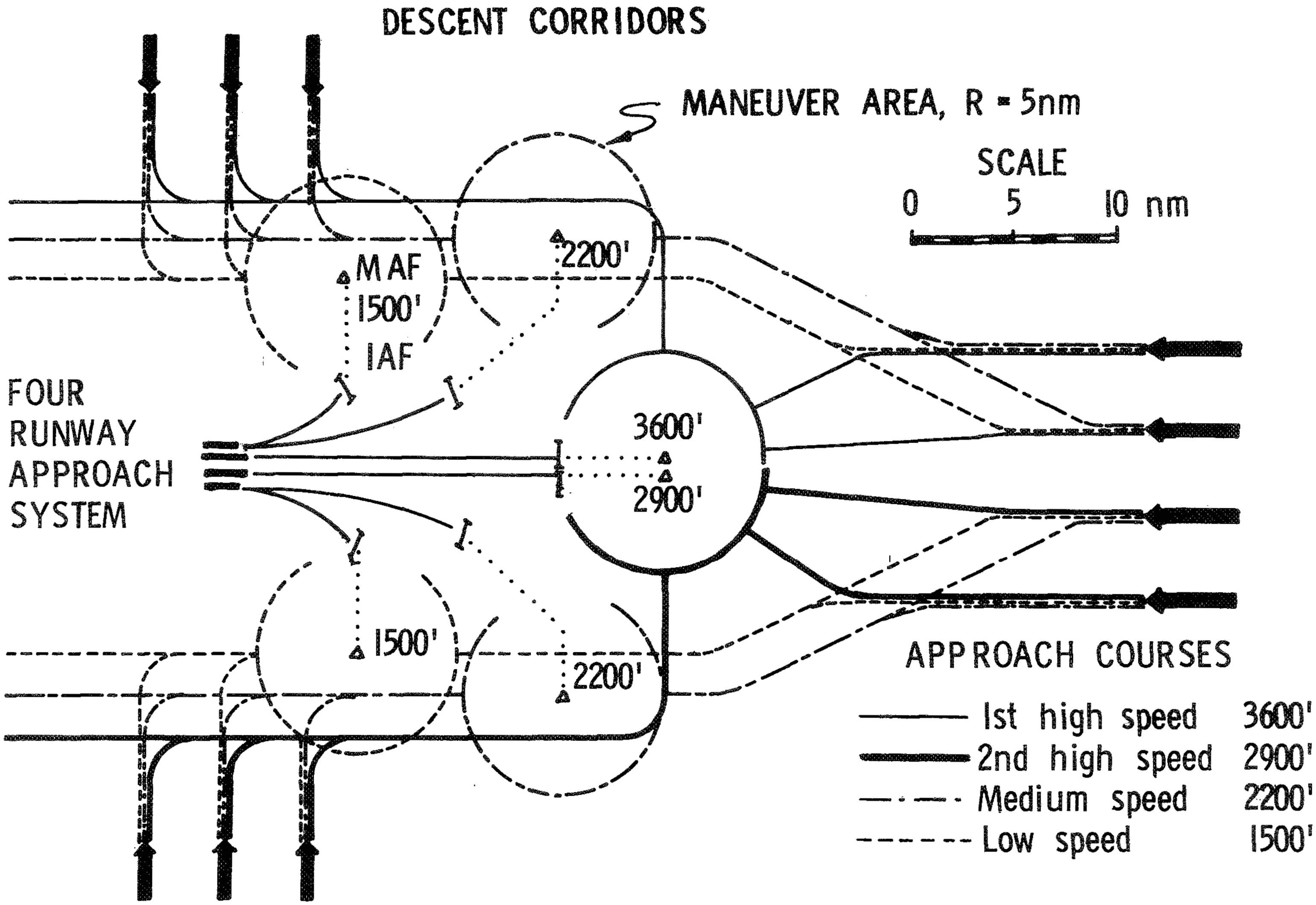


Figure 3.37: Multiple Runway Airport Airspace Configuration

present day fashion.[16] This change in procedure should not reduce efficiency or safety because the aircraft are speed segregated and should be able to land with the minimum allowable time separation.[17]

Multiple Airports

Two or more airports in close proximity in the terminal area greatly reduce the airspace available for speed segregated approach paths. No general path configuration can be specified because the best path structure depends on the particular airport arrangement. However, as more of the side-entering low and medium speed approaches must be eliminated, the closer the path structure approaches the current technology straight-in ILS approach course.

Figure 3.38 is a model of the New York City area approach path structure assuming additional runways at JFK, Lagurdia, and Newark airports. The figure shows how cramped the airspace can become.

Summary

The terminal area air traffic control system that has been presented extrapolates the present day ideas of computer aided final approach sequencing and airspace reservations to an entirely computer-managed system of close scheduling and optimal sequencing. The system is designed to maximize airport landing capacity and minimize inflight delays to aircraft. Capacity increases are the result of reduced time separation between arrivals made possible by optimal sequencing, close scheduling, and the abandonment of the three mile distance separation criteria in favor of a minimum collision avoidance separation. Implicit in the system's close scheduling capability is the more accurate delivery of

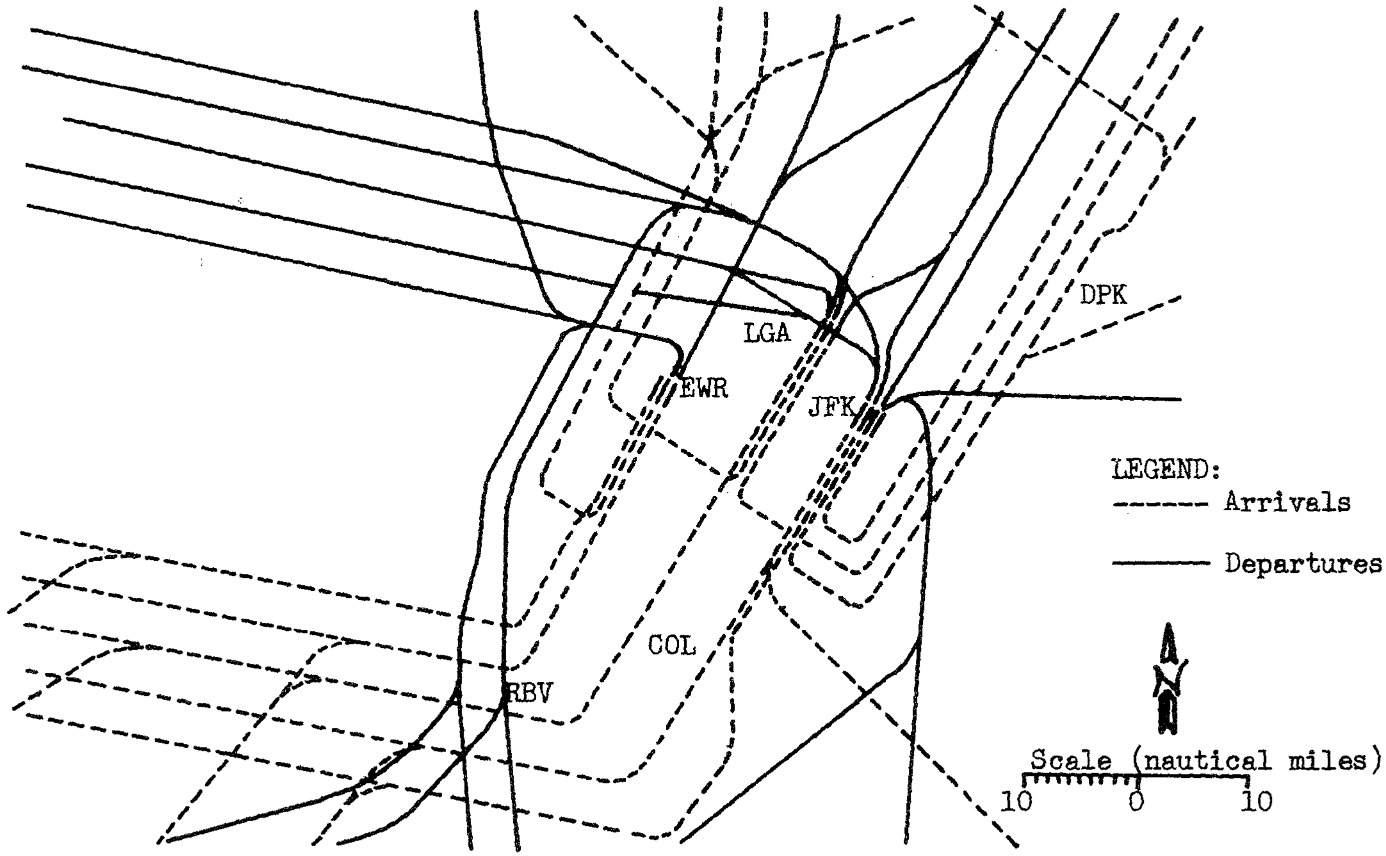


Figure 3.38:

Proposed New York City Airspace Structure to Accomodate Additional Runways at JFK, Newark, and LaGuardia aircraft to their final approach fixes insured by the support hardware forecast for the next three decades. Inflight delays are reduced in three ways. First, aircraft fly on descent/deceleration profiles which are tailored to the aircraft's performance and allow it to fly as fast to the airport as its schedule permits. Secondly, the approach paths are laid out to be direct to the airport as possible, which reduces flying time. And thirdly, optimum sequencing of arrivals insures minimum delay to all aircraft.

3.6 CONCLUSIONS

As a result of the investigation, the following conclusions were developed:

1. Air collision avoidance in a future terminal area may be accomplished through automated system management and improved air traffic control procedures. Collision alarm and maneuver recommendation systems revert into a backup role for positively controlled aircraft.

2. The runway configuration which provides the greatest capacity for future airport systems is parallel arrangements of dual runways.

3. An approach system employing the microwave ILS, curved paths and altitude separation appear to be the most desirable for accommodating anticipated air traffic up to the year 2000.

4. Controlled aircraft in a future terminal area must be equipped with a flight director for four dimensional vectoring in addition to present IFR equipment requirements.

5. With the MILS lateral separations may be modified to
   a. Less than one-half mile in flight
   b. 2500 feet between parallel runways

6. Minimum separation distances may be maintained along MILS flight paths for aircraft landing at a rate of 90 aircraft per hour.

7. The trilateration system is most desirable for handling aircraft in a high density terminal area as a primary system with the phased array radar used as a system backup.

8. The proposed terminal area system is capable of delivering aircraft at a rate of 90 aircraft per hour per runway with a ± 5 second delivery accuracy.

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CHAPTER IV

TERMINAL AREA SIMULATION

4.1 INTRODUCTION

In accordance with the systems approach to the terminal area study, a fast-time computer model was developed. The simulation provided an effective means of studying the present-day terminal area. This model should prove a useful tool for examining evolutionary and revolutionary changes in terminal area hardware and procedures.

The model was designed to be general enough to simulate the terminal area operations of any airport, regardless of size, location, or geometric constraints. This primary constraint required that the model possess a number of capabilities and characteristics. The model would have to be:

1. Flexible enough to simulate multiple runways, several approaches to each runway, and a holding queue for each approach.

2. Capable of generating random arrivals with inter-arrival times based on an expected number of arrivals by category per hour.

3. Capable of studying all types of aircraft with their individual approach and landing characteristics.

4. Capable of including effects of equipment improvements, wind and weather changes, and pilot and controller errors.

5. Flexible enough to simulate aircraft characteristics, demand levels, and terminal area procedures of the present as well as those proposed for the year 2000.

6. Capable of simulating both the interaction between two or more runways at one airport and the interaction between several airports in one metropolitan area.

Indeed, such a model represented an interesting and difficult challenge. Contained in the body of this chapter is a description of the model. This description includes the following sections:

1. Model development. The general philosophy and initial assumptions used with the model are presented.

2. A brief description of the programming methods. The GASP simulation language is discussed. Also the contents of the non-GASP subroutines are explained and their flexibilities are illustrated. Flow charts are included to provide the reader with the detail necessary for following the program logic.

3. Description and tabulation of model input data. The format of the necessary input data is presented for readers wishing to use the model for their own study.

4. Results and conclusions. Experiments performed using the various model options are summarized and the output is analyzed.

5. Possible extensions of the model. The model's versatility is demonstrated in the discussion of some feasible extensions.

4.2 DEVELOPMENT OF THE MODEL

In order to include the flexibilities and capabilities listed in the introduction, the model was necessarily general and abstract rather than a more detailed point-by-point simulation. A general simulation language, GASP, was employed for the study. GASP, which works on a discrete events philosophy, is described in Section 4.3. By using the discrete events rationale rather than a spatial approach, the events became abstract and easily moved within the system. This technique permitted the effect of critical parameters and individual characteristics of the system's performance to be separated and studied.

Research into various references (given at the end of the chapter) uncovered some previous simulations of the terminal area. These earlier models fell into two categories:

1. Real-time simulations.

2. Detailed fast-time simulations.

This work provided a background of ideas but was not ultimately adopted for this project. The first type of model was eliminated since both the equipment and time required to work in this area were not available. The second approach was also eliminated since it was felt that the necessary generality and flexibility were lacking.

Several assumptions were made before proceeding with the model:

1. Landings only would be considered. According to current air traffic control procedures, takeoff priority is secondary to landing priority.

2. Aircraft would be divided into the categories as presented in Chapter 2. Each classification represents aircraft with similar performance and landing characteristics. Present aircraft and those predicted for the year 2000 would be evaluated.

3. Arrivals would be random with a Poisson distribution. A different arrival rate, based on current and projected data for the Atlanta terminal, was assigned for each of ten hours per day (from 8 am to 6 pm); (see Section 4.4). The Atlanta terminal arrival data was chosen since it was readily available.

4. The model would have the capability of considering a maximum of two runways, each with three approach corridors. There would be an assigned holding or queueing area for each approach. The queues would constitute the arrival points into the system and aircraft would be segregated by performance categories among the queues. The queue location, in time to touchdown, would reflect optimum aircraft performance considerations. As an example, the queue for jet aircraft would be located further from touchdown and at a higher altitude than the queue assigned to general light aircraft.

5. The model would assume no interaction between airports (see Section 4.6).

6. All aircraft in the terminal area would be under positive control, thus assuring correction separation between aircraft at all times. By this assumption, the possibility of mid-air collisions was not considered and a collision

avoidance system was proposed as a backup only. The precision of the positive control assumed was representative of the year 2000. However, because the model dealt in discrete events rather than in spatial movement, this assumption was necessary to allow one aircraft to pass another on the approach in the terminal area.

7. Enroute air traffic control would not be considered in the model. It was assumed that enroute vectoring assured that the aircraft would arrive at the correct queue. In the case that the aircraft must be held in a queue, correct arrival altitude was also assumed. Inter-arrival times may be less than those which would actually occur in real operations. This reflects the effect of the abstract queues.

Using the previous assumptions, the model development progressed in three phases. Successive phases added more details and more adequately represented the true terminal system. Table 4.1 indicates the workload and factors considered for each phase.

The model included three nodes through which all aircraft must travel:

1. The queueing area, an abstract holding point for each approach, positioned only by aircraft flight time to the runway.

2. The merge point, the first point on the final glide path common to all approaches. This point is located at approximately the middle marker.

3. The touchdown point, a point over the runway where an aircraft is committed to land.

The queueing areas represent the first decision point encountered by an aircraft arriving into the terminal area system. If the aircraft was restricted from advancing directly to touchdown by one of the approach sequencing logics, then it was placed in a queue and held. This point was an abstraction in that it did not represent an actual physical location. In today's air traffic control procedures the queue would be representative of a holding stack. For future systems with tighter scheduling the queue could be located at the origin airport if desired.

At the logically designated time for an aircraft to leave a queue, a time error was generated and added to the scheduled time of the next depart-queue event (See Section 4.3, Subroutine DEPQUE). This error was used to simulate the time difference in scheduled and actual depart-queue events. Such error arose if, for example, at the time of the scheduled event, the aircraft's position was not readily accessible for leaving the queue. For the departing aircraft the future merge and touchdown times were calculated and stored. This information was used for sequencing of future arrivals in the approach and for scheduling the merge event occurrences.

The critical node was merge, since aircraft on all approaches to a runway had to be sequenced and spaced correctly at this point. The spacing at this node also had to account for proper separation at touchdown as well as runway rollout delays.

The effects of errors in the system such as aircraft location error, velocity and deceleration profile errors, wind and weather distractions, and pilot and controller errors were consolidated into one randomly-generated error and added to an aircrafts scheduled merge event. Where necessary, the approach aircraft and the successive aircraft were delayed in flight to assure proper separation. This error factor was difficult to predict. Greater accuracy would necessitate measurement of actual terminal operations.

The touchdown point is the final node. The model developed did not actually follow a plane past merge into touchdown. Since no passing was tolerated past the merge point, the aircraft was assured a safe landing at the designated touchdown time.

TABLE 4.1 PHASES OF MODEL DEVELOPMENT

Phase I	Phase II	Phase III
Single Airport	Single Airport	Multiple Airports
Single Runways	Two Independent Runways	Runway Interaction
Two Approaches	Multiple Approaches	Multiple Approaches
Two Queues	Three Queues	Multiple Queues
Present Aircraft Categories	Present Aircraft Categories	Future Aircraft Categories
Statistics	Improved Statistics	Improved Statistics
Landings Only	Wave-offs	Wave-offs
System Errors	System Errors	System Errors
FIFO Sequencing (first-in-first-out)	Three Sequencing Logics	Three Sequencing Logics
	Priority Entrances	Priority Entrances
	Basic Effects	Refined Effects
	Equipment	Equipment
	Procedures	Procedures
	Wind	Wind
	Weather	Weather
Present System	Present System	Year 2000
Three mile spacing	Closer Spacing	

The possibility of a waveoff was included in the model. Based on a fixed probability (0.01), the possibility of a waveoff was randomly allotted to an aircraft on final approach. Details of system errors and waveoffs are explained in Section 4.3, subroutine MERGE.

Figure 4.1 is a descriptive flow chart of the simulation program. This figure maps an aircraft's advancement from entrance to landing. A summary including flow charts of the respective subroutines follows in Section 4.3.

4.3 PROGRAM DESCRIPTION

This section provides a more comprehensive examination of the computer program model of the terminal area. The philosophy of employing the general simulation language, GASP, for this model is briefly presented.

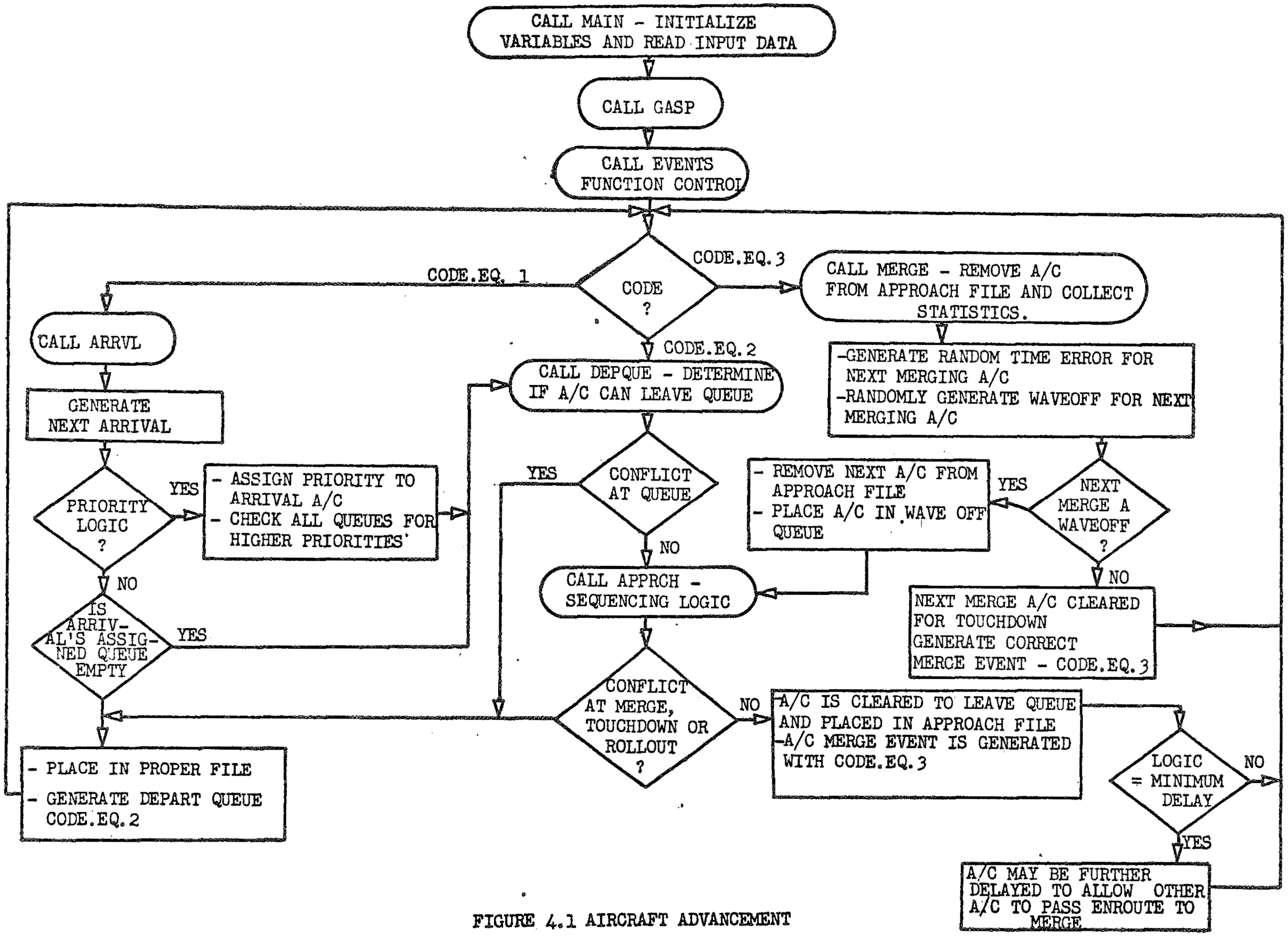


FIGURE 4.1 AIRCRAFT ADVANCEMENT

A computer listing of the GASP subroutines is provided in Appendix G; however, no attempt is made of describing the interworkings of these subroutines. For this information, the reader is referred to Pritaker, A. Alan B., "Simulation With GASP II," as listed in the bibliography.

Also included in this section is a summary and functional analysis of the non-GASP subroutines. The respective comments and flow charts should prove useful to the reader wishing to use the model or to perform similar simulations in other areas. To further assist the reader, a list of the non-GASP variables used in the program is provided in Appendix E. The non-GASP subroutines are listed in Appendix F.

Main Program

The MAIN simulation program reads the non-GASP data and initializes the non-GASP variables. The non-GASP data as well as the various codes and logics available with the program provide the flexibility necessary to make the model an effective working tool. MAIN also calls GASP to perform the executive and even-selection functions for the simulation. Figure 4.2 shows the flow chart for MAIN. The main program is listed under the name WWWW in Appendix F.

GASP Description

The GASP simulation language was utilized in this study to provide a conceptual and an operational framework in which to develop the simulation model of air-terminal operations. GASP provides an efficient means of attacking large scale system simulation and employs a philosophy quite adaptable to an air terminal operation model.

GASP is essentially a set of FORTRAN subroutines which may be manipulated to effect many types of simulations. The basic philosophy

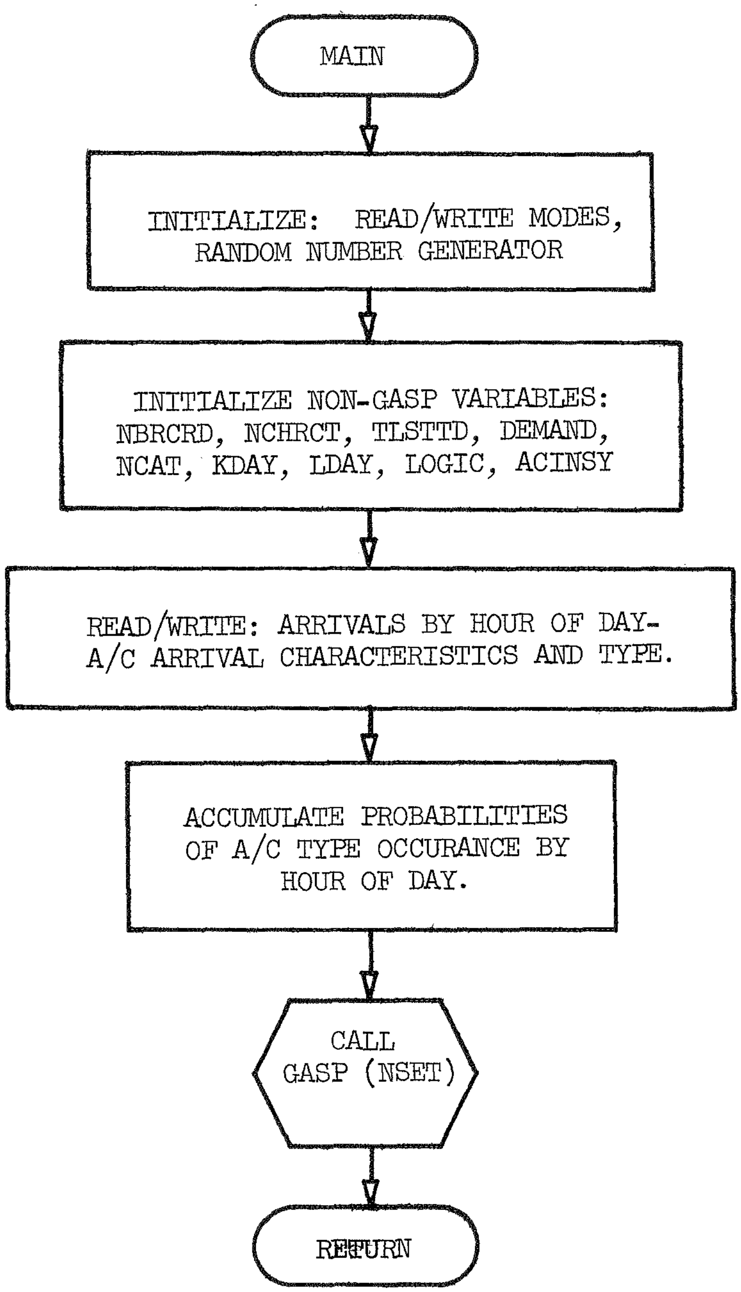


Figure 4.2: Main Program

employed is the discrete-events philosophy. An event is defined as an occurrence which changes the state of the system. To perform a simulation, only events must be processed. The system to be simulated must be decomposed into the pertinent events which may occur, and a separate non-GASP subroutine must be developed to process each event. GASP acts as the executive controller of the simulation, collect desired statistics, generates output reports, and provides efficient, dynamic storage of operating variables in an array called NSET.

Various items can be segregated in files which are stored dynamically within the NSET array. File one triggers the various events which may occur in the system. This study used files three and four to store various characteristics (termed attributes) of aircraft on approach to simulated runways one and two, respectively. Files five through ten were used to store attributes of aircraft in holding queues five through ten. File two was not used.

The coding schemes used for various events and files are given in Table 4.2. Attributes, or characteristics, of entries stored in the various files are delineated in Table 4.3.

Non-GASP Subroutines

One of the specific functional capabilities supplied by GASP is event control. Four events were identified in the model: aircraft arrival into the terminal system, departure from a queue, arrival at the merge point, and end of day. The changes in the state of the system due to an event occurrence were programmed into the respective non-GASP subroutines: ARRVL, DEPQUE, MERGE and EVNTS.

TABLE 4.2 CODING SCHEMES USED IN GASP

Event Codes	File Numbers	Description	Codes
2		Arrivals to approach (Codes 1-4 not used for approaches)	5 6 7 8 9 10
	5 6 7 8 9 10	A/C in que, for approach (Codes 1-4 not used for queues)	5 6 7 8 9 10
5 IQ+ 6 7 8 9 10		Depart queue, check event, for queue	5 6 7 8 9 10
3 IG≠ 4		Merge at runway	1 2
13		End of day event	
	3 4	A/C between queue and merge point	
	1	Event file	
	2	Not used	

+IQ is used as a code describing queue number for an A/C
≠IG is used as a code describing merge point for an A/C

TABLE 4.3 GASP FILE STRUCTURE

FILE 1--Events File
Ranking in file: lowest time, ATRIB (1), first

ATRIB (1)	(ATRIB (2)	
(Time of occurence)	(Event code)	
	2	Arrival to system (queue point)
	3	Merge at runway 1
	4	Merge at runway 2
	5	Check and depart from queue 5+
	6	6
	7	7
	8	8
	9	9
	10	10
	13	End of day event

FILE 2--Not used

FILE 3, 4--A/C on flight path from queue to merge point at runway 1, 2.
Ranking in file: last merge time, ATRIB (3), first

ATRIB (1)	ATRIB (2)	ATRIB (3)	ATRIB (4)	ATRIB (5)	ATRIB (6)	ATRIB (7)
Time of arrival into	A/C category (1-7)	Arrival time at merge point	Arrival time at touchdown point	Delay on flight path only	Approach path code (5-10)	Cummulative delay on flight path and in holding stack

FILES 5-10--Queues or holding stacks (6 possible)
Ranking in file: earliest arrival time, ATRIB (1), first

ATRIB (1)	ATRIB (2)	ATRIB (3)	ATRIB (4)	ATRIB (5)	ATRIB (6)	ATRIB (7)
Time of arrival into system	A/C category (1-7)	Duration to merge point	Duration to touchdown point	Future time when A/C will be ready to leave queue	Queue number code (5-10)	Not used

+ Queues and approaches 5, 6, and 7 feed runway 1
Queues and approached 8, 9, 10 feed runway 2

Subroutine EVNTS

The end of day event is performed by subroutine EVNTS. The event-selection control is also provided by this subroutine. At each scheduled event time stored in the vent file, GASP calls subroutine EVNTS which then directs the simulation to the respective non-GASP subroutines based on the code IX. The code IX is stored as ATRIB (2) in the event file and passed to subroutine EVNTS as an argument. Figure 4.3 shows a flow chart of subroutine EVNTS.

Subroutine EVNTS is called at the end of each simulated day to allow all aircraft in the system to land and to reject all new arrivals. At the end of each simulation run, the non-GASP variables and random numbers are initialized to begin the next run. At this time subroutine EVNTS triggers the output reports on the statistics collected by GASP. Before the next run, the logic code options are specified.

Subroutine ARRVL

Whenever a scheduled event occurs with an arrival code, subroutine ARRVL is called by EVNTS. This subroutine employs an exponential distribution to generate the next arrival time. The distribution is a function of the hour of day. The next arrival time is then stored in the event file. A random number from a random rectangular distribution is used in a Monte Carlo technique to assign a category to a new arrival. This technique uses a cumulative probability distribution generated from the number of arrivals by category per hour of day. On the basis of the aircraft's category, the queuing area and approach corridor are then assigned and initial arrival statistics are collected. The difference between the one and two runway simulations lies in the queue assignment made for Categories I and II. The approach corridor is governed by the queue delegation.

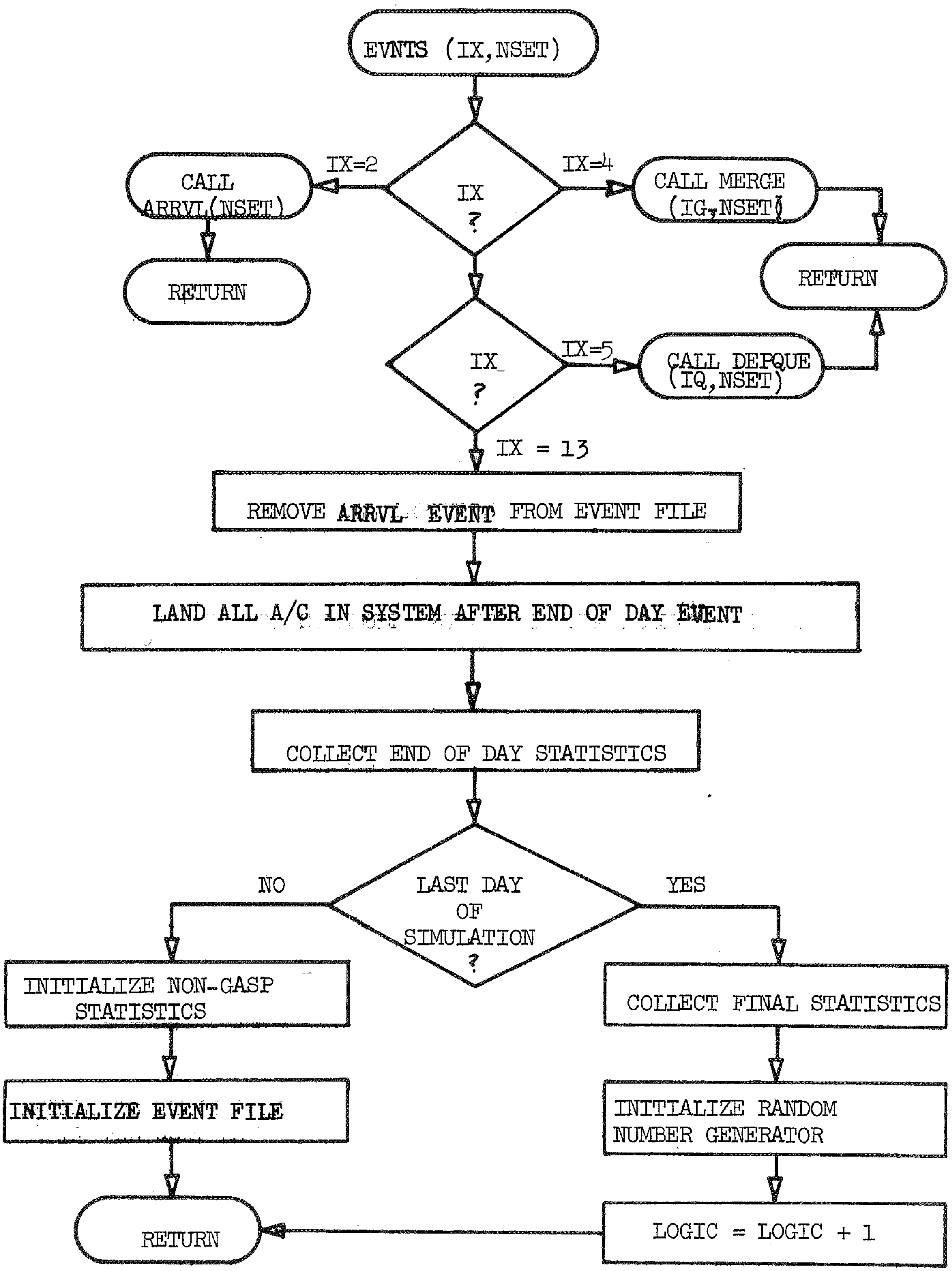


Figure 4.3: Subroutine EVNTS

If a previous arrival is already holding in the chosen queue, the current arrival is placed at the top of that queue. If no previous aircraft is holding, subroutine DEPQUE is called to determine when the arrival can leave the queue. For the more sophisticated priority entrance logic, subroutine ARRVL calls DEPQUE to determine the arrival's exit queue time. Figure 4.4 shows a flow chart of subroutine ARRVL.

Subroutine DEPQUE

Subroutine DEPQUE (see Figure 4.5 for flow chart) is called to determine if an arriving aircraft or an aircraft in queue can be allowed to proceed toward merge and touchdown. It is called from EVNTS subroutine whenever a depart-queue-check event is to occur or from the ARRVL subroutine whenever an aircraft enters the system and the designated queue is empty. Subroutine DEPQUE performs the function of placing the aircraft in the proper approach file if it is allowed to leave the queue or holding the airtraft for the necessary time if it is not allowed to proceed.

The DEPQUE subroutine selects which aircraft is to be checked for release. An aircraft may be selected because it has just arrived into the system, because it is the next in line to leave the queue, or because it has the highest priority based on accrued delay and aircraft category. It is the user's option to choose the algorithm he rerfers, and this is accomplished by setting the input variable priority LFLAG, equal to zero or one (for priority release LEFAG equals one). The sequencing of this aircraft is then investigated. If the last aircraft from the queue in question is not far from the queue (in flight time), the aircraft to be sequenced is held. If the last aircraft is the

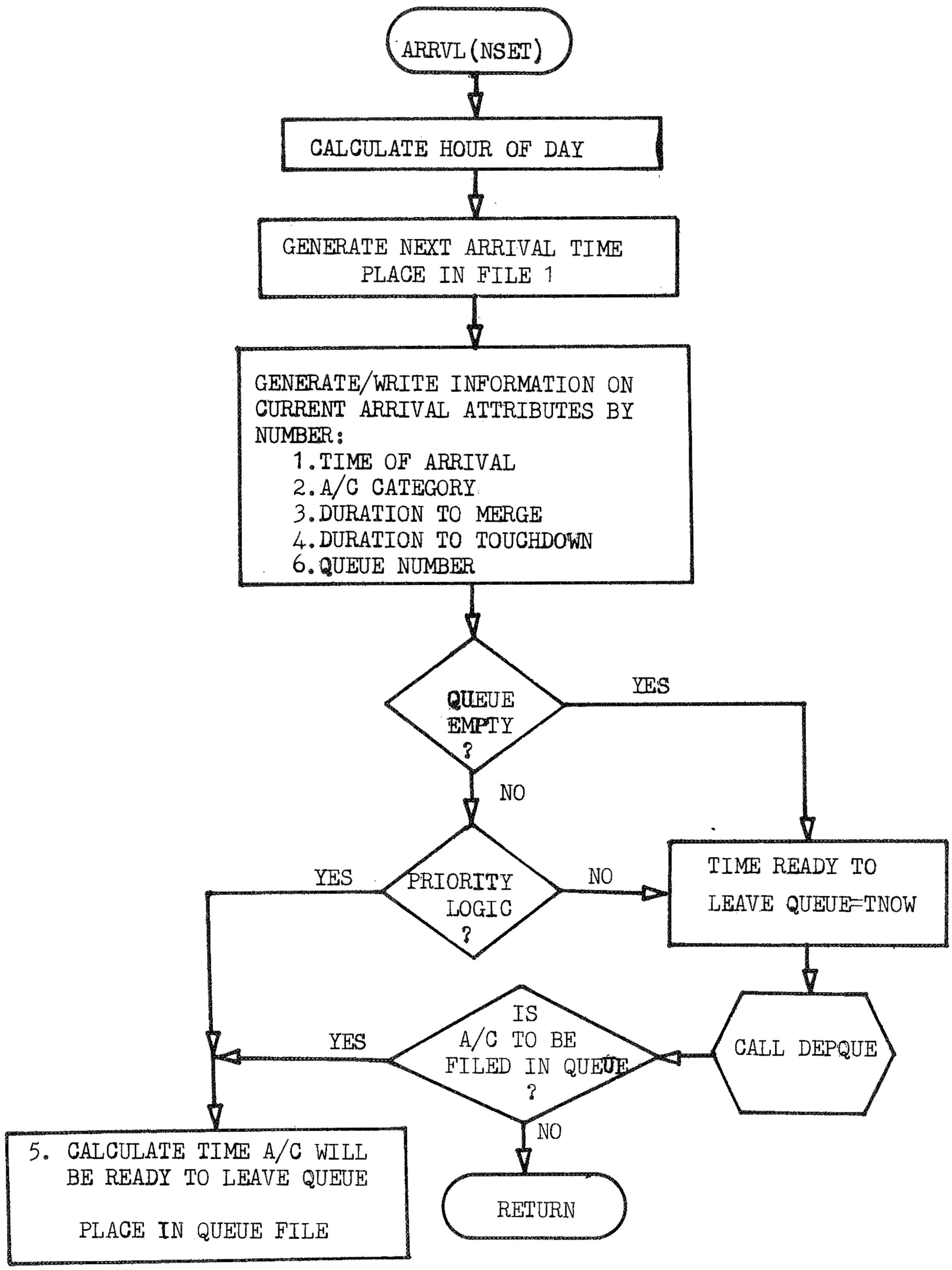


Figure 4.4: Subroutine ARRVL

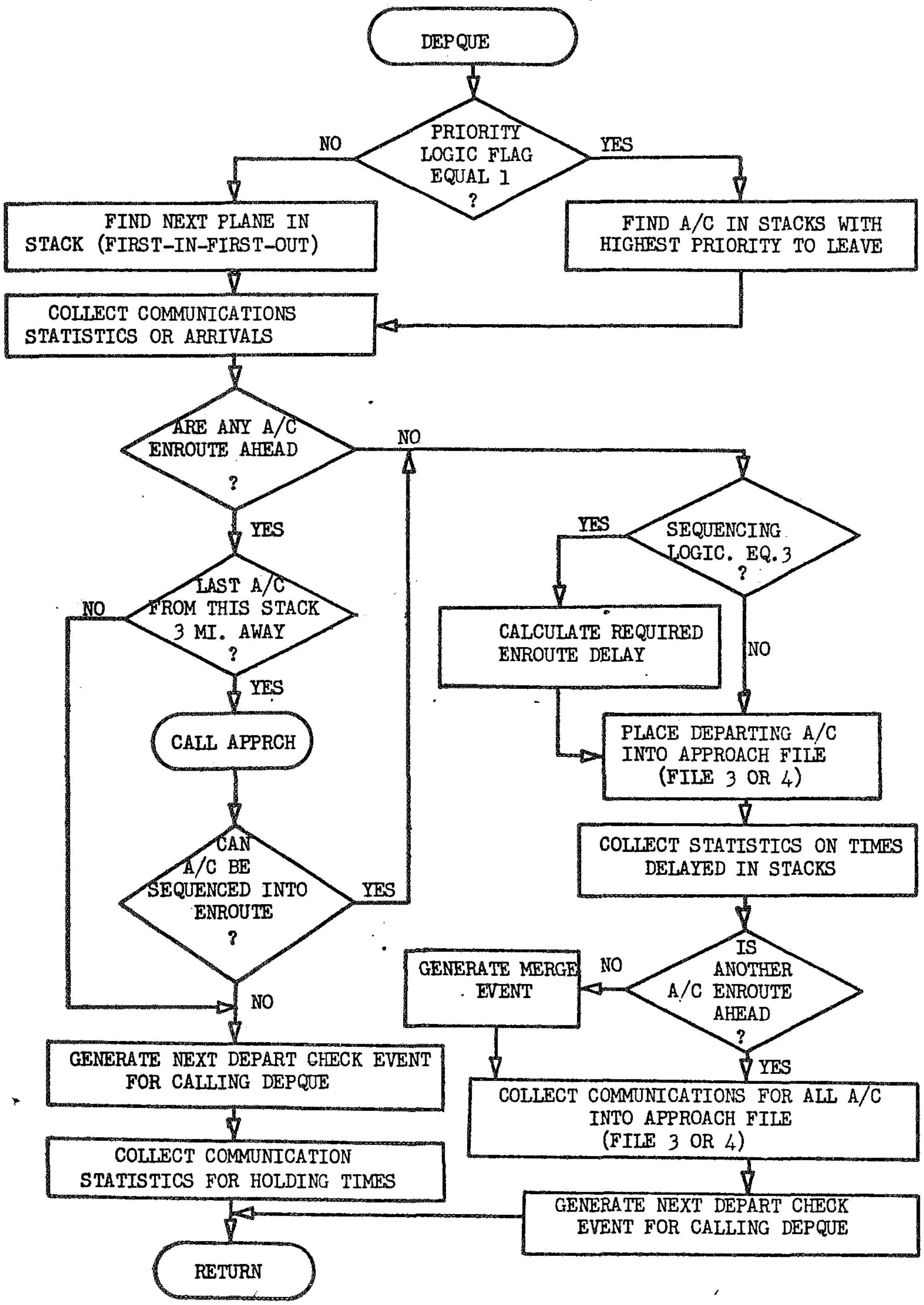


FIGURE 4.5 SUBROUTINE DEPQUE

required time away from this queue, the APPRCH subroutine is called to determine if the aircraft in question may proceed (see section on subroutine APPRCH). If a conflict occurs at a future node, the aircraft is held in the queue. If it can proceed, the aircraft is removed from the queue and placed in the approach file. Whenever an aircraft is held or released, the next departing event check time is generated and stored in the event file so as to provide for the next entry into the subroutine DEPQUE.

The priority selection routine for determining which aircraft should be released from the holding areas is based upon the calculated priority of each aircraft. This routine is chosen if the input LFLAG is set equal to unity. The aircraft priority is the sum of the accrued delay of each aircraft, the aircraft-type category, and the number of aircraft in the particular queue in question. Each of these three values is multiplied by an input constant (XK1, XK2, XK3) which may be varied by the user to affect different priority schemes. Priorities for all aircraft in queue as well as the arriving aircraft are computed by DEPQUE. The priority of a newly arrived aircraft is determined by its aircraft-type category multiplied by a fourth input multiplier (XK4), the value of which is also chosen by the user. It is these priority values which are compared to determining which aircraft will be allowed to leave the queues next. Through the use of the four multipliers (XK1, XK2, XK3, XK4), the user can therefore vary the relative weighting given to aircraft delay and different aircraft categories.

In the real-world situation, the aircraft in the queues are not exactly in the proper position to leave when the controller clears them from the holding area. This effect is simulated in DEPQUE by generating two random errors (ERRLV and ERRHD) which are added to the present simulated time (TNOW) to generate the next depart-queue check event. For example, if the aircraft presently being investigated by DEPQUE is released, the depart-check event for the next potential aircraft to leave would be at TNOW plus ERRLV. However, if the present aircraft cannot be sequenced into approach and is held, the next depart-queue check event for that aircraft would be TNOW plus ERRHD plus the expected additional holding time (HOLDTM). The ERRLV values are drawn from a distribution with a larger mean than that of ERRHD. This will provide time for other aircraft in the queue to descent to a lower altitude after an aircraft departs from that queue.

Subroutine APPRCH

Subroutine APPRCH is called from subroutines MERGE and DEPQUE. The function performed by APPRCH is to properly sequence aircraft enroute to the merge point. This sequencing is accomplished at three levels of sophistication depending on the LOGIC code. APPRCH is called from MERGE in the case of a waveoff. The waveoff aircraft circles and waits to be resequenced to the merge node. APPRCH is called from DEPQUE when a depart-queue-check takes place. Figure 4.6 shows a flow chart for subroutine APPRCH.

LOGIC Levels for Subroutine APPRCH

There are three levels of logic available to the model user. The difference between the logic levels represents the amount of aircraft handling and interaction allowed after leaving the holding area. Figures 4.7 a, b and c show the flow charting for the respective logic codes.

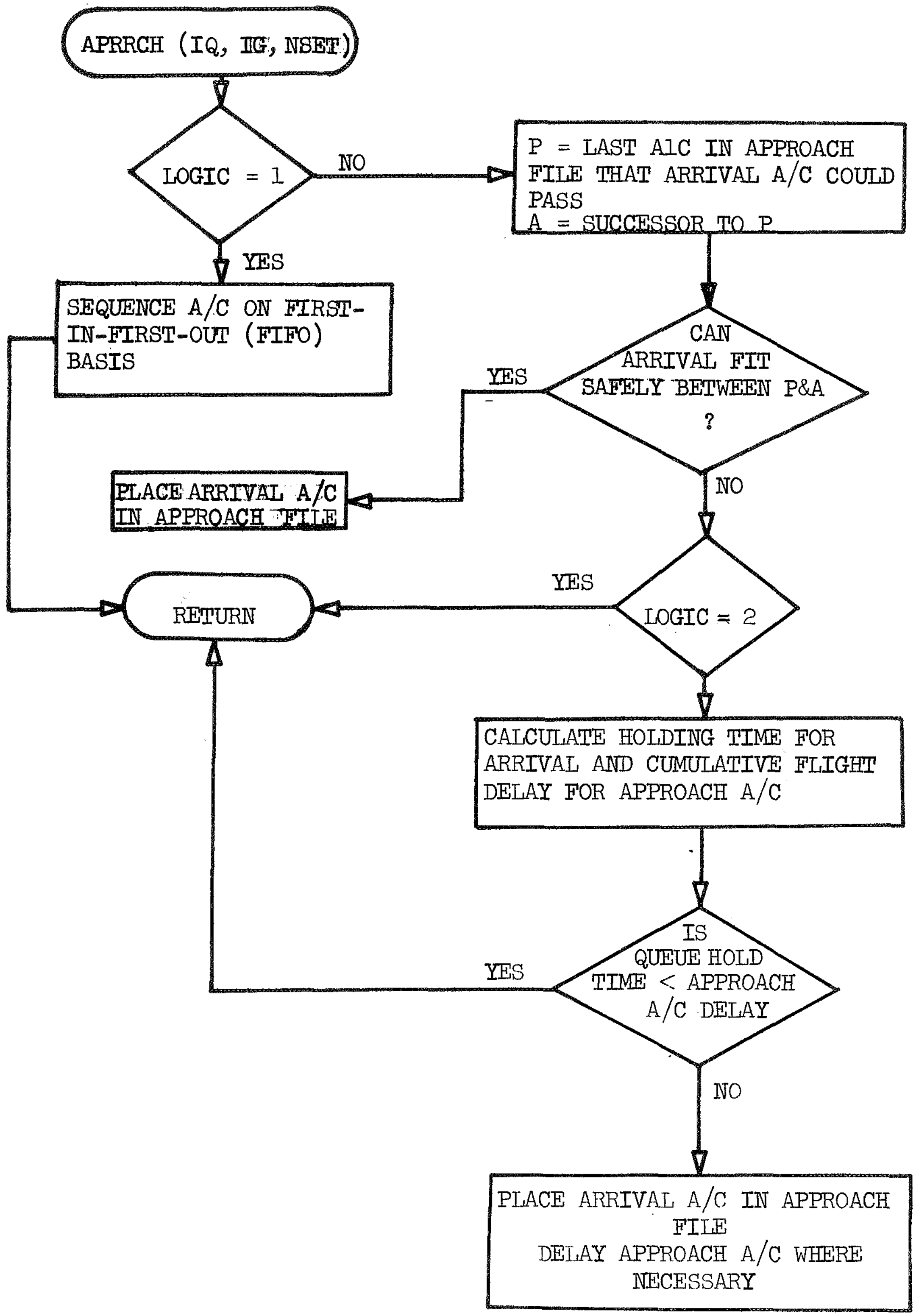


Figure 4.6: Subroutine APPRCH

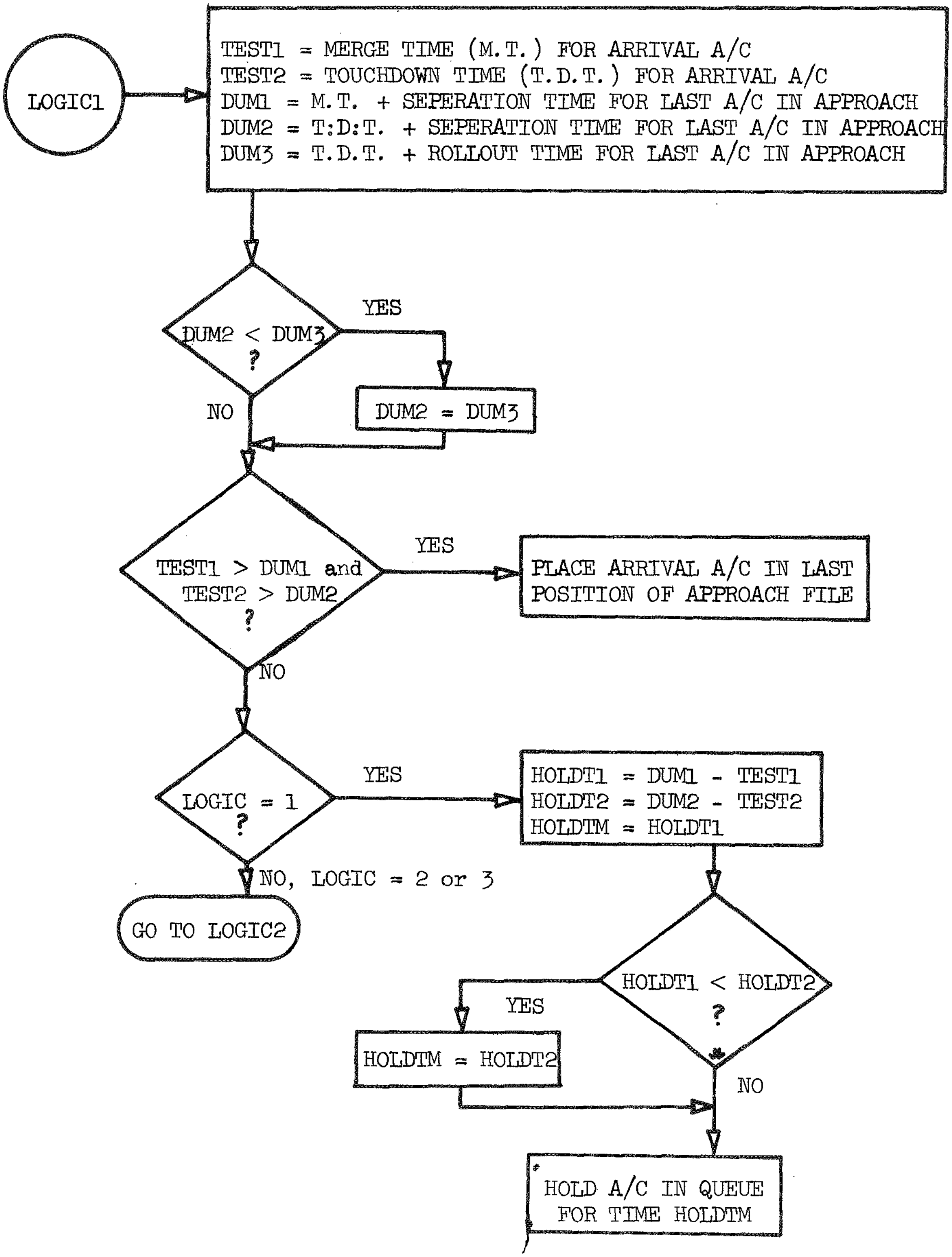


Figure 4.7a: Logic code 1

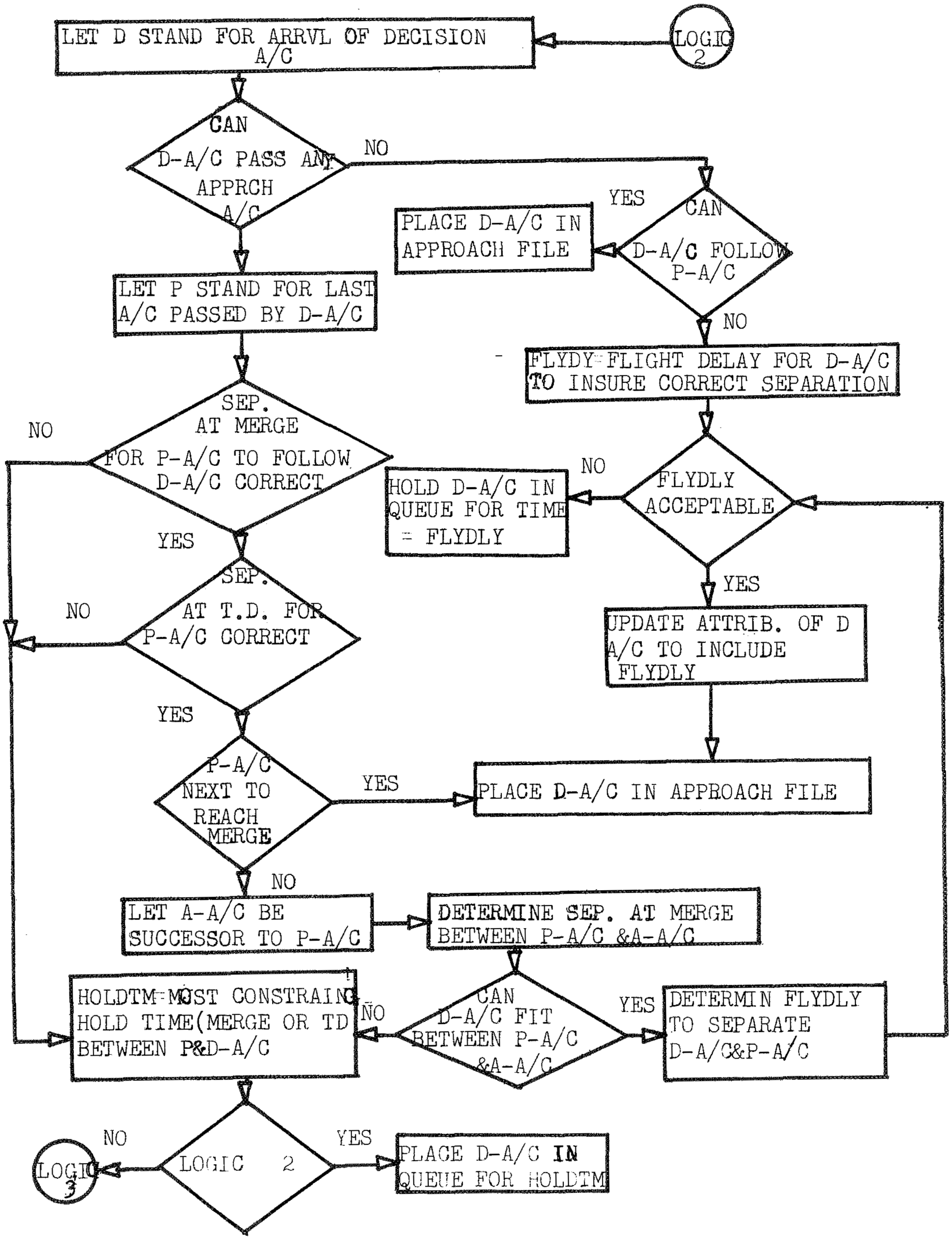


Figure 4.7b: Logic code 2

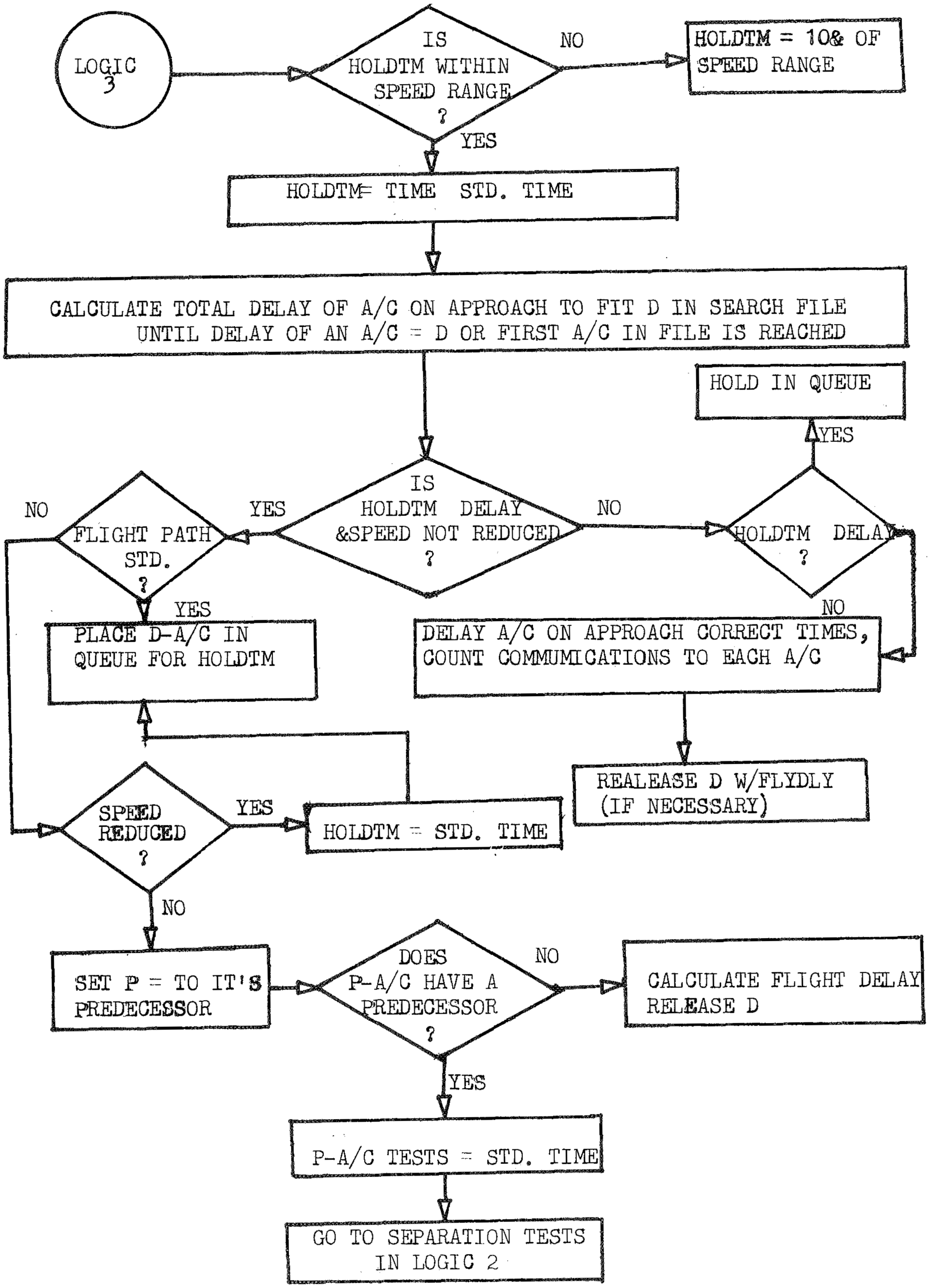


Figure 4.7c: Logic code 3

Logic code 1, which is the first and simplest logic level, is first-in-first-out (FIFO) sequencing. This logic permits an aircraft to proceed only if it can safely follow the aircraft which will arrive at the merge node last. That is, no aircraft can pass another in the entire system regardless of the queue from which it entered.

Logic code 2, the next level of sophistication, allows faster aircraft to pass slower aircraft already in the approach phase. This accounts for the differences in queue-to-merge times for the different categories and holding queue locations. This algorithm searches the approach file for any aircraft which the aircraft in question can pass before its tentative merge time. If the decision aircraft is unable to pass anyone, the program checks to see if it can fit behind the final aircraft in the approach file. If it can pass slower aircraft, the algorithm checks for proper separation at merge, touchdown and runway rollout between the aircraft in question and the last possible aircraft it can pass. If the minimum separation constraint (chosen by the model user) is satisfied, then separation behind the first aircraft which the decision aircraft cannot pass is checked. If separation can again be assured, the aircraft is allowed to proceed on its determined flight path. If interference is detected on either of the checks and separation cannot be guaranteed, the decision aircraft is held in queue for a calculated hold time (HOLDTM).

Logic code 3, the highest level, uses a minimum flight path for the decision aircraft. It then calls logic code 2 to determine if any interference will occur with aircraft passed on approach. However, the aircraft whose sequence is in question can arrive at merge before another already on approach, but separation is less that the minimum specified, it is permitted to leave queue if it fulfills the established criterion. The criterion used for logic code 3 is that the flight delay which all aircraft on approach need encounter to be passed with proper separation at merge be less than the holding delay incurred by the aircraft in question. If the criterion is not satisfied, a hold time is calculated and the logic attempts to sequence the plane into the system at a later point in time. If the calculated hold time is greated than the category's speed range, the decision aircraft is held in queue for the designated time. Logic 3 represents the greatest work load on the controller and pilot.

Subroutine MERGE

When an aircraft reaches the merge point, subroutine MERGE is called. If another aircraft is in flight (this corresponds to additional entries in the approach file after removal of the merging aircraft) a random time adjustment is generated and added to the next scheduled merge. This random adjustment is used to represent equipment, weather effect, controller, pilot, and velocity profile error encountered on approach. Whenever the next merge is delayed, proper separation for all aircraft in the approach file is checked and adjustments made as necessary. The random merge error is a function of aircraft category. This reflects the differences in flight geometries and performance characteristics of the different aircraft types.

This subroutine also considers the possibility of a waveoff. In the case of a waveoff, the next merging aircraft is removed from the approach file and a time, which is also a function of aircraft category, is added to ATRIB (3) and ATRIB (4) to simulate circling. Subroutine APPRCH is then called to determine proper resequencing. The waveoff aircraft is then relocated in the approach file to account for the change in its scheduled merge event. The delay encountered in the wave-off queue represents a penalty the aircraft must pay for missed approach.

Since no passing is allowed beyond the merge point, the merging aircraft is removed from the simulation and its final statistics are collected at this time. Before returning control to GASP, the MERGE subroutine generates the next merge event based on the attributes stored in the approach file. Figure 4.8 shows a flow chart for MERGE.

4.4 MODEL INPUT DATA

Model input data included pertinent aircraft characteristics, arrival rate statistical parameters and system error statistical parameters. This input was grouped according to aircraft performance categories. For 1970 data (Table 4.4a), the aircraft were separated into seven categories and for 2000 data (Table 4.4b), the projected air traffic mix was segregated into six categories. For a complete description of the present and future aircraft categories, see Chapter II. The input used in the model is listed as follows:

1. Arrival rates for each aircraft category.
2. Times required to fly the aircraft separation distances.
3. Times required to fly the approach paths.
4. Times to clear the runway after touchdown.
5. Error distributions.

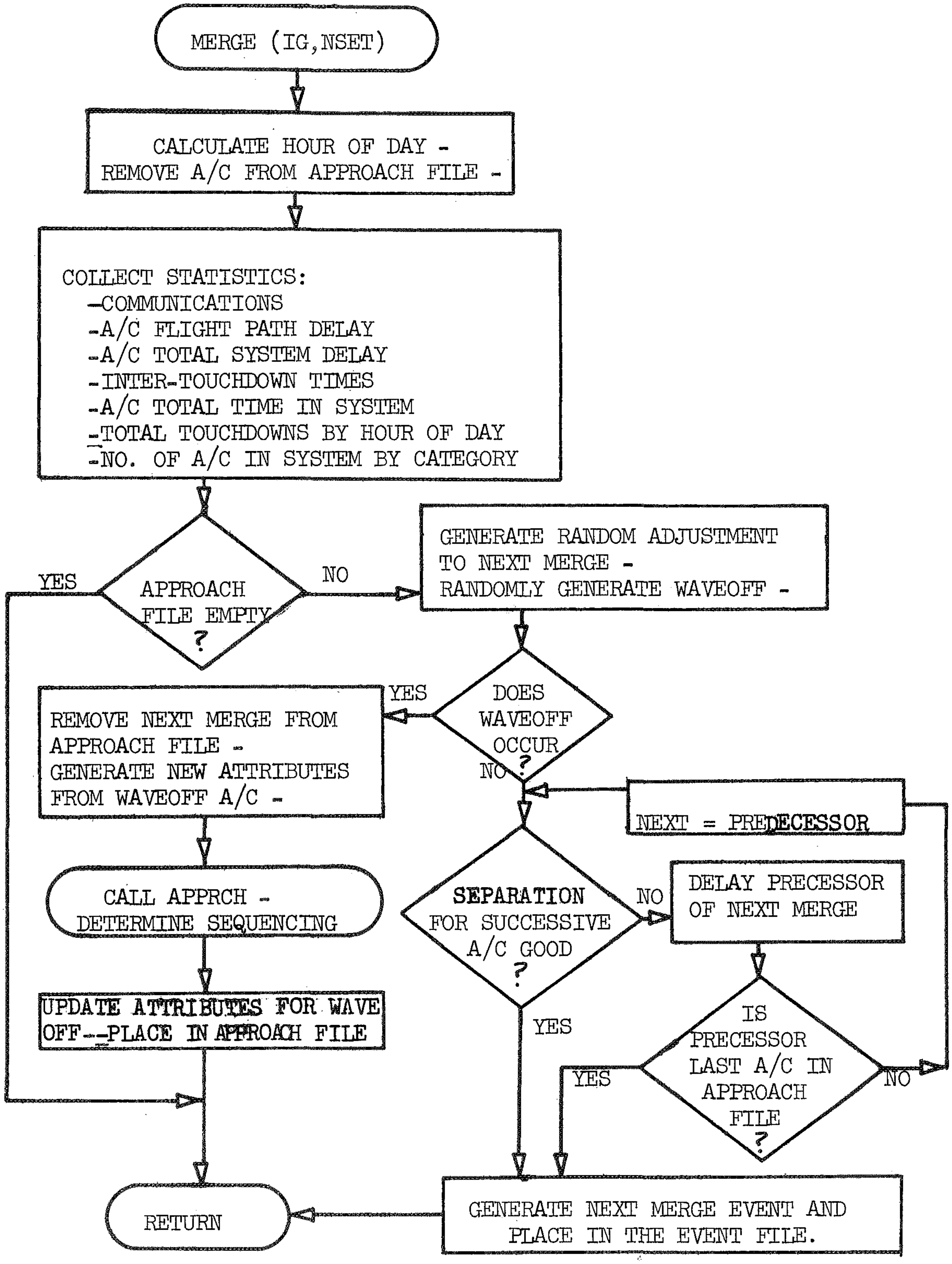


Figure 4.8: Subroutine MERGE

TABLE 4.4a AIRCRAFT PERFORMANCE DATA, 1970

AIRCRAFT CATEGORY	TRAN-SISTION SPEED	TIME TO FLY X-MILES (MIN.)		APPROACH SPEED (KTS.)	TIME TO FLY X-MILES (MIN.)		FINAL SPEED (KTS.)	TIME TO FLY X-MILES (MIN.)		RUNWAY ROLLOUT TIME (MIN.)
		X=1.5	X=3.0		X=1.5	X=3.0		X=1.5	X=3.0	
1	140	0.56	1.12	95	0.83	1.65	80	0.98	1.95	0.50
2	150	0.52	1.04	120	0.65	1.31	105	0.75	1.49	0.45
3	156	0.50	1.00	135	0.58	1.16	115	0.68	1.36	0.50
4	175	0.45	0.89	150	0.52	1.04	130	0.60	1.20	0.48
5	200	0.39	0.78	170	0.46	0.92	150	0.52	1.04	0.57
6	205	0.38	0.76	180	0.44	0.87	155	0.50	1.01	0.61
7	215	0.36	0.73	185	0.43	0.85	165	0.48	0.95	0.66

TABLE 4.4b PROJECTED AIRCRAFT PERFORMANCE DATA, 2000

AIRCRAFT CATEGORY	TRAN-SISTION SPEED	TIME TO FLY X-MILES (MIN.) X=1.5	X=3.0	APPROACH SPEED (KTS.)	TIME TO FLY X-MILES (MIN.) X=1.5	X=3.0	FINAL SPEED (KTS.)	TIME TO FLY X-MILES (MIN.) X=1.5	X=3.0	RUNWAY ROLLOUT TIME (MIN.)
1	105	0.87	1.74	0.85	1.06	2.12	75	1.22	2.44	0.45
2	140	0.64	1.28	115	0.78	1.56	100	0.90	1.80	0.45
3	165	0.55	1.10	135	0.67	1.33	117	0.77	1.54	0.50
4	170	0.53	1.06	140	0.64	1.28	121	0.74	1.48	0.61
5	165	0.55	1.10	135	0.67	1.33	117	0.77	1.54	0.50
6	201	0.45	0.90	165	0.55	1.10	143	0.63	1.36	0.66

Arrival Rates

Arrival rates per hour for each aircraft category for 10 hours per day were required to generate a realistic random number of aircraft entering the system. The present hourly arrival rates were generated using available data from the Atlanta area. This data was also extended to obtain approximate arrival rates for the future. The program divides the total number of hourly arrivals into arrivals in that hour for each category. These average arrival rates are given in Table 4.5a (1970) and 4.5b (2000), and stored in the array RATE.

Times to Fly the Aircraft Separation Distances

Separation times were needed to maintain the spacing required between each aircraft in the system. These times were checked when each aircraft arrived at the three nodes in the model. If aircraft maintained the required separation at these three nodes, the model assumed correct separation along the entire approach path. The nodes are described in Section 4.2.

Separation times at the respective nodes were calculated for both 3 and 1.5 nautical mile separation. An internally generated array, DTLVQ, was used to assure proper separation at the queue. DTLVQ stored the first available time for an aircraft to leave the respective queues. This time was calculated in the last depart-queue event by storing the time required for the last aircraft leaving that queue to fly the designated separation. The separation times at queue for the different categories, shown in Table 4.6, were stored in row 8 of a storage array called PLANE having dimension 20 x 7. The seven columns correspond to the aircraft categories, while the rows are used for the different parameters.

FIGURE 4.5a: ARRIVALS/HOUR, 1970

SEQUENCE HOUR	1	2	3	4	5	6	7	8	9	10
HOUR OF DAY	8:00 9:00	9:00 10:00	10:00 11:00	11:00 12:00	12:00 1:00	1:00 2:00	2:00 3:00	3:00 4:00	4:00 5:00	5:00 6:00
Category 1	5	7	3	6	2	1	2	3	4	7
Category 2	0	0	0	0	0	0	0	0	0	0
Category 3	1	1	1	1	0	1	1	1	1	1
Category 4	8	15	12	10	2	8	11	8	7	15
Category 5	17	32	24	22	5	17	24	18	14	32
Category 6	0	0	0	0	0	0	0	0	0	0
Category 7	0	0	0	0	0	0	0	0	0	0

FIGURE 4.5b: ARRIVALS/HOUR, 2000

SEQUENCE HOUR	1	2	3	4	5	6	7	8	9	10
HOUR OF DAY	8:00 9:00	9:00 10:00	10:00 11:00	11:00 12:00	12:00 1:00	1:00 2:00	2:00 3:00	3:00 4:00	4:00 5:00	5:00 6:00
Category 1	33	33	33	33	28	28	28	28	33	33
Category 2	13	17	8	15	5	5	5	7	10	17
Category 3	17	16	16	16	14	11	14	14	16	16
Category 4	8	3	3	3	3	3	3	3	3	3
Category 5	16	12	12	12	11	10	10	11	12	12
Category 6	3	3	3	3	3	2	2	3	3	3

TABLE 4.6 TIMES TO FLY SEPARATION AT QUEUE*

	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5	CATEGORY 6	CATEGORY 7
				1970 DATA			
3 N.M. SEP.	1.12	1.04	1.00	0.89	0.78	0.76	0.73
1.5 N.M. SEP.	0.56	0.52	0.50	0.45	0.39	0.38	0.36
				2000 DATA			
3 N.M. SEP.	1.74	1.28	1.10	1.06	1.10	0.90	---
1.5 N.M. SEP.	0.87	0.64	0.55	0.53	0.55	0.45	---

* ALL TIMES ARE IN MINUTES

For the remaining two nodes, separation times were based on one aircraft following the previous aircraft at the respective nodes. Tables 4.7a and c give 1970 separation time data and Tables 4.7b and d give 2000 separation time data. This information is stored by category in rows 1 - 7 and 12 - 18 of the PLANE array for the touchdown and merge nodes, respectively. The seven rows used for each node allow data to correspond to aircraft category of the leading and following aircraft in case the user wished to provide different separation distances in each case.

Times to Fly the Approach Paths

Times for each aircraft to fly from node to node along the approach path were obtained using velocity and deceleration profiles (see Tables 4.4a and 4.4b). The times for each aircraft category to fly from the

TABLE 4.7a SEPARATION TIMES FOR AIRCRAFT AT MERGE, 1970*

3 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6	CAT.7
CAT.1	1.65	1.65	1.65	1.65	1.65	1.65	1.65
CAT.2	1.31	1.31	1.31	1.31	1.31	1.31	1.31
CAT.3	1.16	1.16	1.16	1.16	1.16	1.16	1.16
CAT.4	1.04	1.04	1.04	1.04	1.04	1.04	1.04
CAT.5	0.92	0.92	0.92	0.92	0.92	0.92	0.92
CAT.6	0.87	0.87	0.87	0.87	0.87	0.87	0.87
CAT.7	0.85	0.85	0.85	0.85	0.85	0.85	0.85

1.5 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6	CAT.7
CAT.1	0.82	0.82	0.82	0.82	0.82	0.82	0.82
CAT.2	0.66	0.66	0.66	0.66	0.66	0.66	0.66
CAT.3	0.58	0.58	0.58	0.58	0.58	0.58	0.58
CAT.4	0.52	0.52	0.52	0.52	0.52	0.52	0.52
CAT.5	0.46	0.46	0.46	0.46	0.46	0.46	0.46
CAT.6	0.44	0.44	0.44	0.44	0.44	0.44	0.44
CAT.7	0.43	0.43	0.43	0.43	0.43	0.43	0.43

*ALL TIMES ARE IN MINUTES

TABLE 4.7b SEPARATION TIMES FOR AIRCRAFT AT MERGE, 2000*

3 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6
CAT.1	2.12	2.12	2.12	2.12	2.12	2.12
CAT.2	1.56	1.56	1.56	1.56	1.56	1.56
CAT.3	1.33	1.33	1.33	1.33	1.33	1.33
CAT.4	1.28	1.28	1.28	1.28	1.28	1.28
CAT.5	1.33	1.33	1.33	1.33	1.33	1.33
CAT.6	1.10	1.10	1.10	1.10	1.10	1.10

1.5 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6
CAT.1	1.06	1.06	1.06	1.06	1.06	1.06
CAT.2	0.78	0.78	0.78	0.78	0.78	0.78
CAT.3	0.67	0.67	0.67	0.67	0.67	0.67
CAT.4	0.64	0.64	0.64	0.64	0.64	0.64
CAT.5	0.67	0.67	0.67	0.67	0.67	0.67
CAT.6	0.55	0.55	0.55	0.55	0.55	0.55

*ALL TIMES ARE IN MINUTES

TABLE 4.7c SEPARATION TIMES FOR AIRCRAFT AT TOUCHDOWN, 1970*

3 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6	CAT.7
CAT.1	1.95	1.95	1.95	1.95	1.95	1.95	1.95
CAT.2	1.49	1.49	1.49	1.49	1.49	1.49	1.49
CAT.3	1.36	1.36	1.36	1.36	1.36	1.36	1.36
CAT.4	1.20	1.20	1.20	1.20	1.20	1.20	1.20
CAT.5	1.04	1.04	1.04	1.04	1.04	1.04	1.04
CAT.6	1.01	1.01	1.01	1.01	1.01	1.01	1.01
CAT.7	0.95	0.95	0.95	0.95	0.95	0.95	0.95

1.5 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6	CAT.7
CAT.1	0.98	0.98	0.98	0.98	0.98	0.98	0.98
CAT.2	0.75	0.75	0.75	0.75	0.75	0.75	0.75
CAT.3	0.68	0.68	0.68	0.68	0.68	0.68	0.68
CAT.4	0.60	0.60	0.60	0.60	0.60	0.60	0.60
CAT.5	0.52	0.52	0.52	0.52	0.52	0.52	0.52
CAT.6	0.50	0.50	0.50	0.50	0.50	0.50	0.50
CAT.7	0.48	0.48	0.48	0.48	0.48	0.48	0.48

*ALL TIMES ARE IN MINUTES

TABLE 4.7d SEPARATION TIMES FOR AIRCRAFT AT TOUCHDOWN, 2000*

3 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6
CAT.1	2.44	2.44	2.44	2.44	2.44	2.44
CAT.2	1.80	1.80	1.80	1.80	1.80	1.80
CAT.3	1.54	1.54	1.54	1.54	1.54	1.54
CAT.4	1.48	1.48	1.48	1.48	1.48	1.48
CAT.5	1.54	1.54	1.54	1.54	1.54	1.54
CAT.6	1.26	1.26	1.26	1.26	1.26	1.26

1.5 NAUTICAL MILES SEPARATION

PLANE BEHIND \ PLANE AHEAD	CAT.1	CAT.2	CAT.3	CAT.4	CAT.5	CAT.6
CAT.1	1.22	1.22	1.22	1.22	1.22	1.22
CAT.2	0.90	0.90	0.90	0.90	0.90	0.90
CAT.3	0.77	0.77	0.77	0.77	0.77	0.77
CAT.4	0.74	0.74	0.74	0.74	0.74	0.74
CAT.5	0.77	0.77	0.77	0.77	0.77	0.77
CAT.6	0.63	0.63	0.63	0.63	0.63	0.63

*ALL TIMES ARE IN MINUTES

queue to the merge point is stored in the PLANE array, row 9, while the time to fly from the merge point to touchdown point is stored in row 10 of the PLANE array.

Times to Clear the Runway After Touchdown

The rollout time required for an aircraft to leave the runway after touchdown is given in the last column of Tables 4.4a and b. These times were stored in row 11 of the PLANE array with the columns corresponding to aircraft category.

Waveoffs, or missed approaches, which occur with a probability of 1%, were also generated when a aircraft reached a merge node. The times required for an aircraft to circle and be in position for resequencing after a wave-off are given in Table 4.8. This information in the program is stored by category in row 19 of the PLANE array.

TABLE 4.8 WAVE OFF GO-ROUND TIMES

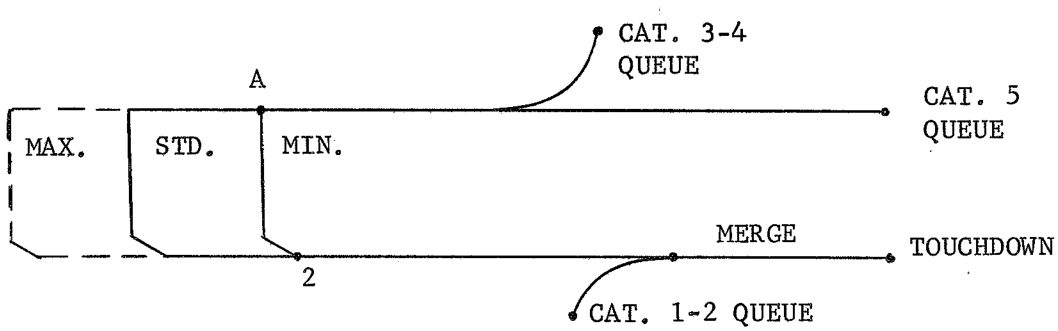
	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5	CATEGORY 6	CATEGORY 7
TIME (MIN.)	3.70	3.30	11.70	10.50	9.20	8.80	8.50

Configuration one (accompanying Table 4.9) of the model represented a present day single runway system. This configuration was used for determining the times between nodes for the aircraft categories. The configuration consisted of three queues (for Jet Aircraft (Cat V-VII), Large Propeller and Small Jet Aircraft (Cat III and IV), General Aviation and VFR Aircraft (Cat I and II)); a merge node where all traffic join on a common final apprach path; and a touchdown node, 2

TABLE 4.9 FLIGHT TIMES FOR SINGLE RUNWAY GEOMETRY, 1970*

CATEGORY	TMIN	TMN	TMD	TDMIN	TDN	TN
1	--	2.40	1.50	--	3.90	--
2	--	2.30	1.14	--	3.44	--
3	9.68	10.73	1.04	11.21	10.17	5.34
4	8.69	9.12	0.92	9.61	10.04	4.80
5	18.14	18.53	0.80	18.94	19.33	4.22

*ALL TIMES ARE IN MINUTES



SINGLE RUNWAY GEOMETRY

TMIN = MINIMUM TIME TO FLY FROM QUEUE TO MERGE
TNM = STANDARD TIME TO FLY FROM QUEUE TO MERGE
TMD = TIME TO FLY FROM MERGE TO TOUCHDOWN
TDN = STANDARD TIME TO FLY FROM QUEUE TO TOUCHDOWN
TDMIN = MINIMUM TIME TO FLY FROM QUEUE TO TOUCHDOWN
TN = STANDARD TIME TO FLY FROM A TO 2

nautical miles from the merge node. Aircraft could be routed along a minimum, nominal, or maximum approach path to eliminate time errors or to allow passing on the approach.

Configuration two (accompanying Table 4.10) of the model considered independent dual runways using present and future air traffic arrival rates. The configuration is similar to configuration one for Category III - VII aircraft. Category I and II aircraft are routed to a second runway independent of Category III - VII aircraft approach paths.

Error Distributions

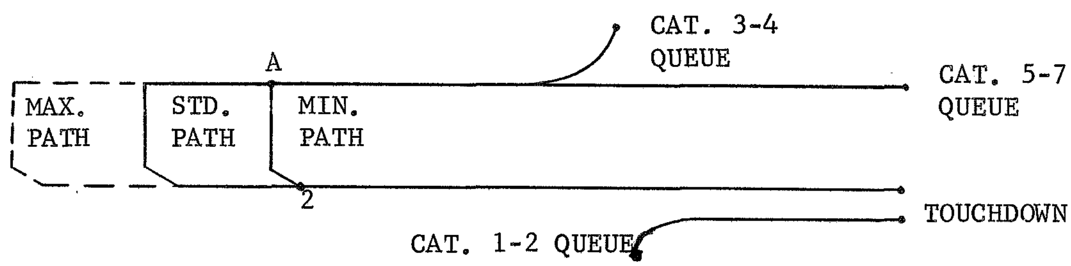
When an aircraft arrives at the merge point a random system error time is generated for the next aircraft to arrive at merge. This error represents the pilot, controller, and tracking error on delivery at the merge point. These error times are drawn from statistical distributions for which the mean, minimum value, maximum value, and standard deviation must be input and loaded into the PARAM array, rows 1 - 7. Table 4.11 lists the values used for the merge-time errors for the seven aircraft categories for year 1970 data. For the purpose of the test cases run, these times were somewhat arbitrary.

Another system error time was included to represent the effect of non-optimum aircraft position within the holding pattern at the time of release from the queue. If the aircraft next to leave the queue is released, a random leave-time is generated from distributions with the statistics given in Table 4.11. (The absolute value of this random number is taken so the leave time is always greater than zero.) When this aircraft leave the queue, another leave-time error is generated for the next aircraft to leave this queue. These leave-time errors

TABLE 4.10 FLIGHT TIMES FOR INDEPENDENT DUAL RUNWAY GEOMETRY

CATEGORY	TMIN	TMN	TMD	TDMIN	TDN	TN
			1970 DATA			
1	--	2.40	1.50	--	3.90	--
2	--	2.30	1.14	--	3.44	--
3	9.68	10.73	1.04	11.21	10.17	5.34
4	8.69	9.12	0.92	9.61	10.04	4.80
5	18.14	18.53	0.80	18.94	19.33	4.22
6	17.54	17.91	0.77	18.32	18.68	4.02
7	16.82	17.17	0.73	17.54	17.90	3.90
			2000 DATA			
1	--	2.15	1.41	--	3.56	--
2	--	2.90	1.04	--	3.94	--
3	9.24	9.69	1.02	10.26	10.72	4.98
4	21.45	21.94	0.99	21.47	22.93	5.09
5	9.24	9.69	1.02	10.26	10.72	4.98
6	18.23	18.61	0.84	19.06	19.46	4.32

ALL TIMES ARE IN MINUTES



DUAL RUNWAY GEOMETRY

TMIN = MINIMUM TIME TO FLY FROM QUEUE TO MERGE
TNM = STANDARD TIME TO FLY FROM QUEUE TO MERGE
TMD = TIME TO FLY FROM MERGE TO TOUCHDOWN
TDMIN = MINIMUM TIME TO FLY FROM QUEUE TO TOUCHDOWN
TDN = STANDARD TIME TO FLY FROM QUEUE TO TOUCHDOWN
TN = STANDARD TIME TO FLY FROM A TO 2

are generated from Gaussian distributions with the statistics shown in Table 4.12 which are also input into the PARAM array, rows 8 - 14. These values have a non-zero mean since this aircraft must descend in the queue.

TABLE 4.11 MERGE-TIME ERROR STATISTICS*

A/C Category	Mean	Min. Value	Max. Value	Std. Dev.
CAT I	0.0	-0.80	0.80	0.36
CAT II	0.0	-0.70	0.70	0.35
CAT III	0.0	-0.50	0.50	0.20
CAT IV	0.0	-0.50	0.50	0.18
CAT V	0.0	-0.45	0.45	0.15
CAT VI	0.0	-0.40	0.40	0.15
CAT VII	0.0	-0.40	0.40	0.15

* ALL TIMES IN MINUTES

TABLE 4.12 QUEUE LEAVE-TIME ERROR STATISTICS*

A/C Category	Mean	Min. Value	Max. Value	Std. Dev.
CAT I	2.0	0.5	3.5	0.5
CAT II	1.3	0.5	2.8	0.5
CAT III	1.2	0.5	2.7	0.5
CAT IV	1.1	0.5	2.6	0.5
CAT V	1.0	0.5	2.5	0.5
CAT VI	1.0	0.5	2.5	0.5
CAT VII	1.0	0.5	2.5	0.5

* ALL TIMES IN MINUTES

4.5 RESULTS AND CONCLUSIONS

Although time did not permit the evaluation of all the possible program options, some test cases were completed, and the results are presented in this section as an example of the program output. Table 4.13 summarizes the cases that were run.

TABLE 4.13: TEST CASES RUN

Sequence Logic*	One Runway		Two Runways **
	3 mi. sep.	1.5 mi. sep	3 mi. sep.
1	CASE 1	CASE 4	CASE 7
2	CASE 2	CASE 5	CASE 8
3	CASE 3	CASE 6	CASE 9

* Logic Code: 1 -- No passing of aircraft
2 -- Passing with approach flight delay to departing aircraft.
3 -- Passing with approach flight delay to departing or passed aircraft, whichever is less.

**No interaction assumed.

It is believed that the five sequencing logics (logics 1, 2, 3 and priority sequencing with logics 2 and 3) work properly. However, preliminary tests using the priority release logic indicated that system performance was very poor because excessive delays in the queues were incurred. The highest priority aircraft often incurred large delays which held all other aircraft in the queues with no chance to be released.

The cases in Table 4.13 use year 1970 aircraft characteristics and Atlanta data. Year 2000 aircraft data is presented in the Section 4.4 and could be loaded into the program directly. It is noted that since the Atlanta traffic demand data was used (this data representing a two-runway system), the delays for the one-runway three mile separation cases are excessive. However, the relative performance of the sequencing logics and other variables can still be compared.

Program Results

Table 4.14 presents the hourly mean arrival rates used as input for all the cases, along with the actual average arrival rates obtained for the ten days simulated. These arrivals are Poisson distributed

TABLE 4.14 HOURLY MEAN ARRIVAL RATES FOR ALL AIRCRAFT

	Hour of Day									
	1	2	3	4	5	6	7	8	9	10
Theoretical Average Arrivals	31	55	40	39	10	27	38	30	26	55
Actual Average Arrivals	29.9	55,8	40.3	38.5	13.5	23.6	37.7	27.1	28.3	56.3

resulting in an exponentially distributed inter-arrival-time. Shown in Table 4.15 is the average number of arrivals per day by aircraft category obtained from the simulation. This aircraft category mix is also representative of the Atlanta traffic of the 1970's.

TABLE 4.15 AVERAGE DAILY ARRIVALS BY AIRCRAFT CATEGORY

	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5	CAT 6	CAT 7	Total
Average Daily Arrivals	40.6		10.4	98.5	201.5	0	0	351

The computer program made multiple simulation runs for a given input condition. Each sequencing logic was simulated over a ten-hour-per-day, ten day period. The flexibility of the program is represented by the fact that only 14 data cards need be changed to simulate 1.5 mile separation instead of 3 mile separation, and only 2 cards need be changed to land aircraft categories 1 and 2 on the second runway. The computer program including the GASP simulation language, used 34K computer storage locations and a typical multiple run took 80 seconds on a CDC 6600 computer. (Approximately 10 seconds for compilation and 2 seconds for each day simulated.) This compact size permits many extensions to be added to the basic model.

All random number generators were initialized to the same reference values for each run. Therefore, each run had to accommodate random arrivals, category assignment, waveoffs, and errors, but all runs saw the same demand and sequence of arrivals. This permitted a direct comparison of the sequencing logics since each saw the same demand.

The types of system measurements collected for each run and the code foreach are outlined in Table 4.16. The statistics presented in this section are based on 10 day runs. Further work is needed to determine if longer simulation periods would yield improved statistics, more closely coverging to population parameters. Only the more significant results are presented.

Figure 4.9 compares the total delays for 3510 aircraft over 10 days incurred for each case. Table 4.17 summarizes these results, showing the best logic under each condition (BL), and the best condition for each logic (BC). Case 6 (1 runway, 1.5 mile separation, logic 3) resulted in the lowest total delay. As shown in Figure 4.10 (1 runway, 1.5 mile separation, logic 2) resulted in the lowest number of communications, a measure of the relative work loads on the pilots and ATC personnel. This case also yielded the second best delay.

Figure 4.11 shows the maximum number of aircraft in each queue and on approach for each case. It is noted that the maximum number of

TABLE 4.16 SYSTEM MEASUREMENTS

COLCT Generated Data		HISTØ Histograms		TMST Time Generated Data	
Code	Description	Code	Description	Code	Description
1 2 3 4 5 6	Total Delay at Queue-- 5 6 7 8 9 10	1	Number of arrivals by hour of day, 1-11 Number of touchdowns by hour of day 12-22	1 2 3 4 5 6 7	Number of A/C in system by A/C category 1 2 3 4 5 6 7
7 8 9 10 11 12	Total Delay along approach path-- 5 6 7 8 9 10	2	Number of communications by hour of day (1-11), by A/C category (12-22), by location Arrival to system 23 Hold or Depart que 24 Update Depart level time 25 Descend in que Logic 3 approach delay 27 Clear for TD at merge 28 Delay on approach 29 Waveoff 30	8 9 10 11 12 13	Number of A/C in 5 6 7 8 9 10
13 14 15 16 17 18 19	Total Delay for A/C category--	3	Runway vacancy times		
20	Inter-touchdown time	5	Runway vacancy times (runway no.2)		
29	Total A/C time in system	4 6 7 8 9 10	Total delay by A/C category 1 3 4 5 6 7		
30	Total daily number of arrivals				

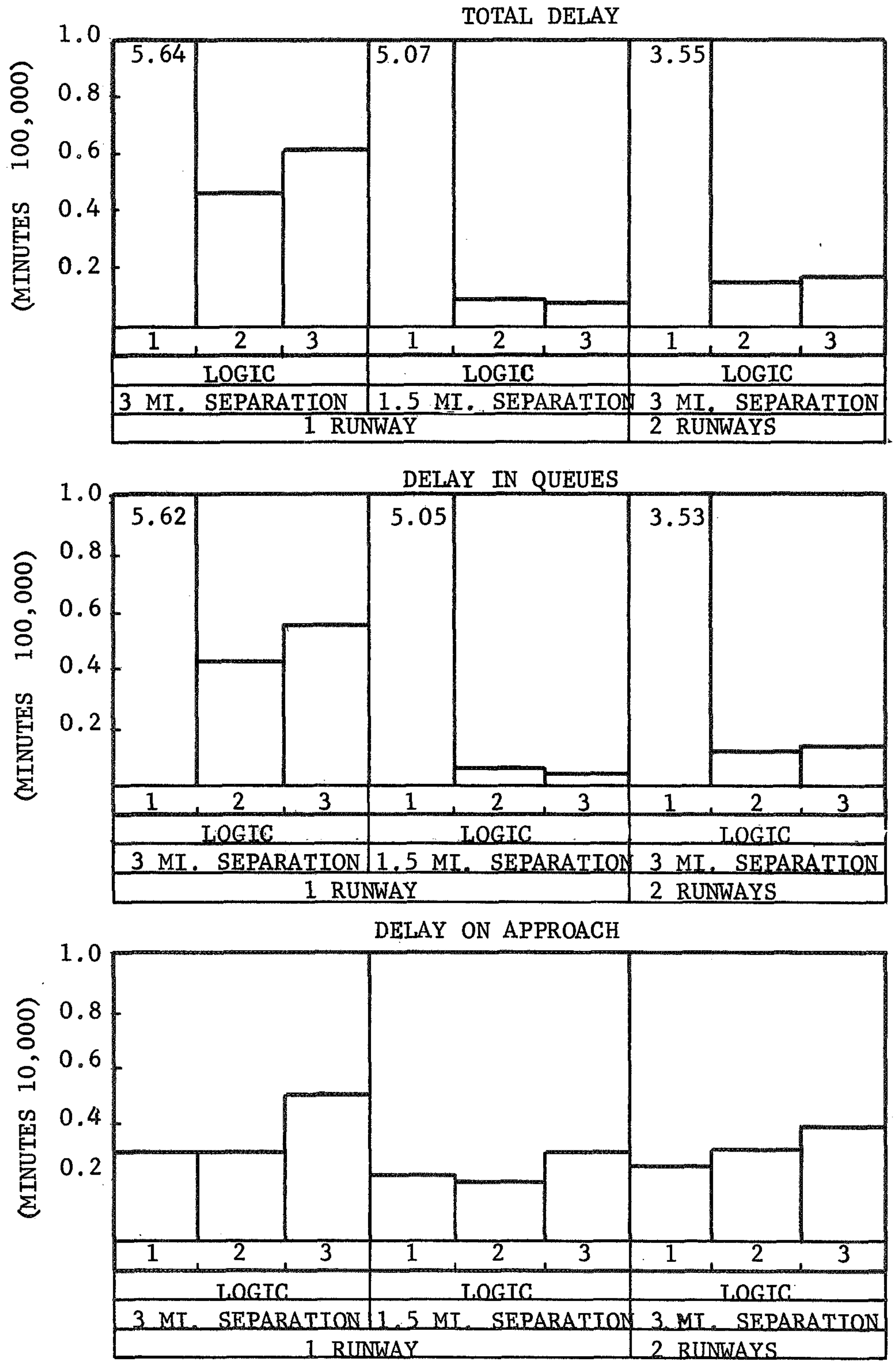


Figure 4.9 COMPARISON OF DELAY TIMES FOR 10 DAYS, 3510 A/C

Table 4.17: Comparison of Delays Incurred by Sequencing Logics Under Various Conditions

CONDITION	LOGIC			LOWEST NO. COMMUNICATIONS
	L1	L2	L3	
One Runway				
3 mile separation		BL		
1.5 mile separation		BC	+BL/BC	L2 lowest
Two Runways				
3 mile separation	BC	BL		

\+ Logic 3 using one runway with 1.5 mile separation appears to be the best combination tested.

++ Logic 2 using one runway with 1.5 mile separation appears to be the second best combination tested

BC = Best condition under a given logic based on total minutes of delay

BL = Best logic under a given condition based on total minutes of delay

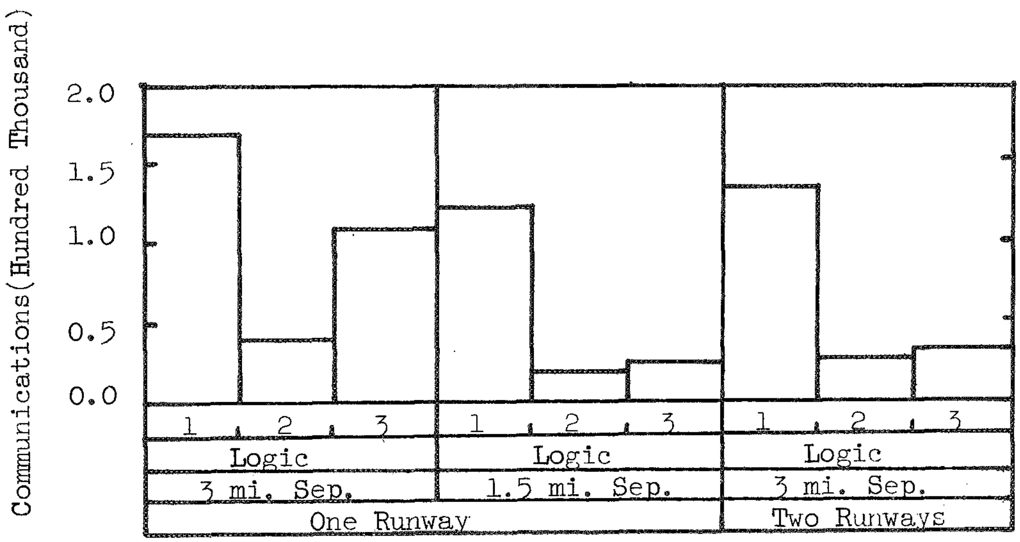
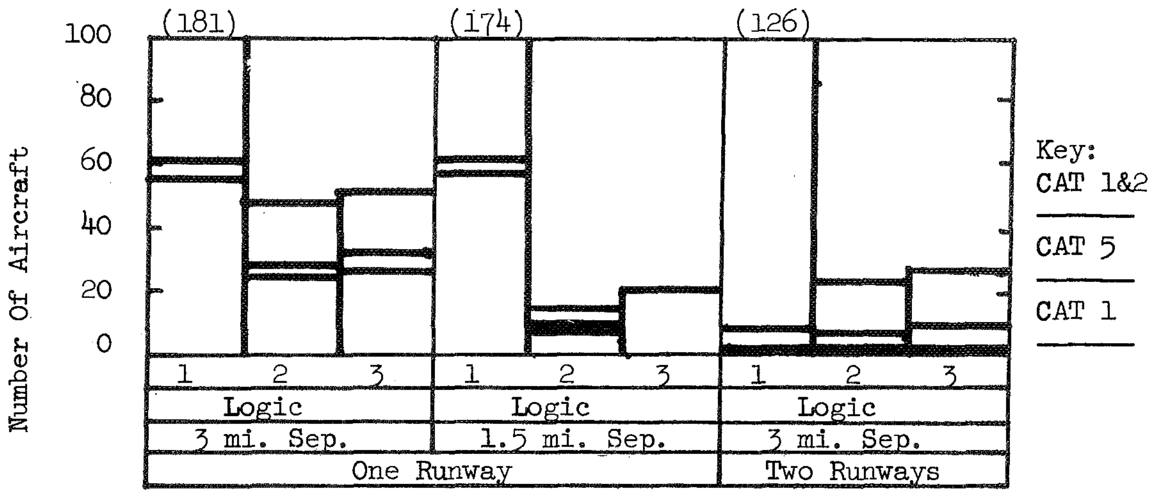
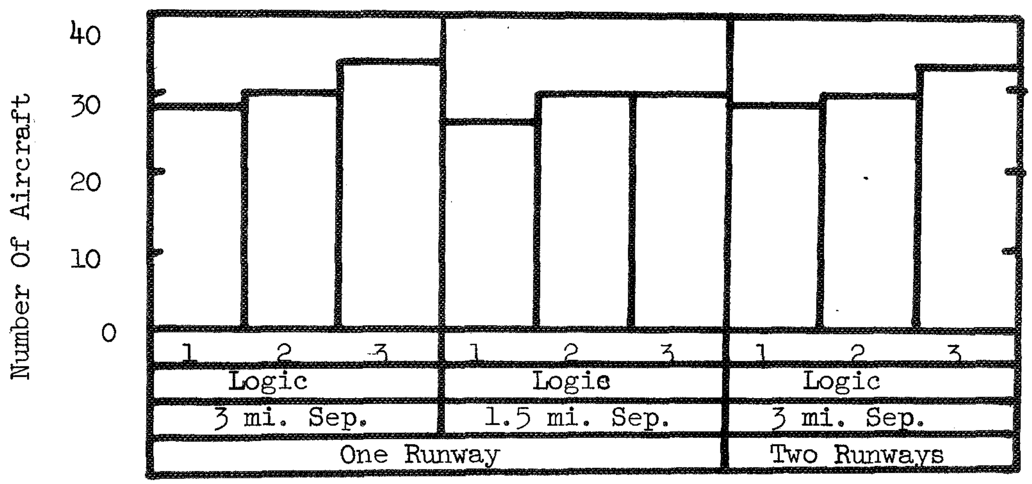


Figure 4.10: Communications Comparison (10 days, 3510 aircraft)



Maximum Number In Queues During 10 Days



Maximum Number In Approach During 10 Days

Figure 4.11: Peak Numbers Of Aircraft In Queues And Approach (10 days, 3510 aircraft)

aircraft on approach using two runways did not appreciably exceed the number on approach for one runway and for the same (3 mile) separation distances. However, use of the second runway resulted in much lower maximums in the queues, allowing aircraft to travel through the system much faster. Results indicated that only aircraft of like characteristics should be landed on a runway since the slower aircraft are always penalized in a mix solution. Higher order logics appeared to penalize the faster aircraft to some degree.

Logic 1 was inadequate in all test cases. However, this logic was not meant to be an actual operating philosophy, but rather a test for model development.

Logic 2 most nearly reflected current day ATC procedures. This logic appeared to be the best, or nearly the best, under all conditions. Many other logics could be developed, however, and this is probably not the optimum.

Logic 3 showed improvement in some cases, but was not superior as was expected. At most decision stages, the lower delay resulted in holding the decision aircraft in queue rather than delaying aircraft already on apprach so as to fit the decision aircraft into approach. This tended to increase delays in queue. Logic 3 also imposes a higher work load and would require a computer to perform the decision making functions.

Although the priority-queue-release routine was not completely checked out, it is believed that the effect would be a lower average delay for higher category aircraft, but an inferior overall system performance (higher runway vacancy times for example). This is due to the fact that for optimum performance, the aircraft with the shorter service time (queue to touchdown time) should be released first. Since the priority scheme in this model was based on aircraft delay, the "optimum" aircraft would not necessarily have the highest priority. However, different ways of assigning priorities could be included in the model.

Table 4.18 summarizes the results for case 8 which employed two runways, three mile separation, and logic 2. All aircraft of categories one and two were landed on the second runway. Of all cases tested, this case probably most adequately reflects the actual Atlanta operations although no data is available to validate the model. On an intuitive basis, the delays and other measurements appear realistic.

Table 4.19 shows the results for case 5, which modeled one runway, 1.5 mile separation, and logic two. This separation is below that permitted under current operation rules and improved equipments and procedures would have to be implemented to permit safe operations with this separation. It is noted, however, that due to the stochastic arrival rate, the occurrence of such a close separation is relatively rare so that more concentrated effort could be applied by controllers to improve safety. Delays and communication workloads under this case were lower than those incurred under the case were lower than those incurred under the previous case. Better runway utilization was realized, aircraft were put through the system in less time, and queues had a lower maximum number of aircraft than in the preceding case. This presents an interesting tradeoff, should equipment which permit closer separation be developed, or should additional runways be provided.

Logic 3 yielded lower delays for this one runway, 1.5 mile separation, case. However, this is at the expense of a somewhat greater workload.

TABLE 4.18 SAMPLE RESULTS
LOGIC = 2, 2 Runways, 3 mile Separation

Statistics (minutes)	Mean	Std. Dev.	Min.	Max.	Obs.
Total Delay in Queue 6 (Cat 3,4)	10.69	13.22	0.0	51.88	1089
Total Delay in Queue 7 (Cat 5)	0.30	0.66	0.0	6.73	2015
Total Delay in Queue 8 (Cat 1,2)	0.21	0.59	0.0	3.44	406
Total Delay in Approach 6 (Cat 3,4)	1.12	2.66	0.0	27.77*	1089
Total Delay in Approach 7 (Cat 5)	0.92	2.89	0.0	26.01*	2015
Total Delay in Approach 8 (Cat 1,2)	0.07	0.26	0.0	3.70*	406
Total Delay A/C Cat 1, 2	0.27	0.70	0.0	5.48*	406
Total Delay A/C Cat 3	10.50	12.04	0.0	45.46*	104
Total Delay A/C Cat 4	11.68	13.61	0.0	51.88	985
Total Delay A/C Cat 5	1.15	2.97	0.0	25.90	2015
Runway (2) vacancy times					
Rnwy 1 (Cat 3-5)	1.48	2.23	.47	22.46**	3104
Rnwy 2 (Cat 1-2)	14.23	21.49	1.45	190.24	406
Average time in system	19.62	10.03	2.03	71.75*	3510
Total Daily Deman (Aircraft)	351.0	21.02	320.0	387.0	10
No. in Approaches (Aircraft) Rnwy 1	9.23	3.65	0.0	26.0	--
Rnwy 2	0.17	0.39	0.0	3.0	--
No. in Queue 6 (Cat 3,4)	1.90	3.28	0.0	19.8	--
No. in Queue 7 (Cat 5)	0.10	0.39	0.0	4.0	--
No. in Queue 8 (Cat 1,2)	0.01	0.12	0.0	2.0	--

	1	2	3	4	5	6	7	8	9	10	11
Avg. No. Arrivals per hour	29.9	55.8	40.3	38.5	13.5	23.6	37.7	27.1	28.3	56.3	
Avg. No. TD per hour	23.0	43.4	44.3	43.8	20.9	19.8	32.1	31.6	28.4	45.3	17.8
Avg. No. Communications per hour	134.6	353.3	491.0	1331.0	76.1	98.7	199.2	191.4	143.9	338.0	107.5
Avg. No. Communications/AC Cat/Day	144.3	--	118.5	1204.2	997.7	--	--	--	--	--	--

*Delay Includes Go-around Time for Aircrafts Waved Off
**Occurs Due to First Arrival of the Day

TABLE 4.19 SAMPLE RESULTS
LOGIC = 2, 1 Runway, 1.5 mile Separation

Statistic (minutes)	Mean	Std. Dev.	Min.	Max.	Obs.
Total Delay in Queue 5 (Cat 1,2)	10.56	14.77	0.0	85.91	406
Total Delay in Queue 6 (Cat 3,4)	1.23	2.75	0.0	20.29	1089
Total Delay in Queue 7 (Cat 5)	0.07	0.28	0.0	4.48	2015
Total Delay in Approach (Cat 1,2)	0.45	1.22	0.0	16.22*	406
Total Delay in Approach (Cat 3,4)	0.76	2.19	0.0	24.99*	1089
Total Delay in Approach (Cat 5)	0.64	2.00	0.0	19.73*	2015
Total Delay A/C Cat 1,2	10.97	14.79	0.0	86.01*	406
Total Delay A/C Cat 3	2.06	3.95	0.0	24.99*	104
Total Delay A/C Cat 4	1.92	3.68	0.0	36.10	985
Total Delay A/C Cat 5	0.71	2.02	0.0	19.73	2015
Runway Vacancy Time	1.24	2.20	0.0	22.40**	3510
Average Time in System	17.52	7.32	1.75	88.53	3510
Total Daily Demand (Aircraft	351.00	21.02	320.0	387.00	10
No. in Approach (Aircraft)	9.26	4.42	0.0	29.00	--
No. in Queue 5 (Cat 1,2)	0.65	1.48	0.0	9.0	--
No. in Queue 6 (Cat 3,4)	0.18	0.57	0.0	5.0	--
No. in Queue 7 (Cat 5) (Aircraft)	0.02	0.17	0.0	3.0	--

	1	2	3	4	5	6	7	8	9	10	11
Avg. No. Arrivals per hour	29.9	55.8	40.3	38.5	13.5	23.6	37.7	27.1	28.3	56.3	--
Avg. No. TD per hour	21.5	46.3	46.2	40.9	19.5	19.9	33.2	32.1	26.9	45.8	18.7
Avg. No. Communications per hour	128.3	289.0	298.0	204.5	61.1	79.5	165.1	126.0	112.0	326.8	73.5
Avg. No. Communications/AC Cat/Day	462.7	--	52.8	499.9	848.5	--	--	--	--	--	--

*Delay includes go0around time for aircraft waved off
**Occurs due to first arrival of the day

A comparison of the average, total delays for each aircraft category under logic two for all three conditions is shown in Figure 4.12. This figure indicates that case 5 (one runway with 1.5 mile separation) yields the lowest delay under logic 2.

Figures 4.13a and b present the runway-vacancy-time probability density histograms for cases 2, 5, 6, and 8. This information gives an indication of how efficiently the aircraft are delivered to the runway threshold from the standpoint of maximizing the number of landings per hour. It also indicates the probability of the runway being vacant for a takeoff at some time during the day. That is, if an aircraft requires 1 minute to roll into the runway and take-off, there is a probability of 40% that the runway would be vacant one minute or more for this aircraft to takeoff for case 2 (the sum of the probabilities above one minute).

The data of Figures 4.13a and b also show that the limiting criterion on maximum landings per hour shifts from the separation criterion to the runway vacancy criterion as the minimum separation is reduced from 3 to 1.5 miles. This is demonstrated by the fact that the runway vacancy time cell with the highest probability is from .05 to 0.75 minutes for the 3 mile separation cases. This occurs since the three mile separation time for category 5 aircraft, for example, is 1.04 minutes, while the roll-out ime for this category is 0.57 minutes. Therefore, if the aircraft are being landed with three-mile separation, the runway vacancy time would be 0.47 minutes, very close to the highest probability cell of 0.5 to 0.75 minutes. On the other hand, the 1.5 mile separation time for this category is 0.52 minutes. Therefore, the runway vacancy time would go to zero if the runway vacancy criteria

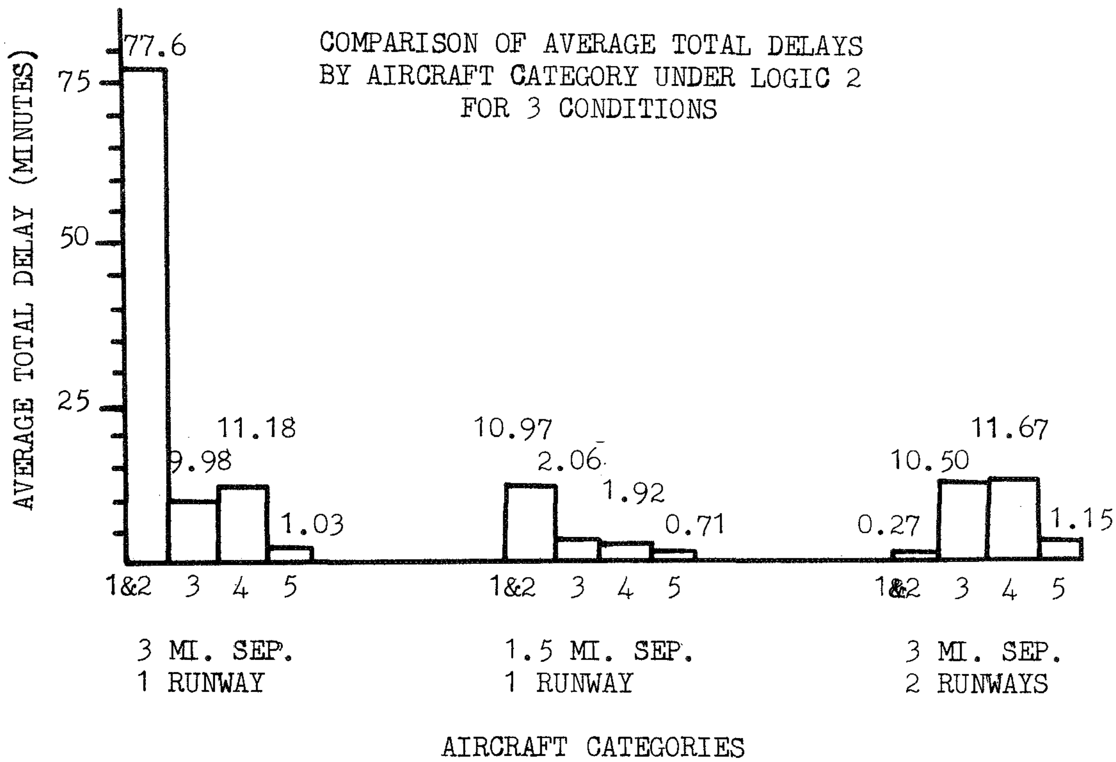


FIGURE 4.12: AIRCRAFT DELAY

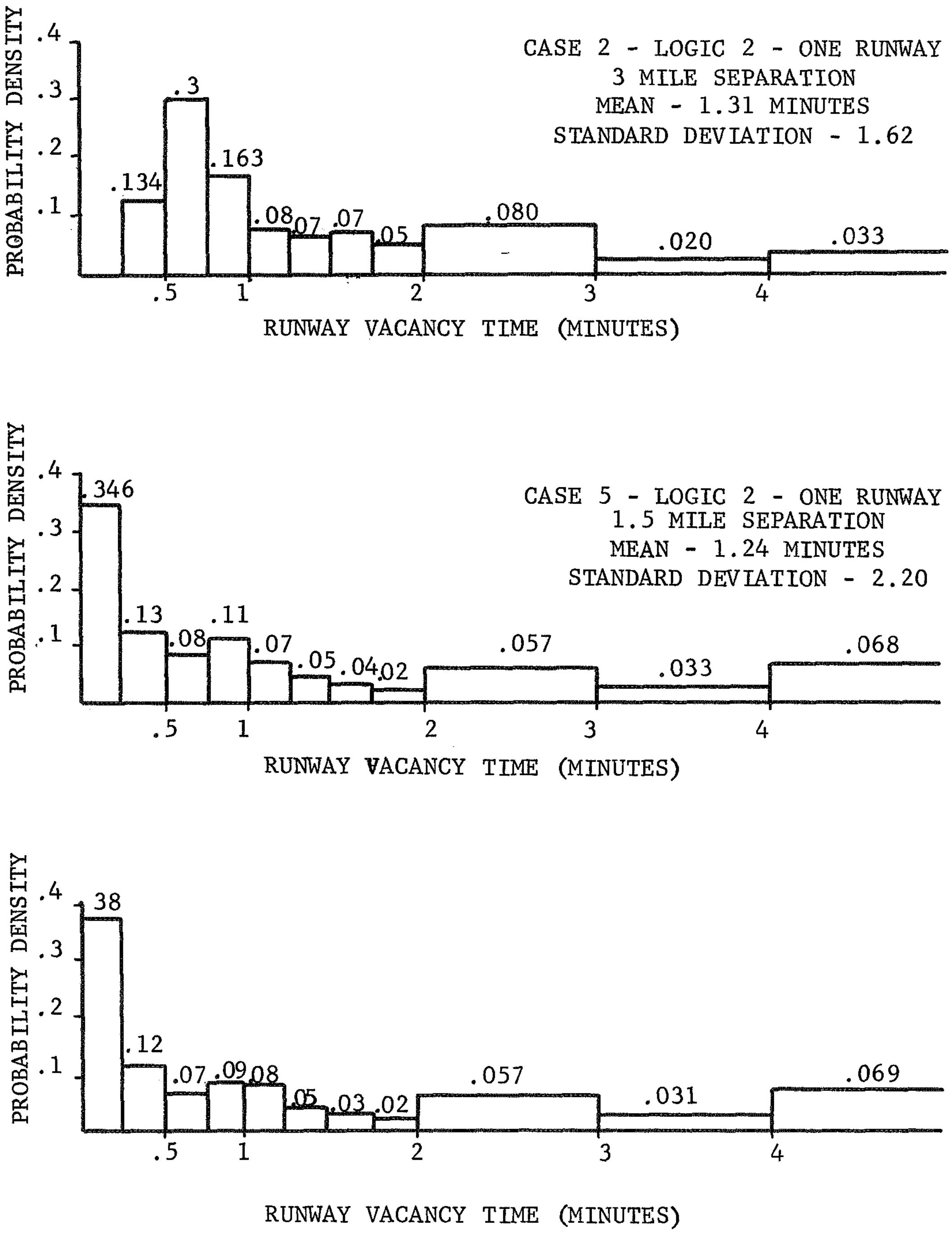


Figure 4.13a - Runway Vacancy Time Histograms

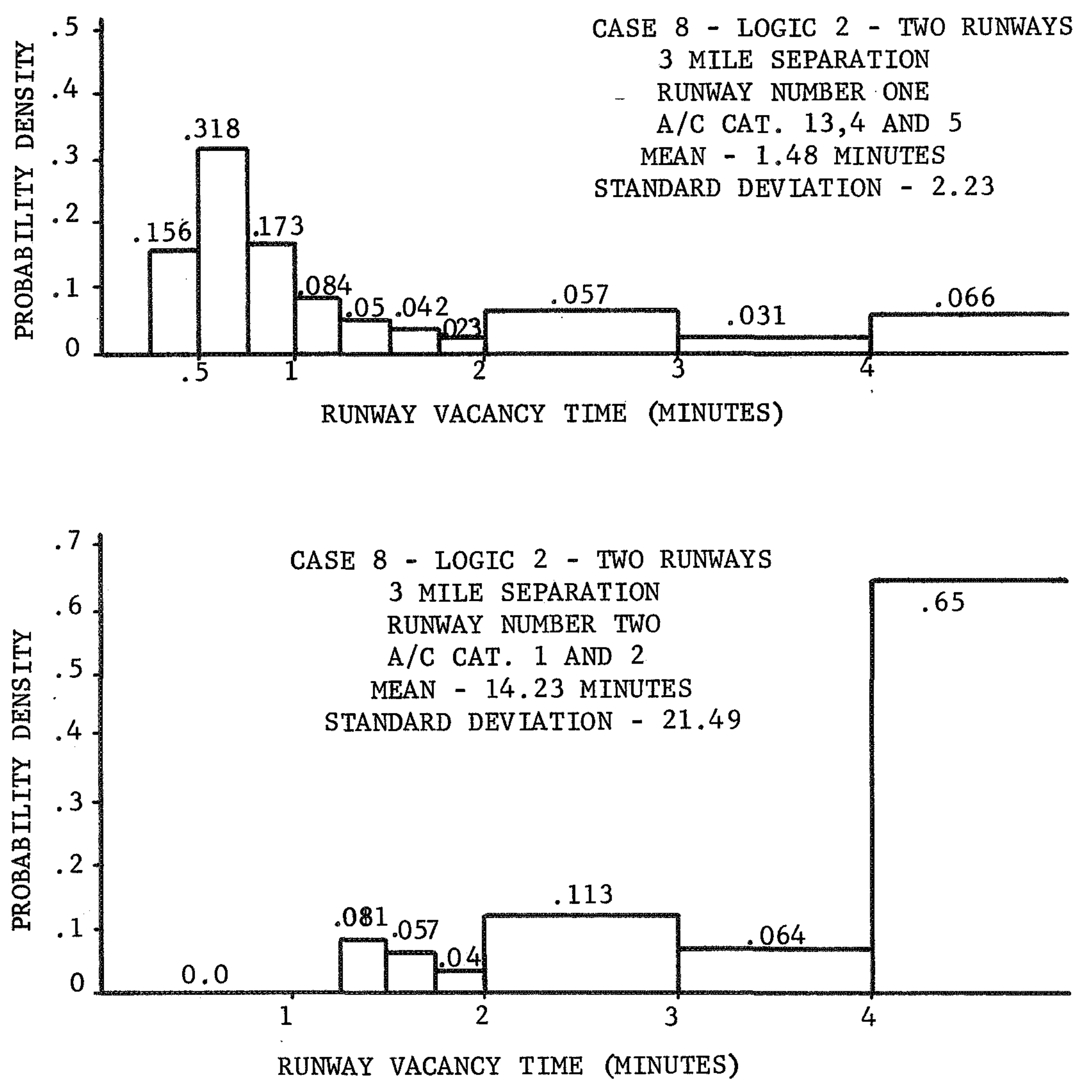


FIGURE 4.13B - RUNWAY VACANCY TIME HISTOGRAMS

were the limiting case. That this does occur is demonstrated in the case 5 data, for which the highest probability cell is the 0.0 to 0.25 minute cell.

Conclusions

Results definitely indicate that discrete-event modeling of system effects can adequately simulate the air-terminal operations system. Many decisions concerning the system can be made with the assistance of such a model.

Further study is required to build more realism into the model. Also needed is a set of actual data to validate the model.

Modeling the flight dynamics of aircraft may not be necessary to answer many questions concerning the air terminal system. However, the model could easily be extended to do so by adding a subroutine to perform the necessary calculations. This event could be called every few seconds (or in some other small time increment) to update aircraft location.

Many tradeoff studies were suggested by the results and could be performed by the model. For example, such tradeoffs as 1.5 mile separation on one runway versus 3 mile separation on two runways, and providing high speed ramps to reduce roll-out times versus retaining current rollout times could be studies.

Not only the total arrival rate is critical to operations but also instantaneous mix of aircraft in the system and the sustained rate of arrival are critical to operational procedures. Improvement in the system performance could be obtained by accepting arrivals at a point only with proper enroute separation. Lower separation times are permitted in the current model to reflect the fact that the decision (queue) nodes are abstract in location and arrivals may not enter the system at the same point or the same altitude.

Results indicated that it is more efficient to land only aircraft of similar flight characteristics on a runway as opposed to mixing aircraft categories. It also appears that the best way to operate the system is to group aircraft as closely as possible for landing regardless of any priority system or delays incurred on approach.

While the model could not be validated with actual data, the results and conclusions drawn from them appear to correspond directly to current operating philosophies. This fact lends much credulence to the model.

4.6 MODEL EXTENSIONS

This sections serves as a framework for extensions that the reader may wish to include in the model. This supplement is subdivided into the following extensions: those formulated from the original model concept recommended in the introduction, and those necessary to perform a specific experiment with the model. The first category considers the following:

1. Interaction between runways at a single airport, including runway changeover.
2. Interaction between airports in a single metropolitan area, including wave offs and landing at an alternate airport.
3. Takeoff simulation capability.

The second category examines the following:

1. Microwave ILS simulation

2. Wake vortex separation and sensitivity analysis on separation effects.

3. Spacing of scheduled arrivals.

4. Stored characteristics of individual aircraft.

5. More realistic system errors with sensitivity studies.

6. Arrival aircraft in an emergency situation.

The capability of readily including these extensions indicates the model's versatility.

Runway Interaction

The interaction between approaches to a two runway airport is the first logical extension to the terminal operations model. This interaction occurs when approach corridors overlap because of geometric constraints or noise abatement procedures, or when crossovers between approach corridors and runways are permitted. Overlapping corridors would require testing for proper spacing at all of the event nodes on the approaches before allowing an aircraft to advance from queue to touchdown. Crossovers on a dual runway system could be handled in two ways. The first method adds several points to the flight path of IFR traffic. The second method moves the merge point to coincide with approach crossovers.

The geometry used with the first method for including crossovers is shown in Figure 4.14a. This geometry was converted to the Time Based Model in Figure 4.14b. VFR or light IFR Traffic will still merge with IFR traffic at approximately the middle marker as shown in Figure 4.14b (the middle marker is located at the merge point). Although several points are added to the system, an algorithm could be developed to consider only two points at any one time.

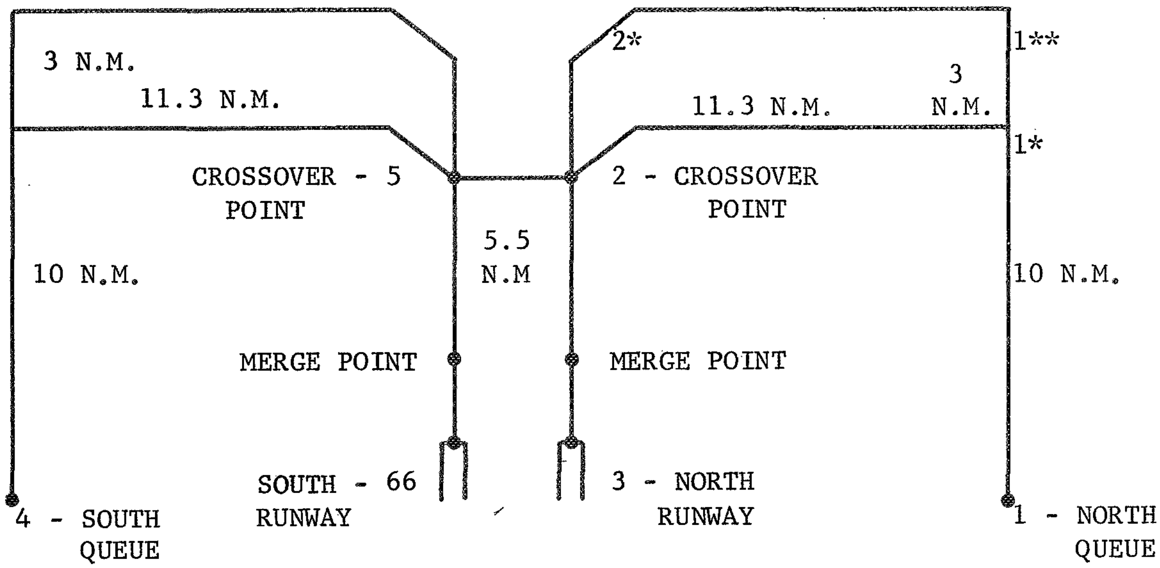


Figure 4.14a - Geometric Model
of Dual Runway System

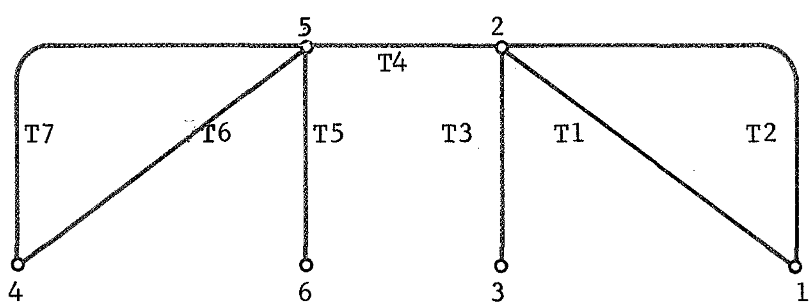


Figure 4.14b - Time-based Model
of Dual Runway System

The time, T1, in the timed based model corresponds to the time it would take an aircraft to follow the shorter geometric path between points 1 and 2 (1-1*-2). T2 corresponds to the longer geometric paths (1-1*-1**-2*-2). The time T3 is the travel time between points 2 and 3, and T4 represents the crossover time between points 2 and 5. Since the north and south geometries are the same, T6 and T1 are the same, T7 and T2 are the same, and T3 and T5 are the same. If different geometries are used for the north and south, these times could easily be corrected to agree with the geometry.

The scheduling process used for the IFR traffic in this model is based on maintaining separation between priviously scheduled aircraft at all common points in the geometry. For example, if an aircraft is being scheduled from the north queue to the south runway, it would be necessary to insure separation at points 1, 2, 5, and 6. The possible paths for aircraft entering the system at the north queue are 1-2-3 or 1-2-5-6. Likewise, aircraft entering at the south queue can use paths 4-5-6 or 4-5-2-3.

When each aircraft is initially considered in the scheduling process, the appropriate separation constraints are developed. The separation constrant for a point is the first time the present aircraft could pass this point and be assured of separation with all previously scheduled aircraft. Stored for each point is the last time an aircraft was scheduled through that point and the aircraft's category. Using the categories of the present and previous aircraft, the time separation necessary to maintain the appropriate physical separation is determined. When the time separation is added to the stored time of the last scheduled aircraft through the point, the separation constrain is obtained.

Utilizing the separation constraints and the time the present aircraft is at the queue, the aircraft is tentatively scheduled to the appropriate merge using both path times between the queue and merge. (i.3., north queue aircraft are scheduled to the north merge point using time T1 and T2, south queue aircraft are scheduled to the south merge point using times T6 and T7.)

The scheduling philosophy from these crossover points to merge and touchdown depends on the landing philosophy used. One philosophy is to consider the north runway as a primary runway and to use the south runway only if it introduced no additional delay for the aircraft. This means that most aircraft will use the north runway, leaving the south runway available for takeoffs. Although takeoffs are not included, it would be easy to include takeoffs, simply by changing the separation constraint at the appropriate runway each time a takeoff is scheduled.

An algorithm describing the geometry of Figures 4.14a and 4.14b could be incorporated into the subroutine APPRCH to determine an aircraft's possible flight paths and event times.

Another arrangement for allowing crossovers which is more easily adapted into the current model involves moving the merge node to coincide witht he approach crossovers. Aircraft departing from the queue would be tested for spacing at merge and touchdown with aircraft already on approach to the designated primary runway for that queue. If the calculated separations are less than the allowed minimum, a crossover time would be added to the scheduled merge, and the spacing tests would be made with aircraft on approach to the other runway. If proper separations are still not assured, the aircraft would be held in queue for a time sufficient to allow the aircraft to be sequenced to its primary runway.

Delay caused by runway changeover, due to a reversal in the direction of the head winds, is an airport problem that could be studied with this model. New arrivals would be assigned to queue locations more accessible for approaching the airport into the new headwind. Aircraft already on approach would be permitted to land in the direction and on the runway originally intended. The approach direction and runway designation for aircraft holding in former queues would be variables to be determined in the study.

Multiple Airports in One Metropolitan Area

The current model does not have the capability of simulating multiple airport hubs such as Kennedy-LaGuardia-Newark, Chicago O'Hare and Midway, and the southern California complex.

Additional event nodes would have to added to the model to effectively simulate interaction of overlapping enroute corridors to different airports.

The possibility of having waveoffs land at an alternate airport within the hub would have to be explored. Shuttle service between the respective airports could be simulated by using a separate approach file but maintaining the same merge nodes.

Takeoff Simulation

The present model collects statistics in the form of a histogram on inter-touchdown times for the one runway and independent wo runway system. This histogram represents the only record of possible takeoff events. A study could be performed on airport ground-handling capacity and runway occupancy time for takeoffs by aircraft category. This study would then provide a basis for adding constraints to the touchdown, merge and depart queue events for arriving aircraft.

Takeoffs in the two runway system could be assumed to occur on one runway only. This would designate one of the runways as the primary landing strip. Since aircraft in the air assume a priority over those on the ground, the takeoffs would be restricted whenever a landing is to occur on the alternate runway.

Microwave ILS

Modeling a future airport with microwave capability could be accomplished by moving the merge node forward to coincide with touchdown. This would allow the aircraft to fly curved final approaches and intersect the glide slope at different gates and at various altitudes as prescribed by performance characteristics. Time separation schemes at the merge node would have to be worked out to assure proper spacing on final approach. Further information on the microwave ILS system is available in Section 3.4

Sensitivity Studies on Separation

In the present model, spacing at the event nodes is based only on the times that it takes the respective categories of aircraft to fly the specified nautical mile separation. A more detailed study of operations could examine the order in which aircraft proceed through the system. Separation constraints would vary according to the relative positioning of aircraft categories on approach. For example, spacing for light aircraft following jumbo jets and SST's might be specified in terms of the probability of a wake vortex encounter. This would add a dynamic variable to the priority entrance algorithm to test the favorability of like category aircraft moving in trains. An experiment of this nature would also provide a gauge on the effect of new aircraft, such as the SST, and overall system performance.

Sensitivity studies on delay and runway utilization could be performed on the basis of varying separation constraints. This type of study could also determine effect vs. cost for new equipment.

Scheduled Arrivals

The present model uses known arrival rates to generate random arrival times and categories. The model could be extended to study optimum scheduling of arrivals by category, given the airport's demand level and handling capability. An additional runway could be proposed to handle pop-up traffic or general aviation. The scheduled arrival times could be further allocated to the various trip generators by demand considerations. In this type of model the queueing areas could be moved to the origin of the flight.

Stored Performance Characteristics

To supplement the scheduling experiments, the classifications could be expanded to individual stored velocity and deceleration profiles, and flight dynamics of aircraft by name or type. Then based on optimal or alternate flight path geometries, the event times could be more precisely calculated by the program.

In addition to the node event codes, another event code could be used to check the state of the system at a selected time increment. This time increment would correspond to stepping the aircraft through the system. GASP would provide the executive control. At each step, the flight dynamics could be used to determine an aircraft's exact position. This type of model could be used to study collision avoidance systems or the overall safety of the terminal operations as the logic codes and separation constraints are varied.

Error Analysis

The current model lumps all system errors into normal distributions based on aircraft category and flight geometry and assigns these errors at the queue and merge nodes. Studies of actual terminal operations could more precisely determine error distributions for internode times and performance categories. More detailed analysis of error accured by weather problems or equipment options would be another useful addition to the model. Sensitivity studies could then determine the effect of varying error distributions on system performance.

Emergency Operations

Whenever an arrival is designated as an emergency aircraft, it would assume the highest possible entrance priority and encounter no enroute delay. This would mean that all aircraft in the approach which the emergency aircraft can pass would be held or waved off when necessary. The model could be extended to include emergency capability by assigning to the arrival an order of magnitude higher priotity and a negative weighting factor on any calculated holding time.

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CHAPTER V

CONCLUSION

A study for the terminal area control system for the year 2000 has produced the following conclusions:

1. Passenger demand is projected to be 20 x 10^8 enplanements per year with the following breakdown:

Distance (miles)	% of Total Enplanements
0-500	51.4
500-1000	24.3
1000-1500	12.3
1500-2500	10.4
over 2500	1.4

2. Cargo demand is projected to be 601,082 millions of ton-miles of which 434,600 million ton-miles will be domestic cargo. This assumes an arrival rate increase of 17% in domestic cargo demand and 13% in international cargo demand. Ninety-nine percent of cargo (ton-miles) will be moved by an all-cargo aircraft fleet.

3. The air carrier fleet is projected to be 8179 passenger aircraft and 3140 all-cargo aircraft. Carrier aircraft will be of six types:

Type	Maximum Range (miles)
VSTOL	1000
Short Haul Jet	1500
Medium Jet	1500
747 Type Jet	over 2500
Transonic Transport	over 2500
Supersonic Transport	over 2500

4. General aviation will grow to 702,300 aircraft, with the following breakdown:

Type	Number
Single Engine	480,000
Multiple Engine	80,500
Turboprop	39,000
Turboject	30,000
Rotorcraft	70,000
Unspecified	2,800

5. In approximately 1985 a Transonic Transport will be introduced to the air carrier fleet having the following characteristics:

a.	Range	over 2500 miles
b.	Speed	650 miles/hour
c.	Payload	273 tons (or 1000 passengers)
d.	Gross Weight	1.75×10^6 pounds

6. Terminal area airspace will be positively controlled from which inadequately equipped aircraft will be excluded. Air collision avoidance will be provided by positive control, with aircraft collision alarm a backup system.

7. The trilateration system is most desirable for the terminal area navigation capacity.

8. Parallel arrangement of dual runways provides the greatest landing capacity.

9. A microwave ILS is the most desirable for terminal area operations for the following reasons:

   a. Curved approach paths are obtained.
   b. Lateral separation may be reduced to less than ½ mile in flight.
   c. 2500 foot separation between parallel runways is possible.

d. Aircraft, of similar landing characteristics, can be landed at a rate of 90 aircraft per hour per runway with a ± 5 second delivery accuracy at the touchdown point.
e. With reduction separation the landing rate is constrained by landing rollout time.

10. Simulation results indicate that a discrete events philosophy of system effects has potential as a technique for simulating air terminal operating systems. Further extensions of this model should be developed to more accurately describe real world conditions. The model was able to verify other conclusions of this study, specifically:

a. Aircraft of similar landing characteristics should land on the same runway.
b. Rollout time becomes the limiting constraint when aircraft separation is reduced.

11. A model has been developed that may, with extension, adequately simulate terminal area operations. Future air control systems will require simulation techniques in order to accurately evaluate new equipment and procedures. The year 2000 aircraft demand can be satisfied by techniques and procedures developed by this study.

APPENDICES

APPENDIX A

FUTURE STOL AND VTOL AIRCRAFT

Several studies have been made to determine the feasibility of using STOL and VTOL aircraft to alleviate the present air traffic congestion.[1,2,3,4] While these studies differ somewhat in their choice of the best type of V/STOL aircraft to use, they all agree that V/STOL operations are feasible and desirable if:

1. They can operate in their own airspace, separate from CTOL, with their own ATC procedures.

2. Noise can be reduced to a level that is acceptable to the public (around 90 PNDB).

The first condition is necessary because V/STOL aircraft have higher operating cost than CTOL. If they are required to fly conventional approach paths with the three degree slide slope and the delays encountered in holding patterns, they cannot operate at a profit and thus will not be acceptable to commercial airlines. The noise problem with V/STOL is at present the limiting factor as far as technology is concerned and it is felt that this can be overcome. The biggest problem facing V/STOL today is that no one is willing or able to take the initiative to start such a service. Aircraft manufacturers are not willing to begin a large research and development program without some assurance that their aircraft will be purchased. On the other hand, commercial airlines are not willing to order a large number of aircraft when they are not sure that the quality of the ride and the type of service that results will be acceptable to the public. To further complicate the problem, local governments are unwilling to set aside land in a downtown area to establish a stolport until they are sure that the service will be acceptable based on safety and noise considerations. Thus, a vicious circle exists that will require some form of government intervention to break. This is not to say the government will become involved in V/STOL as it is in the supersonic transport program, but that some form of government encouragement and direction must be applied.

In preparing this report it has been assumed that the government will encourage its development and that V/STOL service will come into being in the following manner. By 1975 limited STOL service will exist in the northeast corridor. This will consist of small, 60 passenger or less, aircraft operating from separate 2000-foot runways at existing airports and some temporary locations in or near downtown areas. The aircraft used might be either the DeHavilland Twin Otter or Buffalo, the Brigade 941, or possibly a tilt-wing turbo prop vehicle. While all of these vehicles leave something to be desired in the area of ride quality, it appears that they can be made acceptable long before the noise problems associated with jet engine STOL vehicles will be overcome. This service will primarily be intended for VFR conditions since the ATC equipment necessary for STOL IFR landings will not have been installed. It is also highly likely that during this first phase of STOL service the airlines will lose money and require some form of government subsidy.

During the period 1975-1985 STOL service will continually increase and VTOL aircraft will be introduced. The jet flap or fan-in-wing vehicle with 90 to 120 passenger capacity will become operational. Local governments will begin planning and constructing downtown, roof-top stolports and the necessary IFR equipment will be installed.

Once these downtown facilities are complete, and V/STOL aircraft obtain an all-weather capability, the service will grow in popularity until by 2000 it will carry 80 to 90% of all air traffic under 500 miles within the northeast corridor. In less densily populated areas its impact will not be as great and operations will probably be limited to separate runways at existing airports.

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APPENDIX B

ATLANTA ARRIVALS AND DEPARTURES

In order to provide some realistic data to use as input to the simulation model program, it was decided to obtain present-day hourly arrivals and departures at a particular airport. In addition to present day data, some projection of future operations was desired to study the effects of changes in air traffic control procedures and equipment. Thus the following data were compiled for the Atlanta airport. (Atlanta was selected because the data on hourly operations was readily available).

Present Day Operations

Through the cooperation of Mr. Lester Shipp, Tower Supervisor for Atlanta, data on hourly arrivals and departures at the Atlanta airport on July 9, 1970, and average hourly operations for February, June, July, and August 1969 and May 1970, were obtained.

The July 9, 1970, data were used for present-day input. The total figures were broken down into the seven composite categories listed in Chapter II by applying the following percentages:

Category I and II	0%
Category III	1.3%
Category IV	42.7%
Category V	56.0%
Category VI	0%
Category VII	0%

For general aviation the actual numbers were used since these are recorded separately from commercial. The other percentages were obtained using statistics from the CAB's Handbook of Airline Statistics, 1969 Edition. This book lists the percent of revenue passenger miles by aircraft type. Each of the aircraft types used by the CAB was placed in one of the above categories and the percentages summed. Categories VI and VII are zero since they represent the 747 jet and SST. The results of this breakdown are shown in Table B.1.

Operations for the Year 2000

The hourly arrivals and departures for the year 2000 were obtained using the aircraft types and characteristics from Table 2.7, the enplanement projection from Figure 2.1, and the percentage of enplanements by trip length from Table 2.8. The daily enplanements at Atlanta were obtained by dividing total enplanements by 365 and multiplying the result by 0.046. This last number was obtained by averaging Atlanta's percentage of total enplanements for the years 1965, 1967, and 1968 (FAA Statistical Handbook of Aviation, 1966, 1968, 1969) and assuming this will remain constant. Then using the procedure described in Chapter II, the total departures per day by trip length were obtained (see Table B.2). To break this down into hourly departures and arrivals, assuming the total number of arrivals equals departures, profiles of hourly arrivals and departures were projected by using present day profiles, obtained from the data provided by Mr. Shipp, and assuming that steps will be taken to eliminate peaks. The results are shown in Figures B.1 and B.2. Figure B.3 shows a projection for cargo arrivals and departures for the year 2000. Since there were no present day data to work with, this projection was somewhat arbitrary but reflects the belief that the majority of cargo operations will be during the early morning hours when passenger demand is low. By applying these hourly percentages to total departures and arrivals, the projected operations for Atlanta, as shown in Table B.3, were obtained.

TABLE B.1

HOURLY ARRIVALS AND DEPARTURES AT ATLANTA

FOR JULY 9, 1970 BY CATEGORY

Hour		Category							
		I & II		III		IV		V	
		In	Out	In	Out	In	Out	In	Out
0	1	3	1	0	0	4	6	8	12
1	2	4	3	0	0	4	2	8	5
2	3	7	5	0	0	2	1	5	2
3	4	1	2	1	0	3	2	7	5
4	5	1	1	0	0	1	3	1	7
5	6	0	0	1	0	7	2	14	4
6	7	1	0	0	1	0	11	0	22
7	8	2	1	0	0	1	5	3	11
8	9	5	3	1	0	8	3	17	7
9	10	7	8	1	0	15	5	32	11
10	11	3	4	1	1	12	13	24	28
11	12	6	4	1	1	10	15	22	32
12	13	2	6	0	1	2	12	5	26
13	14	1	4	1	0	8	4	17	9
14	15	2	5	1	1	11	8	24	17
15	16	3	9	1	1	8	10	18	22
16	17	4	4	1	1	7	8	14	18
17	18	7	6	1	1	15	8	32	17
18	19	6	7	0	1	4	13	9	28
19	20	3	0	1	0	16	6	34	12
20	21	1	1	0	1	5	12	10	24
21	22	2	2	0	1	6	10	12	22
22	23	4	0	0	0	6	5	12	10
23	24	3	0	1	0	10	1	22	3

TABLE B.2

DAILY DEPARTURES BY TRIP LENGTH

	V/STOL.	S.H.J.	T.S.T.	S.S.T.
0-500				
ENP	92,280	39,120		
ENP/DEP	162	325		
DEP	563	120		
0-1000				
ENP	6,170	43,190	12,340	
ENP/DEP	135	260	300	
DEP	46	166	41	
0-1500				
ENP		3,120	24,960	3,120
ENP/DEP		195	300	210
DEP		16	83	15
0-2500				
ENP			15,840	10,560
ENP/DEP			400	300
DEP			40	35
0-3000				
ENP			381	3,429
ENP/DEP			400	360
DEP			1	10
TOTAL DEP	609	302	165	50

TABLE B.3

HOURLY OPERATIONS AT ATLANTA IN 2000

Hour	Gen Avia		Cargo							
			Short Haul		Med. Haul		747		Jumbo	
	In	Out	In	Out	In	Out	In	Out	In	Out
0 - 1	8	3	0	0	1	1	8	8	7	7
1 - 2	10	8	0	0	1	1	8	8	7	7
2 - 3	17	13	0	0	1	1	8	8	7	7
3 - 4	3	5	0	0	0	0	8	8	7	7
4 - 5	3	3	0	0	0	0	8	8	7	7
5 - 6	1	1	0	0	0	0	8	8	7	7
6 - 7	3	1	0	0	0	0	8	8	7	7
7 - 8	5	3	1	1	0	0	8	8	7	7
8 - 9	13	8	1	1	0	0	8	8	7	7
9 -10	17	20	0	0	0	0	3	3	3	3
10--11	8	10	0	0	0	0	3	3	3	3
11--12	15	10	0	0	0	0	3	3	3	3
12--13	5	15	0	0	0	0	3	3	3	3
13--14	3	10	0	0	0	0	3	3	3	3
14--15	5	13	0	0	0	0	3	3	3	3
15--16	7	22	0	0	0	0	3	3	3	3
16--17	10	10	0	0	0	0	3	3	3	3
17--18	17	15	0	0	0	0	3	3	3	3
18--19	15	17	0	0	0	0	3	3	2	2
19--20	8	1	0	0	0	0	3	3	2	2
20--21	3	2	0	0	0	0	5	5	5	5
21--22	5	5	0	0	0	0	5	5	5	5
22--23	10	1	0	0	0	0	5	5	5	5
23--24	7	1	0	0	0	0	6	6	5	5

TABLE B.3 - (CONCLUDED)

Hour	V/STOL		Passenger					
			S.H.J.		T.S.T.		S.S.T.	
	In	Out	In	Out	In	Out	In	Out
0 - 1	15	15	8	8	4	4	1	1
1 - 2	15	15	8	8	4	4	1	1
2 - 3	15	15	8	8	4	4	1	1
3 - 4	15	15	8	8	4	4	1	1
4 - 5	15	15	8	8	4	4	1	1
5 - 6	15	18	8	9	4	5	1	2
6 - 7	15	18	8	9	4	5	1	2
7 - 8	15	18	8	9	4	5	1	2
8 - 9	33	18	16	9	9	5	3	2
9 -10	33	34	16	17	9	9	3	3
10--11	33	34	16	17	9	9	3	3
11--12	33	34	16	17	9	9	3	3
12--13	28	34	14	17	8	9	3	3
13--14	28	34	14	17	7	9	2	3
14--15	28	31	14	15	7	8	2	3
15--16	28	31	14	15	8	8	3	3
16--17	33	31	16	15	9	8	3	2
17--18	33	31	16	15	9	8	3	2
18--19	33	30	16	15	9	8	3	2
19--20	33	30	16	15	9	8	3	2
20--21	28	27	14	13	7	8	2	2
21--22	28	27	14	13	7	8	2	2
22--23	28	27	14	13	7	8	2	2
23--24	28	27	14	13	7	8	2	2

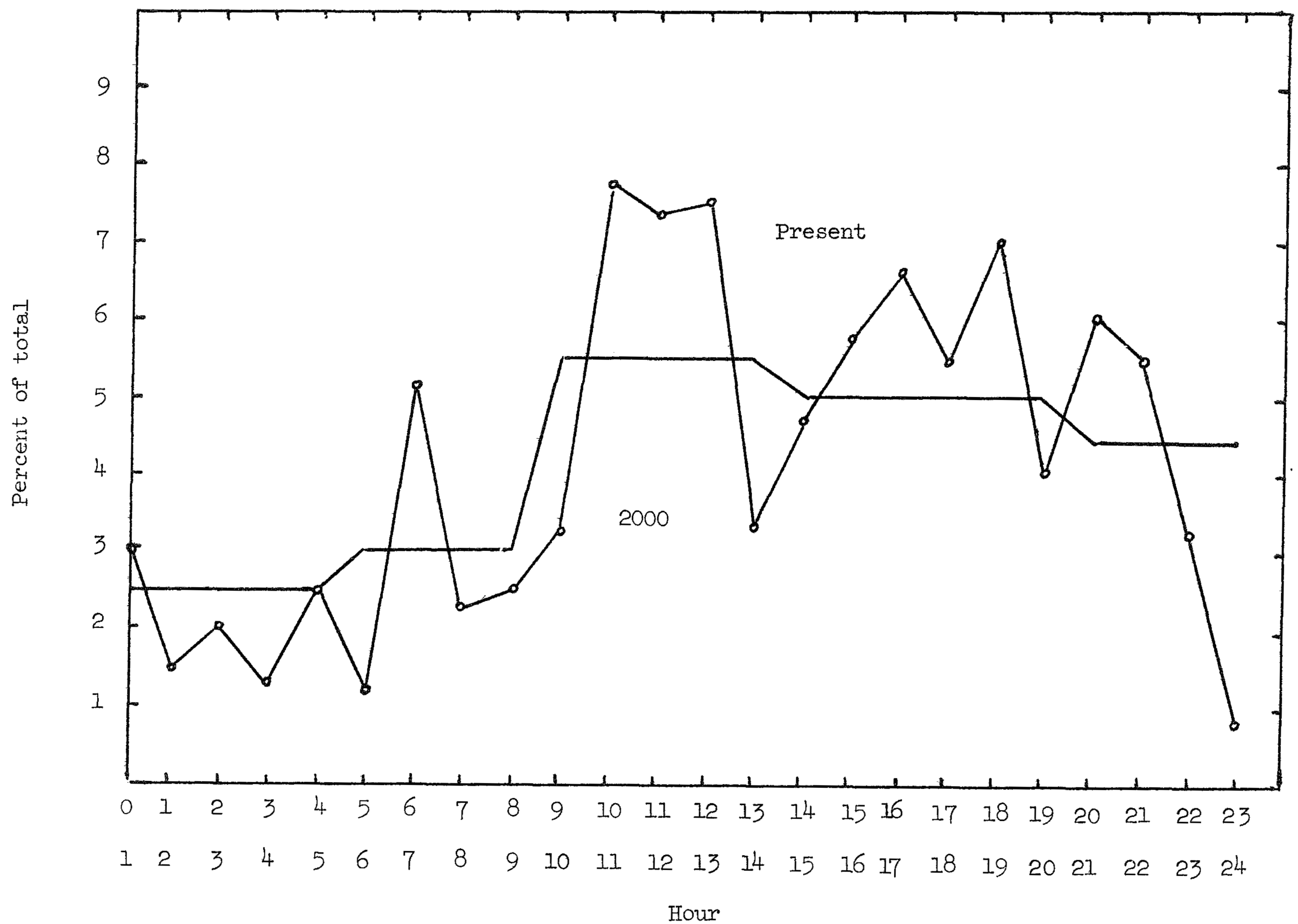

Figure B.1 Percent of total departures by hour.

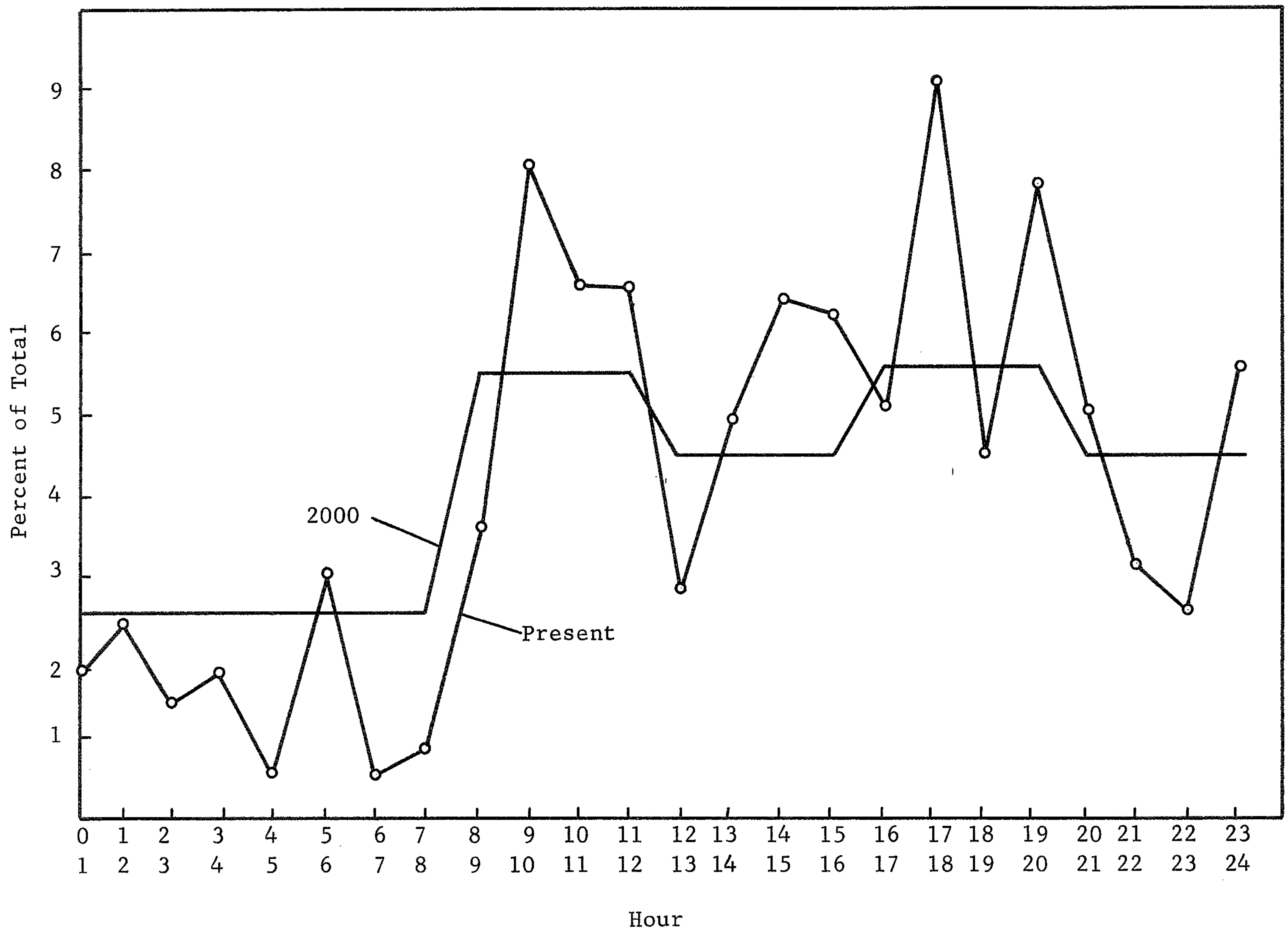

Figure B.2 Precent of total arrivals by hour.

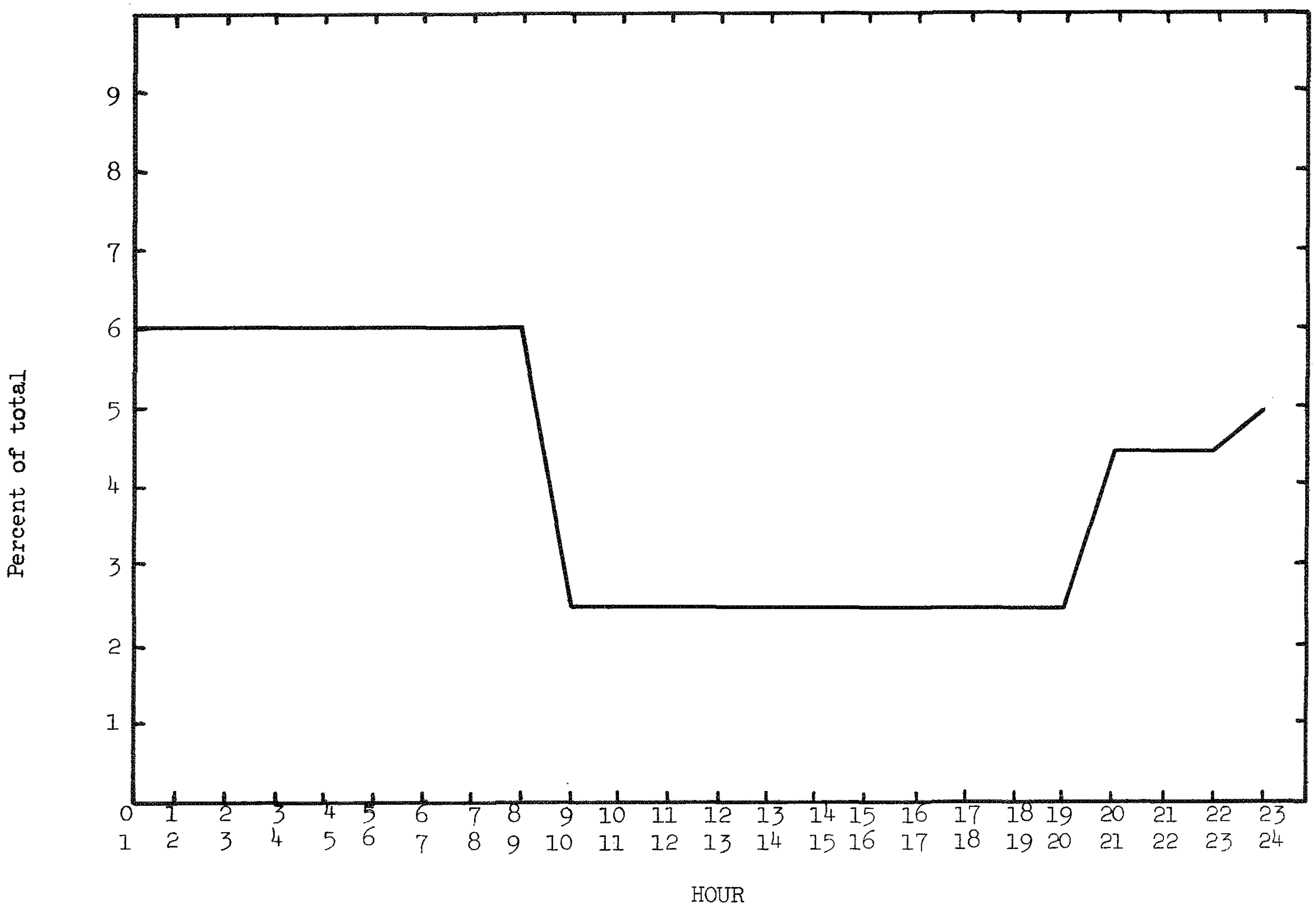

Figure B.3 Percentage of cargo arrivals and departures by hour

APPENDIX C

AIRCRAFT PERFORMANCE CHARACTERISTICS

Aircraft Stopping Performance

Minimum runway occupance time is the time from touchdown until turnoff, assuming maximum deceleration performance and ideal exit location.

Given the following aircraft performance characteristics:

V_1 = Landing speed

a = Deceleration

V_2 = Turnoff speed

minimum runway occupance time ($t_{min.}$) and the total runway occupancy limit (T_a) can be determined.

$$T_{min} = \frac{V1 - V2}{a} \qquad \text{C.1}$$

$$T_a = T_{min} + \frac{1000 \text{ ft.}}{V_1} \qquad \text{C.2}$$

The above performance characteristics (V_1, V_2, a) also permit the distance to the ideal exit to be determined. This is done by the following equation

$$D = \frac{V1^2 - V2^2}{2a} \qquad \text{C.3}$$

Aircraft-Runway Subsystem Capacity

For each approach/landing speed, V_1, a total runway occupancy time, T_a is determined. Mean runway occupancy time is computed using a weighted average of occupancy times over the percentage distribution of aircraft performance categories in the traffic.

Landing capacity vs. approach/landing speed is determined using total runway occupancy time instead of mean runway occupancy time. Total runway occupancy time is determined for selected values of turnoff speed and deceleration.

Approach/Runway System Landing Performance

System landing capacity is one of the most vital terminal area parameters. It is determined by a combination of approach separation capacity, interarrival time capacity and approach/landing speed capacity vs. approach/landing speed.

The results and relationships described in this appendix are illustrated in the figures which follow.

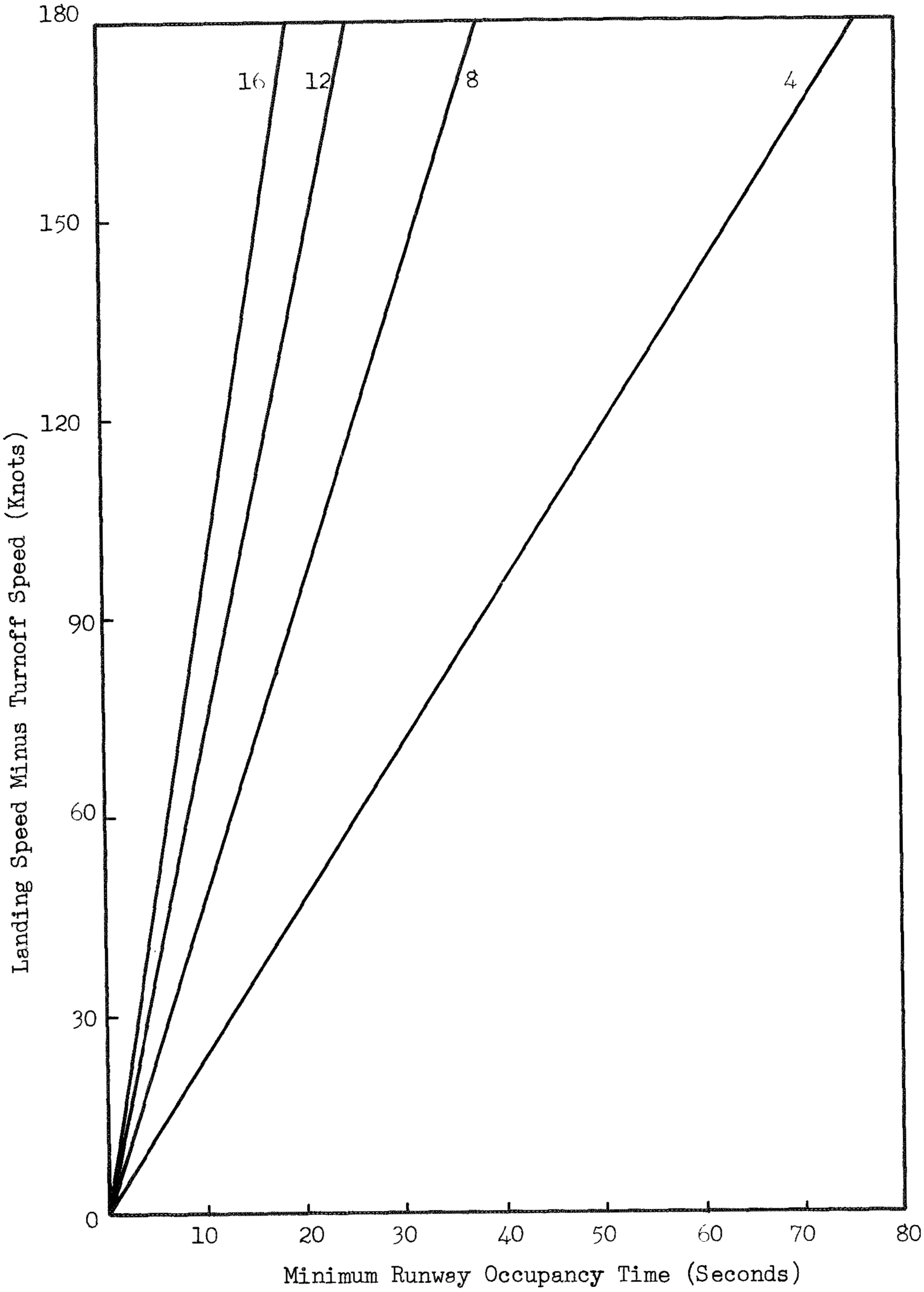

Figure C.1: Aircraft Stopping Performance

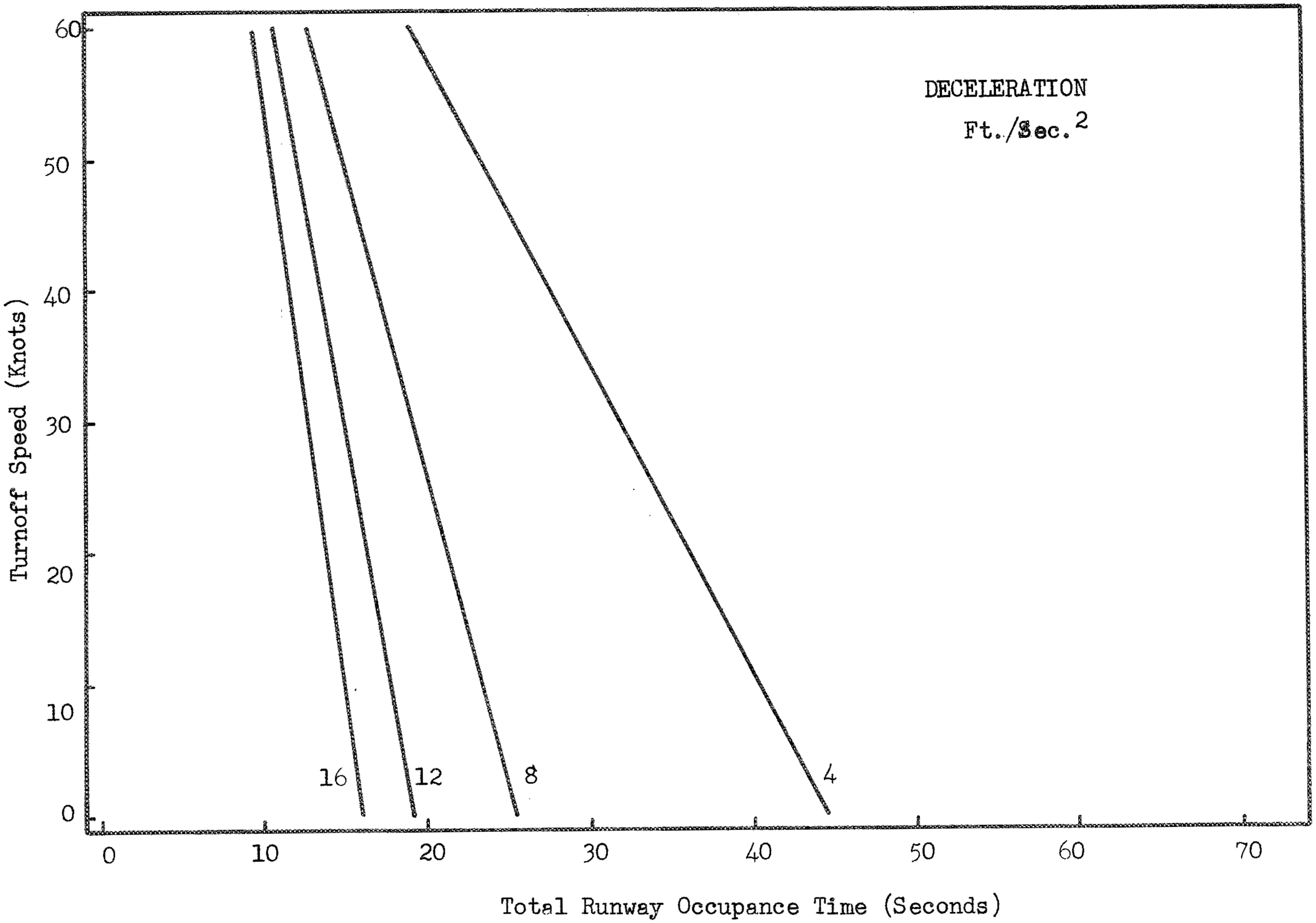

Figure C.2: Aircraft Landing Performance, 90 Knot Landing Speed

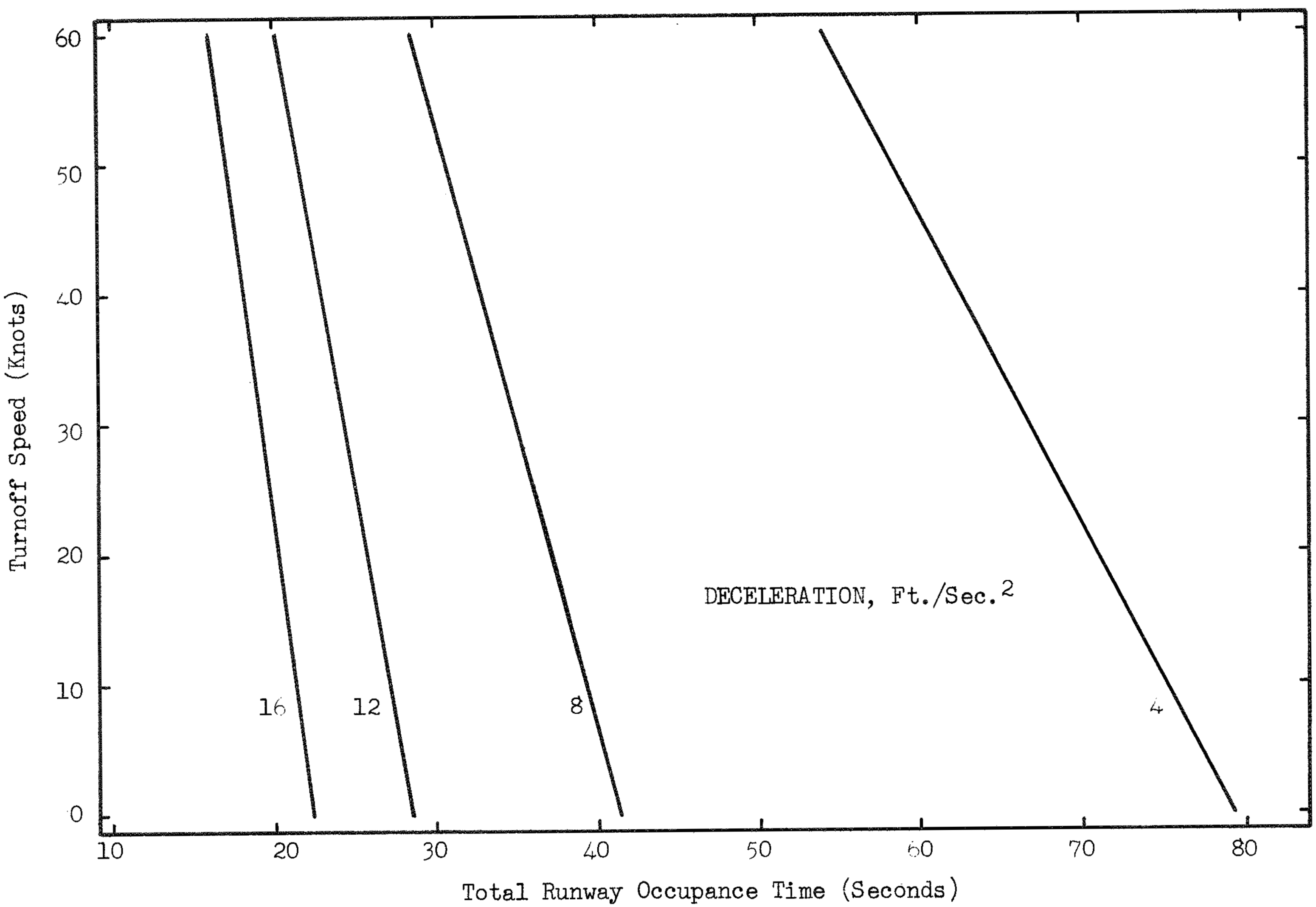

Figure C.3: Aircraft Landing Performance, 180 Knot Landing Speed

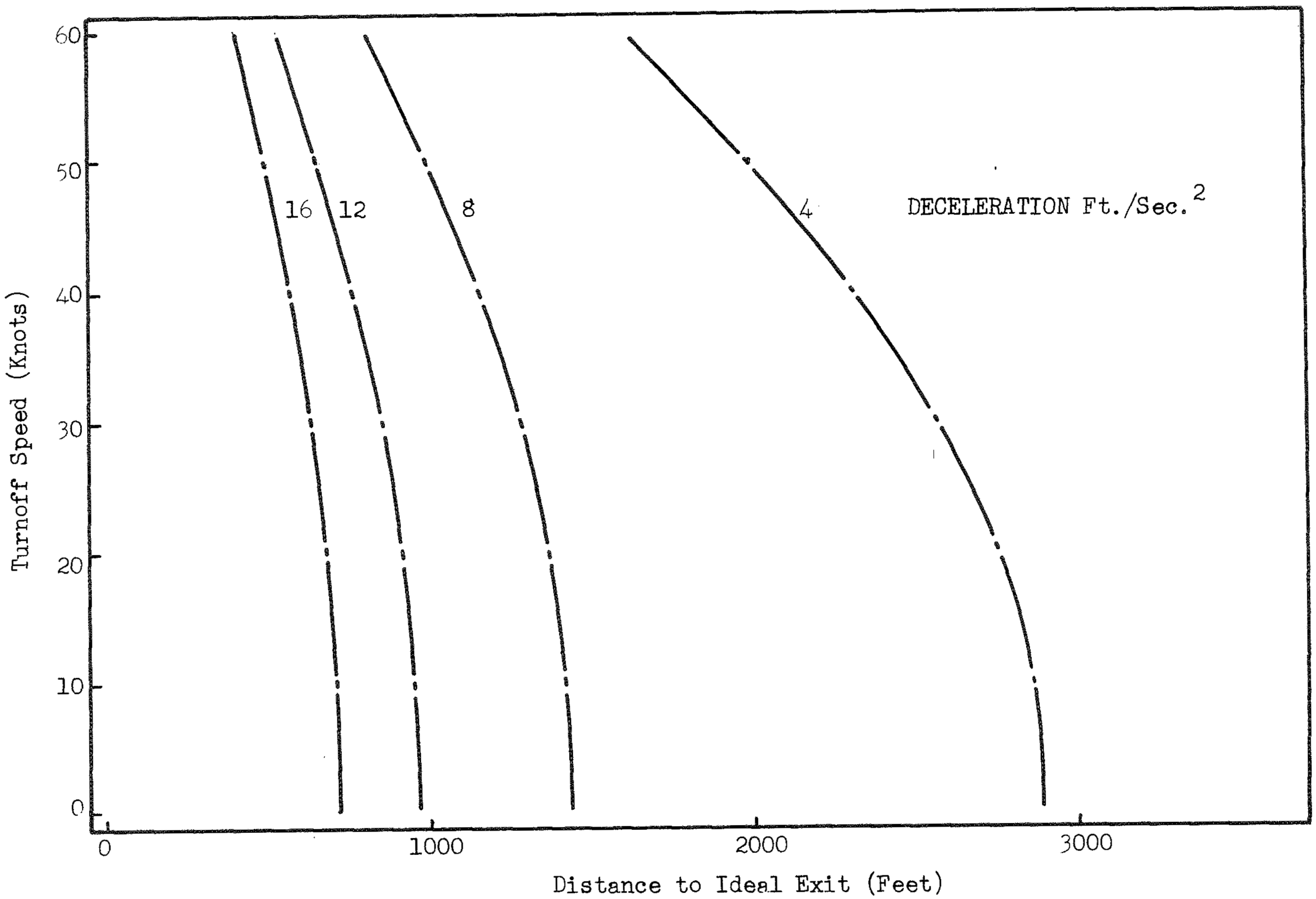

Figure C.4: Aircraft Stopping Performance, 90 Knot Landing Speed

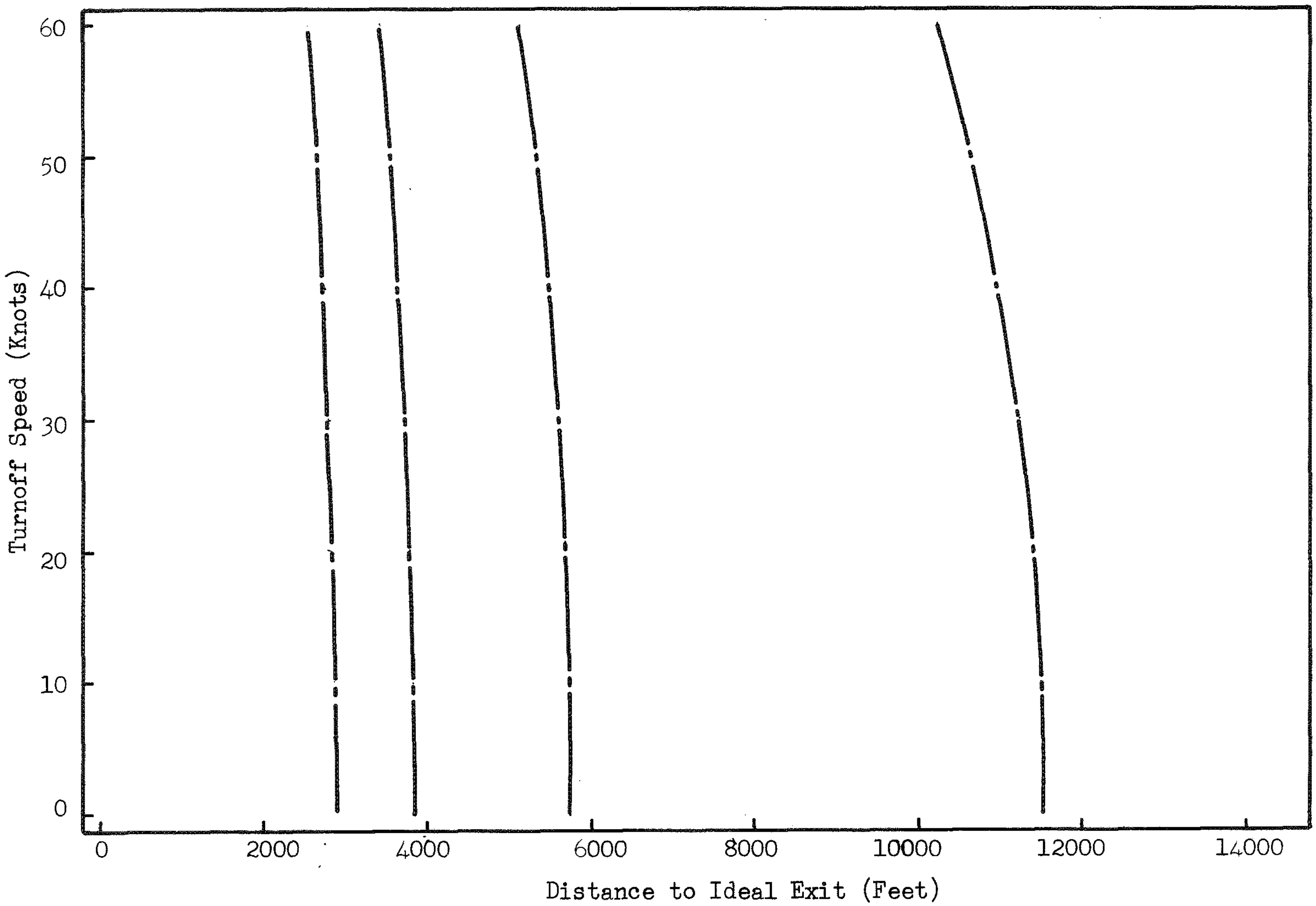

Figure C.5: Aircraft Stopping Performance, 180 Knot Landing Speed

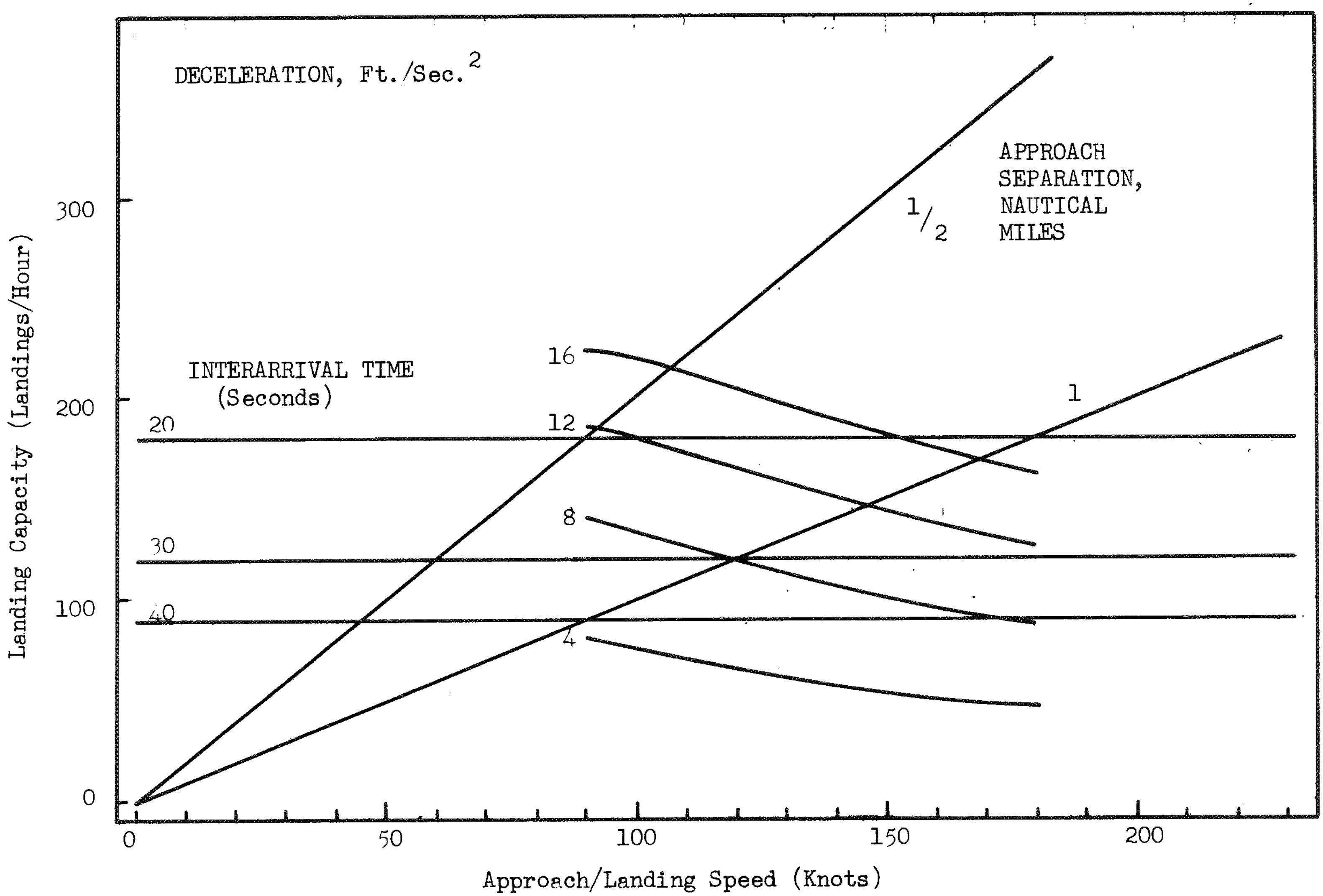

Figure C.6: Approach/Runway System Landing Performance, 0 Knot Turnoff Speed

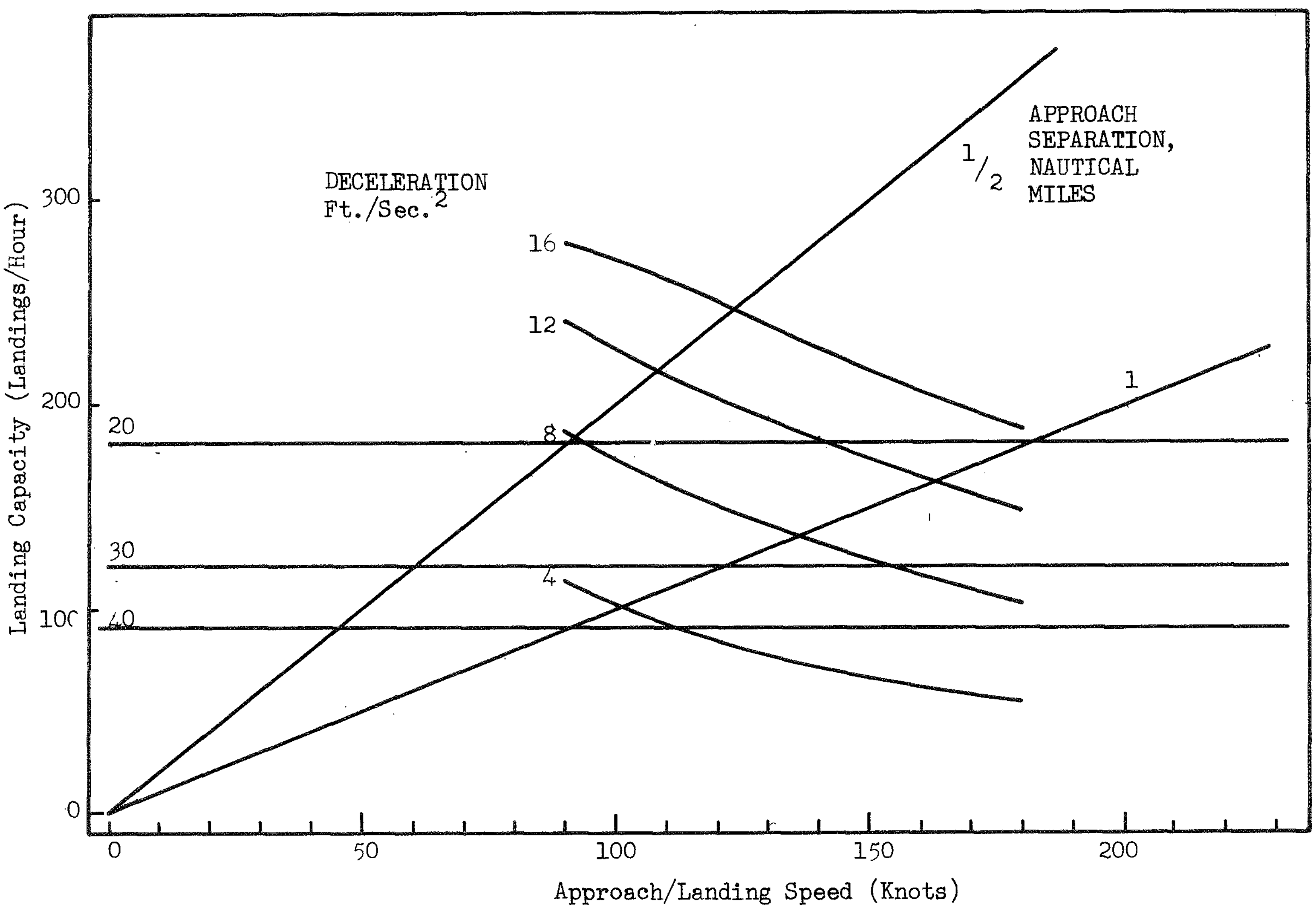

Figure C.7: Approach/Runway System Landing Performance, 30 Knot Turnoff Speed

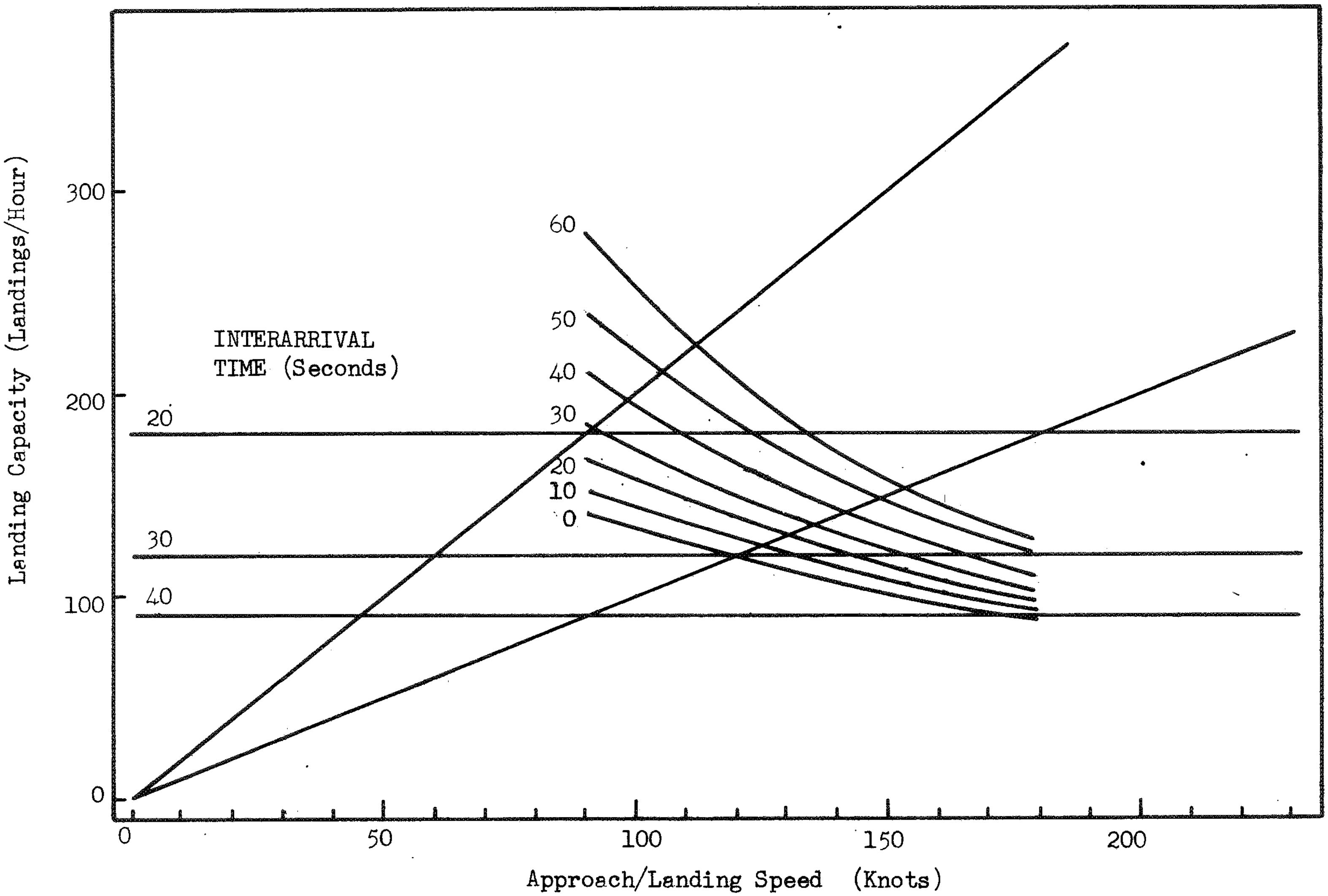

Figure C.8: Approach/Runway System Landing Performance, 8 ft./sec.^{2} Deceleration

APPENDIX D

SEPARATION PROGRAM

A computer program was written to simulate airplanes in the final approach phase. The purpose of the program was to calculate the minimum lateral separation and the minimum vertical separation experienced by airplanes during the final approach phase. The airplanes were flown on constant radius curves as discussed in section 3.4. A flowchart of the program is shown in Figure D.1.

The program randomly selects an airplane according to the statistics from the distribution in Table 3.4. The final approach gate is selected according to the other airplanes in the system and according to the entering sector shown in Figure 3.30. The time at the marker and the time at landing is calculated for each airplane based on a forty second landing interval. The position of each airplane in the system at the current time is calculated. The lateral and vertical separations of each airplane in the system is calculated; and, if the minimums are exceeded, a warning is printed out. The collision avoidance area is calculated, and, if this area is crossed, a warning is printed out. All the airplanes are advanced by one time increment, and the process is repeated.

The program was used on 1000 randomly selected aircraft and none of the separation minimums were exceeded. Since the program only prints out warnings if the minimums are violated, there is no example output, with the exception of the sentences "number of separation conflicts = 0" and "number of collision alarms = 0."

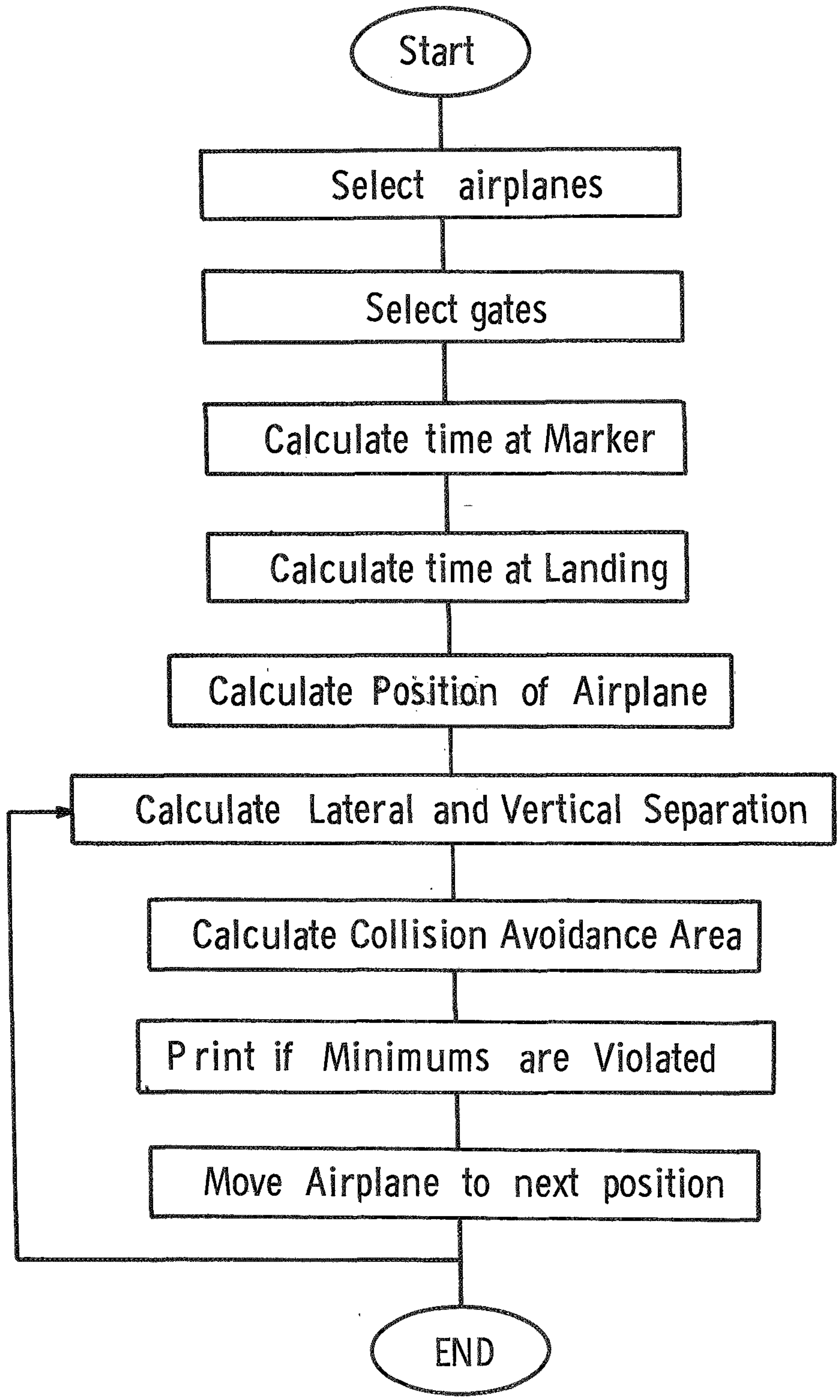

Figure D.1 Separation program flowchart

APPENDIX E

DEFINITION OF NON-GASP VARIABLES USED IN THE TERMINAL AREA SIMULATION

VARIABLE	DESCRIPTION	PROGRAM LOCATION
Arrays:		
ACINSY ( )	Number of A/C in system by A/C category	MAIN, ARRVL, MERGE, EVNTS, DEPQUE, APPRCH
DLY ( )	Stored delay times	APPRCH
DTLVQ ( )	Time A/C can leave queue	MAIN, ARRVL, MERGE, EVNTS, DEPQUE, APPRCH
PLANE ( )	A storage array for A/C parameters as a function of A/C category (reference Section 4.4)	same as above
PRBCAT ( )	Comulative probabilities of A/C arrivals by hour of day	" " "
RATE ( )	Mean arrival rates by hour of day for all approach corridors and A/C category	" " "

Simple Variables:

Note: A/C=KCOL indicates A/C whose attributes are contained in KCOL.

VARIABLE	DESCRIPTION	PROGRAM LOCATION
ACCSP1	Acceptible spacing at merge	MERGE
ACCSP2	Acceptible spacing at touchdown	"
ACCSP3	Acceptible spacing at rollout	"
BLOCK	Flag used with logic 3 to assure that the flight time of the D-A/C is reduced by 10% only once	APPRCH
DELAY	Total time delayed in queue or at takeoff	DEPQUE, APPRCH, MERGE
DELAYM	Flight delay necessary for the D-A/C to follow the A-A/C at merge	APPRCH

VARIABLE	DESCRIPTION	PROGRAM LOCATION
DELAYT	Flight delay necessary for the D-A/C to follow the A-A/C at touchdown	APPRCH
DELMAX	Max. allowable delay in priority scheme for departing queues	MAIN, DEPQUE
DEMAND	Total no. of A/C that have arrived in a day	MAIN, ARRVL, EVNTS
DLYM	Difference in merge times of the P-A/C and D-A/C minus the necessary time separation	APPRCH
DLYT	Difference in touchdown times of the P-A/C and D-A/c minus the necessary time separation	APPRCH
DUM1	Clock time to merge plus separation for A/C=KCOL; used with logic 1 only	APPRCH
DUM2	Clock time to touchdown plus separation for A/C=KCOL; used with logic 1 only	APPRCH
DUM3	Clock time to touchdown plus rollout for A/C=KCOL; used with logic 1 only	APPRCH
ERRLV	Queue leave-time error after an A/C leaves	DEPQUE
ERRHD	Queue leave-time error when an A/C is held	DEPQUE
FLYACT	Difference in touchdown or merge times between the D-A/C or A-A/C	APPRCH
FLYDLY	Inflight delay predicted at time of departing queue	DEPQUE, APPRCH
FLYMG	Separation constraint for the D-A/C following the A-A/C at merge	APPRCH
FLYTD	Separation constraint for the D-A/C following the A-A/C at touchdown	APPRCH

VARIABLE	DESCRIPTION	PROGRAM LOCATION
HOLDT1	Holding constraint for arrival A/C to follow A/C= KCOL at merge; used with logic 1 only	APPRCH
HOLDT2	Holding constraint for arrival A/C to follow A/C=KCOL at touchdown; used with logic 1 only	APPRCH
HOLDMG	Hold time necessary to fit decision A/C behind approach at merge; used in logics 2 and 3	APPRCH
HOLDTD	Hold time necessary to fit decision A/C behind approach A/C at touchdown; used in logics 2 and 3	APPRCH
HOLDTM	Additional delay to A/C in queue before departing queue	DEPQUE, APPRCH, MERGE
ICHECK	A flag used in logic 3 to allow the arrival A/C to proceed the encounter delay equal to FLYDLY while on approach	MAIN, DEPQUE, APPRCH, EVNTS, MERGE
KCAT	Category of A/C	ARRVL, MERGE
KCATA	Category of the successor (equal to A-A/C) to the P-A/C; used in logics 2 and 3	APPRCH
KCATD	Category of the arrival or decision A/C (equal to D-A/C); used in logics 2 and 3	APPRCH
KCATP	Category at least A/C (equal to P-A/C) which the D-A/C can pass before merge; used with logics 2 and 3	APPRCH
KCATWO	Category of A/C waved off	MERGE
KCAT1	Category of A/C=KCOL	APPRCH
KCAT2	Category of arrival A/C current day being simulated	DEPQUE, APPRCH

VARIABLE	DESCRIPTION	PROGRAM LOCATION
KCOL	Column of NSET in which the attributes of A/C are stored	ARRVL, DEPQUE, APPRCH, MERGE
KH	Hours per day to be simulated	MAIN
LDAY	Last day to be simulated	MAIN, EVENTS
LFLAG	Sequencing variable- LFLAG=0, first-in-first out of queue entrance; LFLAG=1, priority entrance	MAIN, DEPQUE, EVENTS, ARRVL
LOGIC	Approach sequence logic code: LOGIC 1: No passing, FIFO LOGIC 2: Passing, no delay for approach A/C LOGIC 3: Passing, min. delay algorithm	MAIN, DEPQUE, EVENTS, APPRCH
MAXCOL	A column of NSET in which the attributes of the A/C with the highest priority is stored. (NSET is a GASP array name)	DEPQUE
NADJMG	Adjustment to merge time; used to consider system errors	MERGE
NBRCRD	No. of approach corridors	MAIN
NCAT	No. of A/C categories in the simulation	MAIN, EVNTS, ARRVL
NCHRCT	No. of parameters for each A/C category	MAIN
NHR	No. of minutes per day to simulate	MAIN, ARRVL, DEPQUE, EVNTS, DEPQUE, APPRCH
NHDY	Current hour of day being simulated	ARRVL, MERGE, EVNTS, DEPQUE, APPRCH
NSTACK	No. of stacks in system	MAIN, DEPQUE
PRIMAX	Max. priority for an A/C in queue	MAIN, EVNTS, ARRVL DEPQUE, APPRCH, MERGE

VARIABLE	DESCRIPTION	PROGRAM LOCATION
SEEDK SEEDL SEEDM	Used in random number generation for arrival rates, waveoffs, and A/C category, respectively	MAIN
SEPACT	Actual separation at touchdown or merge between P-A/C and D-A/C	APPRCH
SEPMG	Necessary separation at merge between the P-A/C and A-A/C in order for D-A/C to fit between	APPRCH
SEPT	Difference at touchdown between the P-A/C and D-A/C	APPRCH
SEPTD	Necessary separation at touchdown between P-A/C and A-A/C for the D-A/C to fit between	APPRCH
SPACE 1	Working variables to calculate separation between A/C on approach	MERGE
TDTIME	Time A/C touches down	MERGE
TEST1	Clock time to merge for arrival A/C	APPRCH
TEST2	Clock time to touchdown for arrival A/C	APPRCH
TLSTTD	Time of last touchdown	MAIN, MERGE, EVENTS
TOTTME	Total A/C time in the system	MERGE
WAVEOFF	Random number used to determine whether an A/C waves off	MERGE
XK1 XK2 XK3 XK4	Priority ranking multi pliers	MAIN, DEPQUE

APPENDIX F

Air Terminal Operations Model-Program and Actual Input Data

(Processor used: CDC 6600)

```
              PROGRAM WWWW(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
000003        DIMENSION NSET(12,200)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003        COMMON HOLDTM,TLSTTD,DEMAND,SEEDK,SEEDL,SEEDM,ICHECK,IFLAG
000003        COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHOY,LDAY,LOGIC,NHR,KH
000003        COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVQ(7),PRBCAT(10,7)
000003        COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
000003        COMMON MAXCOL
        C
        C
        C *************************************************
        C
        C INITIALIZE READ/WRITE MODES
000003        NCRDR=5
000004        NPRNT=6
        C NUMBER OF MINUTES PER DAY SIMULATED--- CHANGE FOR NEW SIMULATION    ***
        C ALSO CHANGE END OF DAY EVENT IN DATA AND ENDDAY INITIALIZATION       ***
000005        NHR=600
        C NUMBER OF HOURS PER DAY SIMULATED  --- CHANGE FOR NEW SIMULATION    ***
000006         KH=10
        C
        C INITIALIZE RANDOM NUMBER GENERATORS
        C ARRIVAL RATES
000007        SEEDK=87415.
000011        X=RANK(SEEDK)
000013        SEEDK=0.0
        C WAVE OFFS
000014        SEEDL=96317.
000015        X=RANL(SEEDL)
000020        SEEDL=0.0
        C A/C CAT
000021        SEEDM=53479.
000022        X=RANM(SEEDM)
000025        SEEDM=0.0
        C ERROR SEED=ISEED INITIALIZED BY GASP
        C
        C *************************************************
```

```
                C
                C READ AND WRITE NBRCRD,NCAT,NCHRCT,LOGIC
000026                READ(NCRDR,10) NBRCRD,NCAT,NCHRCT,LOGIC
000041                WRITE(NPRNT,10) NBRCRD,NCAT,NCHRCT,LOGIC
000055             10 FORMAT(7I10)
                C READ AND WRITE ARRIVAL RATES
000055                READ(NCRDR,20)(RATE(J),J=1,KH)
000070                WRITE(NPRNT,20)(RATE(J),J=1,KH)
000103             20 FORMAT(10F7.2)
000103                DO 25 J=1,KH
000105             25 RATE(J)=RATE(J)/60.0
                C READ AND WRITE PLANE ARRAY
000111                DO 35 I=1,NCHRCT
000112                READ(NCRDR,30)(PLANE(I,J),J=1,NCAT)
000126                WRITE(NPRNT,30)(PLANE(I,J),J=1,NCAT)
000143             30 FORMAT(7F10.4)
000143             35 CONTINUE
                C READ AND WRITE A/C CAT. ARRIVALS BY HOUR OF DAY
000146                DO 70 I=1,KH
000147                READ(NCRDR,65)(PRBCAT(I,J),J=1,NCAT)
000162                WRITE(NPRNT,65)(PRBCAT(I,J),J=1,NCAT)
000176             65 FORMAT(7F10.4)
000176             70 CONTINUE
                C CUMULATIVE PROBABILITIES
000201                DO 90 I=1,KH
000202                PRBCAT(I,1)=PRBCAT(I,1)/(RATE(I)*60.)
000205                DO 80 J=2,NCAT
000206                PRBCAT(I,J)=PRBCAT(I,J)/(RATE(I)*60.)
000213                M=J-1
000215                PRBCAT(I,J)=PRBCAT(I,J)+PRBCAT(I,M)
000222             80 CONTINUE
000224             90 CONTINUE
000226                DO 95 I=1,KH
000230                WRITE(NPRNT,65)(PRBCAT(I,J),J=1,NCAT)
000243             95 CONTINUE
                C *************************************************
                C
                C FURTHER INITIALIZATION
                C
000246                ICHECK=0
000247                IFLAG=0
000250                KDAY=1
000251                TLSEED=0.0
```

```
000252          DEMAND=0.0
000253          DO 100 I=1,NCAT
000254      100 ACINSY(I)=0.0
000260          DO 110 I=1,7
000261      110 DTLVQ(I)=0.0
          C NUMBER OF DAYS SIMULATED            --- CHANGE FOR NEW SIMULATION    ***
000264          IDAY=10
          C NUMBER OF QUEUES SIMULATED  --- CHANGE FOR NEW NUMBER OR TWO RUNWAYS**
000265          NSTACK=3
          C ALSO CHANGE APPROACH CORRIDOR ASSIGNMENT IN ARRVL                      ***
000266          DELMAX=30.0
000267          XK1=1.0/30.0
000271          XK2=1.0/7.0
000272          XK3=1.0/10.0
000274          XK4=3.0/7.0
          C BEGIN SIMULATION
000275          CALL GASP(NSET)
000277          END
```

```
                 SUBROUTINE EVNTS(IX,NSET)
000005           DIMENSION NSET(12,1)
000005           COMMON IO,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KIE,KOL
000005           COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000005           COMMON HOLDTM,TLSTTO,DEMAND,SEECK,SEEOL,SEEDM,ICHECK,LFLAG
000005           COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHDY,LDAY,LOGIC,NHR,KH
000005           COMMON RATE(10),PLANE(20,7),ACINSY(7),OTLVQ(7),PRBCAT(10,7)
000005           COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
000005           COMMON MAXCOL
           C
           C
           C ************************************************
           C
           C SWITCHING DECISION
000005           GO TO(1,2,4,4,5,5,5,5,5,5,5,11,11,13),IX
           C           IX=1,2,3,4,5,6,7,8,9,10,11,12,13
           C
           C ************************************************
           C
           C ARRIVAL EVENT
000025         2 CALL ARRVL(NSET)
000027           RETURN
           C ARRIVAL TO MERGE EVENT
000030         4 IG=IX
000033           CALL MERGE(IG,NSET)
000034           RETURN
           C DEPART QUEUE EVENT
000035         5 IQ=IX
000040           CALL DEPQUE(IQ,NSET)
000041           RETURN
           C
           C************************************************
           C
           C DEBUG PRINT OUT OF FILES
000042        11 IF(TNOW.GE.35.) GO TO 110
           C NEXT DEBUG CHECK
000046           ATRIB(1)=ATRIB(1)+5.
000050           CALL FILEM(1,NSET)
```

```
000052          DO 100 JQ=1,NOQ
000055          IF(NQ(JQ).EQ.0) GO TO 100
000057          CALL PRNTQ(JQ,NSET)
000060      100 CONTINUE
000064      110 RETURN
        C
        C ***********************************************
        C
        C END OF DAY EVENT
        C
        C HOUR OF DAY
000065       13 NHDY=(TNOW+60.-FLOAT(NHR*(KDAY-1)))/60.
000075          SAVTM=TNOW+600.
        C MORE EVENTS IN FILE 1
000076          GO TO 30
        C YES, MORE EVENTS IN FILE
000077       10 CALL RMOVE(MFE(1),1,NSET)
000103          IX=ATRIB(2)+0.001
        C DROP ALL ARRIVALS
000110          IF(IX.EQ.2) GO TO 30
000111          IF(TNOW.GT.SAVTM) GO TO 30
        C TRIGGER EVENT TO OCCUR
000115          IF(IX.GT.11.) GO TO 35
000120           IF (IX.GT.4) GO TO 400
        C MERGE EVENT EOS 3 OR 4
000123          CALL MERGE (IX,NSET)
000124          GO TO 30
        C DEPQUE EVENT EOS 5 TO 10
000126      400 CALL DEPQUE(IX,NSET)
        C MORE EVENTS IN FILE 1
000127       30 IF(NQ(1).GT.0) GO TO 10
        C ALL PLANES HAVE LANDED
        C
000133          GO TO 37
000133       35 DO 36 J=1,NOQ
000135          IF(NQ(IQ).LE.0) GO TO 36
000137          CALL PRNTQ(J,NSET)
000141       36 CONTINUE
000145          GO TO 30
        C
        C ***********************************************
        C
        C COLLECT NECESSARY STATISTICS
```

```
000146       37 CALL COLCT(DEMAND,30,NSET)
            C
            C ***********************************************
            C
            C UPDATE FOR NEXT DAY
000151            DEMAND=0.0
000152            DO 40 I=1,NCAT
000155        40  ACINSY(I)=0.0
000161            TIME=FLOAT(KDAY*NHR)
000164            IF(KDAY.EQ.IDAY) TIME=0.0
000167            DTLVQ(7)=0.0
000170            DO 50 I=1,6
000172         50 DTLVQ(I)=TIME
000176            TLSTID=TIME
            C USED FOR RUNWAY 2 VACANCY TIMES
000177            DTLVQ(6)=TIME
            C UPDATE EVENT FILE 1
000200            DO 70 J=3,IM
000201         70 ATRIB(J)=0.0
            C NEXT END OF DAY EVENT
000205            ATRIB(1)=TIME+FLOAT(NHR)
000210            ATRIB(2)=13.0
000211            CALL FILEM(1,NSET)
            C FIRST ARRIVAL EVENT
000213            ATRIB(1)=TIME
000215            ATRIB(2)=2.0
000216            CALL FILEM(1,NSET)
            C FILE PRINTOUT AT END OF NEXT DAY
000221            ATRIB(1)=TIME+FLOAT(NHR)
000224            ATRIB(2)=12.
000225            CALL FILEM(1,NSET)
000230            NHDY=1
000231            IF(KDAY.EQ.IDAY) GO TO 300
000235            KDAY=KDAY+1
000236            WRITE(NPRNT,80) KDAY
000243         80 FORMAT(1H ,*KDAY=*,I5)
000243            RETURN
            C
            C ***********************************************
            C
            C END OF SIMULATION-COLLECT FINAL STATISTICS
000244       300 NORPT=0
000245            MSTOP=-1
```

```
000246              ICHECK=0
              C DEBUG PRINTOUT OF FILES
000247              ATRIB(1)=TIME+5.0
000251              ATRIB(2)=12.
000253              CALL FILEM(1,NSET)
000256              IF(LFLAG.GT.0) GO TO 320
000262              LOGIC=LOGIC+1
000263              IF(LOGIC.GT.3) GO TO 325
000266              GO TO 305
000266          320 LOGIC=3
000267              GO TO 305
000270          325 LFLAG=1
000271              LOGIC=2
000272          305 KDAY=1
              C INITIALIZE RANDOM NUMBER GENERATORS
              C ARRIVAL RATES
000273              SEEDK=87415.
000275              X=RANK(SEEDK)
000277              SEEDK=0.0
              C WAVE OFFS
000300              SEEDL=96317.
000301              X=RANL(SEEDL)
000304              SEEDL=0.0
              C A/C CAT
000305              SEEDM=53479.
000306              X=RANM(SEEDM)
000311              SEEDM=0.0
              C
000312            1 RETURN
000313              END
```

```
                SUBROUTINE ARRVL(NSET)
000003          DIMENSION NSET(12,1)
000003          COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
               1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
               2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003          COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
               1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
               2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003          COMMON HOLDTM,TLSTTD,DEMAND,SEECK,SEEDL,SEEDM,ICHECK,LFLAG
000003           COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHDY,IDAY,LOGIC,NHR,KH
000003          COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVQ(7),PRBCAT(10,7)
000003           COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
000003          COMMON MAXCOL
          C
          C HOUR OF DAY
000003          NHDY=(TNOW+60.-FLOAT(NHR*(KDAY-1)))/60.
000013          XXXX=FLOAT(NHR*KDAY)
000016          IF(TNOW.GT.XXXX) TNOW=XXXX
          C UPDATE STATISTICS ON ARRIVALS
000021          JCELS(1,NHDY)=JCELS(1,NHDY)+1
000025          DEMAND=DEMAND+1.0
          C
          C ***********************************************
          C
          C GENERATE NEXT ARRIVAL EVENT
000027          TTTT=RANK(SEEDK)
000032          ATRIB(1)=ATRIB(1)-ALOG(TTTT)/RATE(NHDY)
          C ASSURE INDEPENDENCE BETWEEN HOURLY ARRIVALS
000037          NHRTST=(ATRIB(1)+60.-FLOAT(NHR*(KDAY-1)))/60.
000047          NHRTST=NHRTST-NHDY
000051          IF(NHRTST.GT.1) ATRIB(1)=FLOAT(NHR*(KDAY-1)+60*NHDY)
          C PLACE INTO EVENT FILE 1 OF NSET
000061          CALL FILEM(1,NSET)
000064          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 3
000076          WRITE(NPRNT,10)(ATRIB(I),I=1,IM)
000110       10 FORMAT(/1H ,*ARRVL EVENT*, 9X,7F10.4)
          C
          C ***********************************************
          C
          C DETERMINE AIRCRAFT CATEGORY AND INFO
          C TIME ENTER SYSTEM
000110        3 ATRIB(1)=TNOW
```

```
         C GENERATE A/C CAT.
000112         TEST=RANM(SEEDM)
000114         DO 5 J=1,NCAT
000116         KCAT=J
000117         IF(TEST.LE.PRBCAT(NHDY,J)) GO TO 7
000124       5 CONTINUE
000126       7 CALL TMST(ACINSY(KCAT),TNOW,KCAT,NSET)
000133         ACINSY(KCAT)=ACINSY(KCAT)+1.0
000137         ATRIB(2)=FLOAT(KCAT)
         C INITIAL ARRIVAL COMMUNICATION--23
000140         NNN=ATRIB(2)+15.001
000143         JCELS(2,NHDY)=JCELS(2,NHDY)+1
000147         JCELS(2,NNN)=JCELS(2,NNN)+1
000153         JCELS(2,23)=JCELS(2,23)+1
         C ASSIGN APPROACH CORRIDOR            --- CHANGE FOR TWO RUNWAYS       ***
000154         IQ=5
000155         IF(KCAT.GT.2) IQ=6
000161         IF(KCAT.GT.4) IQ=7
000164         ATRIB(6)=FLOAT(IQ)
         C EXPECTED TIME TO MERGE-STAT DIST LATER
000166         ATRIB(3)=PLANE(9,KCAT)
         C ASSIGN MERGE POINT NUMBER
000172         IG=3
000173         IF(IQ.GT.7)  IG=4
         C EXPECTED TIME TO TOUCHDOWN -STAT-DIST LATER
000176         ATRIB(4)=ATRIB(3)+PLANE(10,KCAT)
         C PRINT INFO GENERATED ON CURRENT ARRIVAL
000202         IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 15
000213         WRITE(NPRNT,11)(ATRIB(I),I=1,IM)
000225      11 FORMAT(1H ,*DESCRIPTION*,9X,7F10.4)
         C
         C ***********************************************
         C
         C PLACE INTO QUEUE IF QUEUE NOT EMPTY
000225      15 IF(NQ(IQ).EQ.0) GO TO 30
000230         IF(LFLAG-1)16,17,17
000233      17 ATRIB(5)=TNOW
000235         CALL DEPQUE(IQ,NSET)
000237      16 CONTINUE
000237         NN=IQ+3
000241         TNIQUE=FLOAT(NQ(IQ))
000244         CALL TMST(TNIQUE,TNOW,NN,NSET)
000250         KCOL=MLE(IQ)
```

```
000253          JCAT=FLOAT(NSET(2,KCOL))/SCALE+.0001
000262          ATRIB(5)=FLOAT(NSET(5,KCOL))/SCALE
000267          CALL FILEM(IQ,NSET)
000271          RETURN
          C
          C **********************************************
          C
          C QUEUE EMPTY CHECK DEPART QUEUE TIME
000272       30 ATRIB(5)=TNOW
000274          CALL DEPQUE(IQ,NSET)
000277          IF(ICHECK.LT.10) RETURN
000304          ICHECK=0
000305          GO TO 16
000306          END
```

```
      SUBROUTINE DEPQUE(IQ,NSET)
      DIMENSION NSET(12,1)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
     1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLF,KOL
      COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
     1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
     2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
      COMMON HOLDTM,TLSTTD,DEMAND,SELCK,SEEDL,SEEDM,ICHECK,LFLAG
       COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHDY,IDAY,LOGIC,NHR,KH
      COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVQ(7),PRBCAT(10,7)
       COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
      COMMON MAXCOL
C
C HOUR OF DAY
      NHDY=(TNOW+60.-FLOAT(NHR*(KDAY-1)))/60.
C
C ***********************************************
C
C CALLED UPON NEW ARRIVAL, QUE EMPTY
C OR AT EVENT TIME WITH WAITING
C
      INFLAG=0
C NEW ARRIVAL TEST
      IF(LFLAG.EQ.0) GO TO 10
C DETERMINE WHCIH A/C IN QUEUE TO EXAMINE
   14 DO 1 J=1,NSTACK
      KCOL=MFE(J+4)
      IF(NQ(J+4)-1)6,7,7
    6 PRIMAX(J)=0.
      IF(J.EQ.1) PRIOTY=0.
      GO TO 1
    7 NUPP=NQ(J+4)
      DO 2 I=1,NUPP
      TIN=FLOAT(NSET(1,KCOL))/SCALE
      DELAY=TNOW-TIN
      IF(DELAY-DELMAX)12,13,13
   13 IF(ATRIB(6).GT..0001) GO TO 700
      IQ=J+4
      GO TO 3
  700 ICHECK=10
      RETURN
```

```
000057       12 PRI2=XK1*DELAY+XK2*FLOAT(NSET(2,KCOL))/SCALE+XK3*FLOAT(NQ(J+4))
000073          IF(I.EQ.1) PRI1=PRI2
000077          IF(PRI2-PRI1)4,5,5
000102        5 PRIMAX(J)=PRI2
000105          MCOL(J)=KCOL
000107        4 KCOL=NSET(MX,KCOL)
000113        2 CONTINUE
000116          IF(J.EQ.1) PRIOTY=PRIMAX(1)
000121          IF(PRIOTY-PRIMAX(J)) 8,8,1
000125        8 PRIOTY=PRIMAX(J)
000130          MAXCOL=MCOL(J)
000132          IQ=J+4
000133        1 CONTINUE
000136          IF(ATRIB(6).GT.0.00001) GO TO 15
000141          IF(PRIOTY.LT..001) RETURN
000144          GO TO 11
000145       15 PRIARV=XK4*ATRIB(2)
000147          INFLAG=1
000150          IF(PRIARV-PRIOTY)9,9,20
000153        9 IQ=ATRIB(6)+.0001
000156          IF(NQ(IQ).GT.0) RETURN
000161          ICHECK=10
000162          RETURN
000163       11 KCOL=MAXCOL
000165        3 CALL RMOVE(KCOL,IQ,NSET)
000170          GO TO 20
000172       10 IF(ATRIB(6).GT.0.0001) GO TO 20
             C A/C WAITED
000176          CALL RMOVE(MFE(IQ),IQ,NSET)
000202          NSWIT=1
             C ATRIB NOW CONTAINS SAME INFO FOR BOTH CASES
             C
             C *************************************************
             C
             C TEST TO SEE IF A/C CAN DEPART
000203       20 CONTINUE
             C SYSTEM ERRORS IN QUEUE
000203          MM=ATRIB(2)+7.0001
000206          NN=MM-7
000210          ERRLV=RNORM(MM)
000212          ERRHD=ABS(RNORM(NN))
             C HOLD OR DEPART COMM FOR ARRIVAL
000215          NNN=ATRIB(2)+15.001
```

```
000220          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000224          JCELS(2,NNN)=JCELS(2,NNN)+1
000230          JCELS(2,24)=JCELS(2,24)+1
       C
000231          HOLDTM=DTLVQ(IQ-4)-ATRIB(5)
       C
       C CHECK IF LAST PLANE OUT OF THIS STACK IS 3 MI. OUT
000235          IF(HOLDTM)30,30,70
       C SEE IF ANY PLANES ENROUT
000236       30 IG=3
000237          KKK=ATRIB(6)+.0001
000242          LLL=7
000243          IF(KKK.GT.LLL) IG=4
000246          IF(NQ(IG).EQ.0) GO TO 200
       C MAX NUMBER OF A/C ON APPROACH = 50
000250          IF(NQ(IG).LT.50) GO TO 35
000253          HOLDTM=1.0
000255          GO TO 70
       C
       C*************************************************
       C
       C DETERMINE IF A/C CAN DEPART QUEUE OR NOT
000255       35 CALL  APPRCH(IQ,IG,NSET)
000260          IF(DTLVQ(7).GT.0.0) GO TO 201
000264          IF(ICHECK.EQ.1) GO TO 200
000266          IF(ICHECK.EQ.2) GO TO 200
       C
       C
       C ***********************************************
       C
       C A/C CANNOT DEPART. HOLD ALL A/C IN STACK. UPDATE DEPART LEVEL TIMES
000267       70 ICHECK=0
000270          IF(HOLDTM.LE.0.001) GO TO 200
000273          ATRIB(5)=TNOW+HOLDTM+ERRHD
000275          XXXX=TNOW+30.
000277          IF(ATRIB(5).GT.XXXX) ATRIB(5)=XXXX
000302          IQ=ATRIB(6)+.0001
000305          IF(INFLAG.EQ.1.AND.NQ(IQ).GT.0) RETURN
000317          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 80
000330          WRITE(NPRNT,71) TNOW,HOLDTM,ERRHD,ATRIB(5),DTLVQ(IQ-4)
000350       71 FORMAT(1H ,*HOLDTM CHECK*,8X,5F10.4)
000350       80 CALL  FILEM(IQ,NSET)
000353          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 85
```

```
000366          WRITE(NPRNT,112)(ATRIB(J),J=1,IM)
000400      112 FORMAT(* HOLD*,16X,7F10.4)
          C CREATE NEXT DEPART CHECK EVENT
          C IF ONE EVENT EXISTS, DO NOT GENERATE ANOTHER
000400       85 AIQ=FLOAT(IQ)
000403          CALL FIND(AIQ,5,1,2,KCOL,NSET)
000407          IF(KCOL.EQ.0) GO TO 86
000412          IF(FLOAT(NSET(1,KCOL))/SCALE.LT.ATRIB(5)) GO TO 115
000420          XTIME=TNOW
000421          CALL RMOVE(KCOL,1,NSET)
000424          TNOW=XTIME
000426       86 ATRIB(1)=ATRIB(5)
000430          ATRIB(2)=FLOAT(IQ)
000432          DO 110 I=3,IM
000434          ATRIB(I)=0.0
000436      110 CONTINUE
          C PLACE INTO EVENT FILE 1
000440          CALL FILEM(1,NSET)
000441          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 115
000454          WRITE(NPRNT,111)(ATRIB(J),J=1,IM)
000466      111 FORMAT(* DEPEVENT*,12X,7F10.4)
          C UPDATE DEPART LEVEL TIMES
000466      115 KCOL=MFE(IQ)
          C COMM TO UPDATE DEPART LEVEL TIMES
000472      120 XNNN=FLOAT(NSET(2,KCOL))/SCALE
000477          NNN=XNNN+15.001
000502          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000506          JCELS(2,NNN)=JCELS(2,NNN)+1
000512          JCELS(2,25)=JCELS(2,25)+1
000513          KCOL=NSET(MX,KCOL)
000517          IF(KCOL.GE.7777) GO TO 130
000521          GO TO 120
000522      130 RETURN
          C
          C ************************************************
          C
          C A/C CAN DEPART, BRING A/C DOWN ONE LEVEL
          C DECISION A/C IN ATRIB ARRAY, DEPART A/C
000523      201 FLYDLY=DTLVQ(7)
000525          GO TO 203
000525      200 FLYDLY=0.0
000526          ICHECK=0
000527      203 KCAT2=ATRIB(2) + .0001
```

```
000532          DTLVQ(7)=0.
          C DEFINE A/C FOR APPROACH FILE 3 OR 4
000533          ATRIB(3)=ATRIB(3)+TNOW+FLYDLY
000536          ATRIB(4)=ATRIB(4)+TNOW+FLYDLY
000540          ATRIB(5)=FLYDLY
000541          IQ=ATRIB(6)+.0001
000544          ATRIB(7)=TNOW-ATRIB(1)
000545          DTLVQ(IQ-4)=TNOW+PLANE(8,KCAT2)
          C PUT INTO APPROACH FILE
000552          IG=3
000553          IF(IQ.GT.7) IG=4
000556          CALL FILEM(IG,NSET)
000560          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 207
000573          WRITE(NPRNT,205)(ATRIB(J),J=1,IM)
000605      205 FORMAT(* DEPART*,14X,7F10.4)
          C COLLECT STATISTICS ON DELAY IN QUE
000605      207 NN=IQ-4
000610          DELAY=TNOW-ATRIB(1)
000612          CALL COLCT(DELAY,NN,NSET)
          C GENERATE MERGE EVENT IF NO ONE ELSE IN APPROACH
000615      210 AIG=FLOAT(IG)
000617          CALL FIND(AIG,5,1,2,KCOL,NSET)
000625          IF(KCOL.EQ.0) GO TO 212
000630          TEST=FLOAT(NSET(1,KCOL))/SCALE
000634          IF(TEST.LE.ATRIB(3)) GO TO 230
000636          TEST=ATRIB(3)
000637          XTIME=TNOW
000641          CALL RMOVE (KCOL,1,NSET)
000644          TNOW=XTIME
000646          ATRIB(1)=TEST
000647          CALL FILEM(1,NSET)
000652          GO TO 230
          C GENERATE MERGE EVENT
000654      212 ATRIB(1)=ATRIB(3)
000656          ATRIB(2)=FLOAT(IG)
000657          DO 215 I=3,IM
000661          ATRIB(I)=0.0
000663      215 CONTINUE
          C PUT INTO EVENT FILE 1
000665          CALL FILEM(1,NSET)
          C DESCEND ALL A/C IN QUEUE
000666      230 IF(NQ(IG).EQ.0.AND.LFLAG.EQ.0) RETURN
          C CREATE NEXT DEPART CHECK EVENT
```

```
000677          DO 300 I=1,NSTACK
000701      300 IF(NQ(I+4).GT.0) GO TO 301
000705          RETURN
000706      301 ATRIB(1)=TNOW+ERRLV
000710          ATRIB(2)=FLOAT(IQ)
000712          DO 265 I=3,IM
000713          ATRIB(I)=0.0
000715      265 CONTINUE
          C PUT INTO EVENT FILE 1
000717          CALL FILEM(1,NSET)
000720          KCOL=MFE(IQ)
          C UPDATE DEPART TIME
000724          IF(IFLAG.EQ.1) KCOL=NSET(MX,MAXCOL)
000732          IF(KCOL.GE.7777) RETURN
000736          NSET(5,KCOL)=(TNOW+ERRLV)*SCALE
          C COMM TO DEPART QUEUE
000745      245 XNNN=FLOAT(NSET(2,KCOL))/SCALE
000752          NNN=XNNN+15.001
000755          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000761          JCELS(2,NNN)=JCELS(2,NNN)+1
000765           JCELS(2,26)=JCELS(2,26)+1
000766          KCOL=NSET(MX,KCOL)
000772          IF(KCOL.GE.7777) RETURN
000775          GO TO 245
          C QUE UPDATED
000776          END
```

```
                SUBROUTINE APPRCH(IQ,IG,NSET)
000006          DIMENSION NSET(12,1),DLY(50)
000006          COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
               1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
               2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNO(100),KOF,KLE,KOL
000006          COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
               1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
               2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000006          COMMON HOLDTM,TESTTD,DEMAND,SEECK,SEEDL,SEEDM,ICHECK,IFLAG
000006           COMMON NBRCRD,NCAT,NCHRCT,KCAY,NHDY,IDAY,LOGIC,NHR,KH
000006          COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVO(7),PROCAT(10,7)
000006            COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
000006          COMMON MAXCOL
          C
          C*************************************************
          C
          C HOUR OF DAY
000006          NHDY=(TNOW+60.-FLOAT(NHR*(KCAY-1)))/60.
          C
000015          HOLDTM=0.0
000016          FLYDLY=0.0
000017          K=0
          C
000020          GO TO(32,39,39,39),LOGIC
          C
          C FIFO SIMPLEST LOGIC
000030       32 TEST1=ATRIB(3)+TNOW
000032          TEST2=ATRIB(4)+TNOW
000034          ICHECK=0
          C ABOVE ARE TIMES TO MERGE AND TOUCHDOWN FOR PLANE LEAVING STACK
          C NOW CHECK IF CONFLICT AT MERGE,TD, OR ROLL OUT
000035          KCOL=MFE(IG)
000037          KCAT2=ATRIB(2)+.0001
000042       34 KCAT1= FLOAT(NSET(2,KCOL))/SCALE + .0001
000051          DUM1=FLOAT(NSET(3,KCOL))/SCALE+PLANE(KCAT2+11,KCAT1) -.0001
000064          DUM2=FLOAT(NSET(4,KCOL))/SCALE+PLANE(KCAT2,KCAT1)-.0001
000076          DUM3=FLOAT(NSET(4,KCOL))/SCALE+PLANE(11,KCAT1)-.0001
          C SEE IF ROLL OUT TIME OR 3 MI SEP TIME IS MOST CONTRAINING
000110          IF(DUM2.LT.DUM3) DUM2=DUM3
          C SEE IF PLANE CAN FIT IN 3 MILES BEHIND PLANE IN FRONT
000114          IF(TEST1.GE.DUM1.AND.TEST2.GE.DUM2) GO TO 200
000126       38 GO TO (31,39,39,39) ,LOGIC
```

```
              C
              C************************************************
              C
              C LOGIC 2 OR 3
              C
000136           39 DO 40 J=1,50
000140           40 DLY(J)=0.0
000143              BLOCK=0.0
000144              DELAY=0.0
              C ATRIB CONTAINS INFO ON DECISION A/C
              C DEC A/C CAT
000145              KCATD=ATRIB(2)+0.001
              C APPROACH
000150              IG=3
000151              IF(ATRIB(6).GT.7.001) IG=4
              C TEST = TIME TO MERGE
000154              TEST=TNOW+ATRIB(3)
000156              IF(LOGIC.EQ.3) TEST=TEST-(0.1)*ATRIB(3)
              C FIND A/C ON APPROACH WHICH DEC A/C CAN BEAT
000163              CALL FIND(TEST,2,IG,3 ,JKCOL,NSET)
000170              IIII=JKCOL
              C
              C************************************************
              C
              C DEC A/C BEAT ANY A/C
000172              IF(JKCOL.GT.0) GO TO 45
              C DEC A/C BEATS NO ONE-CAN HE FIT BEHIND LAST A/C
000176              KCOL=MFE(IG)
000200              KCATA=FLOAT(NSET(2,KCOL))/SCALE
000205              GO TO 800
              C
              C************************************************
              C
              C CAN DEC A/C BEAT WITH CORRECT SEP
000206           45 KCATP=FLOAT(NSET(2,JKCOL))/SCALE
              C SEP AT MERGE OK
000214              SEPMG=FLOAT(NSET(3,JKCOL))/SCALE-TEST
000222              IF(SEPMG.GE.PLANE(KCATP+11,KCATD)) GO TO 100
              C
              C************************************************
              C
              C CONFLICT AT MERGE
              C HOLD TIME TO FIT DEC A/C BEHIND P A/C
```

```
000227      50 HOLDMG=(FLOAT(NSET(3,JKCOL))/SCALE-TEST)+PLANE(KCATD+11,KCATP)
000241         HOLDTD=(FLOAT(NSET(4,JKCOL))/SCALE-(TEST+PLANE(10,KCATD)))
              1+PLANE(KCATD,KCATP)
000255         HOLDTM=HOLDMG
000257         IF(HOLDTD.GT.HOLDMG) HOLDTM=HOLDTD
       C MOST CONSTRAINING TIME KNOWN
       C LOGIC 2 HOLDS IN QUEUE. LOGIC 3 CHECKS MIN DELAY
000262         IF(LOGIC.EQ.2) GO TO 1200
       C
       C HOLDTM WITHIN SPEED LIMITS
000264         IF(HOLDTM.GT.(0.2)*ATRIB(3)) GO TO 1190
       C HOLDTM ONLY TIME LESS THAN NOMINAL
000271         IF(BLOCK.GT.0.5) GO TO 55
000274         HOLDTM=HOLDTM-(0.1)*ATRIB(3)
000276         IF(HOLDTM.LT.0.0) HOLDTM=0.0
       C
       C
       C NOW CHECK THIS AGAINST APPROACH TOTAL DELAY
000277      55 DLYM=FLOAT(NSET(3,JKCOL))/SCALE-TEST
000305         DLYM=DLYM-PLANE(KCATP+11,KCATD)
000312         DLYT=FLOAT(NSET(4,JKCOL))/SCALE-(TEST+PLANE(10,KCATD))
000322         DLYT=DLYT-PLANE(KCATP,KCATD)
000327         K=K+1
000331         DLY(K)=DLYM
000333         IF(DLYT.GT.DLYM) DLY(K)=DLYT
       C CONTINUE IF APPROACH DELAY OF THIS A/C IS NEGATIVE OR ZERO
000337         IF(DLY(K).LE.0.001) GO TO 90
000343         DELAY=DELAY+DLY(K)
       C NOW CHECK PRECEEDING A/C
000345         JKCOL=NSET(MXX,JKCOL)
000351         IF(JKCOL.EQ.9999) GO TO 90
000353         KCATD=KCATP
000354         KCATP=FLOAT(NSET(2,JKCOL))/SCALE
000362         TEST=FLOAT(NSET(3,JKCOL))/SCALE+DLY(K)
       C LOOP TO DELAY MORE APPROACH A/C
000371         GO TO 55
       C
       C*************************************************
       C
       C CHECK APPROACH DELAY AGAINST HOLDTM
000371      90 IF(HOLDTM.GT.DELAY.AND.BLOCK.LT.0.001) GO TO 75
000403         IF(HOLDTM.LT.DELAY) GO TO 1200
       C DELAY A/C ON APPROACH
```

```
000405       95 NDLY=DLY(K)*SCALE
000411          IF(JKCOL.EQ.9999) JKCOL=MFE(IG)
000415          NSET(3,JKCOL)=NSET(3,JKCOL)+NDLY
000421          NSET(4,JKCOL)=NSET(4,JKCOL)+NDLY
000424          NSET(5,JKCOL)=NSET(5,JKCOL)+NDLY
000426          NSET(7,JKCOL)=NSET(7,JKCOL)+NDLY
        C COMM TO DELAY
000431          NNN=FLOAT(NSET(2,JKCOL))/SCALE+15.001
000440          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000444          JCELS(2,NNN)=JCELS(2,NNN)+1
000450          JCELS(2,27)=JCELS(2,27)+1
        C RELEASE DEC A/C AFTER UPDATING ALL ON APPROACH
000451          IF(K.EQ.1) GO TO 1000
        C CHECK ON FLYDLY
000452          K=K-1
000453          JKCOL=NSET(MX,JKCOL)
000457          GO TO 95
        C
        C**************************************************
        C
        C HOLDTM WITHIN SPEED LIMITS REDUCE SPEED ONLY ONCE
000457       75 IF(BLOCK.EQ.1.0) GO TO 1200
000461          BLOCK=1.0
000462          IF(NO(IC).LE.1) GO TO 1200
000465          JKCOL=NSET(MXX,LLLL)
000471          LLLL=JKCOL
000472          FLYDLY=HOLDTM-(0.1)*ATRIB(3)
000475          IF(JKCOL.EQ.9999) GO TO 1000
        C CHECK SEP TO PASS PRECEEDING A/C
000477          TEST=ATRIB(3)+TNOW
        C LOOP WITH NEW TEST TIME
000501          GO TO 45
        C IS SEP AT TD OK
000501      100 SEPT=FLOAT(NSET(4,JKCOL))/SCALE-(TEST+PLANE(10,KCATD))
000512          IF(SEPT .GE.PLANE(KCATP,KCATD)) GO TO 205
        C CONFLICT AT TD-DEC A/C IS FASTER
        C LOOP TO EXAMINE HOLD TIMES
000520          GO TO 50
        C
        C**************************************************
        C
        C NO CONFLICT WITH PASSED A/C
        C CAN DEC A/C FIT BEHIND NEXT A/C
```

```
000520      205 KCOL=NSET(MX,JKCOL)
          C DEC A/C BEATS EVERYONE RELAESE
000524          IF(KCOL.LT.7777) GO TO 275
          C D A/C BEATS ALL A/C ON APPROACH
          C CREATE NEW MERGE EVENT
000526          DO 240 J=1,7
000530      240 C(J)=ATRIB(J)
000534          AIG=FLOAT(IG)
000536          CALL FIND(AIG,5,1,2,MGEVNT,NSET)
000542          IF(MGEVNT.LE.0) GO TO 1000
000546          CALL RMOVE(MGEVNT,1,NSET)
000550          ATRIB(1)=TNOW+C(3)+FLYDLY
000553          ATRIB(2)=AIG
000555          CALL FILEM(1,NSET)
000560          DO 245 J=1,7
000564      245 ATRIB(J)=C(J)
000570          GO TO 1000
          C CAT OF NEXT A/C
000571      275 KCATA=FLOAT(NSET(2,KCOL))/SCALE
          C REQUIRED SEP AT MERGE FOR ALL 3 A/C
000577          SEPMG=PLANE(KCATP+11,KCATD)+PLANE(KCATD+11,KCATA)
          C ACTUAL SEP
000606          SEPACT=FLOAT(NSET(3,JKCOL)-NSET(3,KCOL))/SCALE
          C IS SEP GOOD
000616          IF(SEPACT.GE.SEPMG) GO TO 700
          C CONFLICT AT MERGE
          C LOOP TO EXAMINE HOLD TIMES
000620          GO TO 50
          C
          C***************************************************
          C
          C DEC A/C FITS BETWEEN P AND A AT MERGE HOW ABOUT AT TD
          C REQUIRED SEP AT TD
000621      700 SEPTD=PLANE(KCATP,KCATD)+PLANE(KCATD,KCATA)
          C ACTUAL SEP AT TD
000631          SEPACT=FLOAT(NSET(4,JKCOL)-NSET(4,KCOL))/SCALE
          C IS SEP GOOD
000640          IF(SEPACT.GE.SEPTD) GO TO 800
          C CONFLICT AT TD
          C LOOP TO EXAMINE HOLD TIMES
000542          GO TO 50
          C
          C***************************************************
```

```
000765        30 HOLDTM=HOLDT1
000767           IF (HOLDT1.LT.HOLDT2) HOLDTM=HOLDT2
000774           IF (LOGIC.NE.3) GO TO 70
            C
            C***************************************************
            C
000776        70 RETURN
000777       200 ICHECK=2
001000           RETURN
001001           END
```

```
                C
                C DEC A/C FITS BETWEEN P AND A FIND SEP D TO A
                C SEP AT MERGE REQUIRED
000643            800 FLYMG=PLANE(KCATD+11,KCATA)
                C ACTUAL SEP AT MERGE
000650                FLYACT=TEST-FLOAT(NSET(3,KCOL))/SCALE
000656                DELAYM=FLYMG-FLYACT
                C SEP AT TD ACTUAL
000660                FLYACT=(TEST+PLANE(10,KCATD))-FLOAT(NSET(4,KCOL))/SCALE
                C SEP AT TD REQUIRED
000671                FLYTD=PLANE(KCATD,KCATA)
                C IS DELAY NECESSARY
000676                DELAYT=FLYTD-FLYACT
000700                FLYDLY=DELAYM
000701                IF(DELAYT.GT.DELAYM) FLYDLY=DELAYT
000704                IF(FLYDLY.LT.0.0) FLYDLY=0.0
                C RELEASE DEC A/C
                C IF FLYDLY LE .1 * ATRIB(3)
000706                IF(FLYDLY.LE.(0.1)*ATRIB(3)) GO TO 1000
                C HOLD IN QUEUE
000712                HOLDTM=FLYDLY-(0.1)*PLANE(9,KCATD)
000716                GO TO 1200
                C
                C*************************************************
                C
                C RELEASE
000717           1000 DTLVQ(7)=FLYDLY
000721                IF(FLYDLY.EQ.0.0) ICHECK=1
000722                RETURN
                C
                C*************************************************
                C
                C HOLD
000723           1190 HOLDTM=(0.1)*ATRIB(3)
000725           1200 FLYDLY=0.0
000726                GO TO 70
                C
000727             31 HOLDT1=DUM1-TEST1
000731                HOLDT2=DUM2-TEST2
                C SEE IF MERGE OR TD IS MOST CONSTRAINING
000733                IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 30
000744                WRITE(NPRNT,1001) DUM1,DUM2,HOLDT1,HOLDT2,HOLDTM,TEST1,TEST2
000765           1001 FORMAT(* VARIABLES*,11X,7F10.4)
```

```
                SUBROUTINE MERGE(IG,NSET)
000005          DIMENSION NSET(12,1)
000005          COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
               1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
               2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000005          COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
               1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
               2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000005          COMMON HOLDTM,TLSTTD,DEMAND,SELCK,SEEDL,SEEDM,ICHECK,LFLAG
000005            COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHDY,LDAY,LOGIC,NHR,KH
000005          COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVQ(7),PRBCAT(10,7)
000005              COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRTMAX(6),C(7)
000005          COMMON MAXCOL
          C
          C HOUR OF DAY
000005          NHDY=(TNOW+60.-FLOAT(NHR*(KDAY-1)))/60.
          C
          C *************************************************
          C
          C FIRST A/C HAS ARRIVED AND IS MOVED ON
000014          CALL RMOVE(MLE(IG),IG,NSET)
000021          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 30
000034          WRITE(NPRNT,25)(ATRIB(J),J=1,IM)
000046       25 FORMAT(* MERGE*,15X,7F10.4)
          C COMM TO CLEAR FOR TD
000046       30 NNN=ATRIB(2)+15.001
000051          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000055          JCELS(2,NNN)=JCELS(2,NNN)+1
000061          JCELS(2,28)=JCELS(2,28)+1
          C FLIGHT PATH DELAY
000062          NN=ATRIB(6)+2.0
000065          DELAY=ATRIB(5)
000066          CALL COLCT(DELAY,NN,NSET)
          C TOTAL DELAY BY A/C CAT.
000073          NN=ATRIB(2)+12.0001
000076          DELAY=ATRIB(7)
000100          CALL COLCT(DELAY,NN,NSET)
000104          NN=ATRIB(2)+3.0001
000107          CALL HISTO(DELAY,2.0,2.0,NN,NSET)
          C INTER-TOUCHDOWN TIMES
000115          KCAT=ATRIB(2)+0.001
000120          IF(IG.EQ.4) GO TO 40
```

```
000123           TDTIME=ATRIB(4)-TLSTTD
000125           CALL COLCT(TDTIME,20,NSET)
000130           CALL HISTO(TDTIME,0.25,0.25,3,NSET)
000136           TLSTTD=ATRIB(4)+PLANE(11,KCAT)
000143           GO TO 50
000145        40 TDTIME=ATRIB(4)-DTLVQ(6)
000147           CALL COLCT(TDTIME,21,NSET)
000152           CALL HISTO(TDTIME,0.25,0.25,5,NSET)
000160           DTLVQ(6)=ATRIB(4)+PLANE(11,KCAT)
           C TOTAL A/C TIME IN SYSTEM.
000165        50 NN=29
000166           TOTIME=TNOW-ATRIB(1)
000170           CALL COLCT(TOTIME,NN,NSET)
           C TOTAL NUMBER OF TOUCHDOWNS BY HOUR OF DAY
000175           NNN=NHDY+11
000177           JCELS(1,NNN)=JCELS(1,NNN)+1
           C NUMBER OF A/C IN SYSTEM BY CAT.
000203           KCAT=ATRIB(2)+.0001
000206           CALL TMST(ACINSY(KCAT),TNOW,KCAT,NSET)
000214           ACINSY(KCAT)=ACINSY(KCAT)-1.0
           C MORE A/C IN PATH-TEST
000220           IF(NQ(IG).EQ.0) GO TO 500
           C
           C***************************************************
           C
           C FIND RANDOM ADJUSTMENT TO MERGE TIME FOR SECOND A/C
000223           NADJMG=RNORM(KCAT)*SCALE
000227           KCOL=MLE(IG)
000232           NSET(3,KCOL)=NSET(3,KCOL)+NADJMG
000236           NSET(4,KCOL)=NSET(4,KCOL)+NADJMG
           C ADD ADJMRG TO DELAY IF POSITIVE
000241           IF(NADJMG.LE.0) GO TO 120
           C DOES A/C WAVE OFF
000242           WAVOFF=RANL(SEEDL)
000244           IF(WAVOFF.LT.0.02) GO TO 250
000247           NSET(5,KCOL)=NSET(5,KCOL)+NADJMG
000253           NSET(7,KCOL)=NSET(7,KCOL)+NADJMG
000256           GO TO 130
           C
           C***************************************************
           C
           C TEST TO ASSURE CORRECT SEP WITH A/C AHEAD
000257       120 SPACE1=FLOAT(NSET(3,KCOL))/SCALE-TNOW
```

```
000265            SPACE2=FLOAT(NSET(4,KCOL))/SCALE-ATRIB(4)
           C ACCEPTABLE SEPARATION=ACCSPC
000272            NKCAT=ATRIB(2)+.0001
000276            KCAT=FLOAT(NSET(2,KCOL))/SCALE+.0001
000305            ACCSP1=PLANE(KCAT+11,NKCAT)
000311            ACCSP2=PLANE(KCAT,NKCAT)
000315            ACCSP3=PLANE(11,NKCAT)
000320            IF(ACCSP3.GT.ACCSP2) ACCSP2=ACCSP3
           C IS SEPARATION OK
000323            NTEST1=(SPACE1-ACCSP1)*SCALE
000327            NTEST2=(SPACE2-ACCSP2)*SCALE
000333            NTEST=NTEST1
000334            IF(NTEST2.LT.NTEST1) NTEST=NTEST2
000337            IF(NTEST.GE.0) GO TO 300
           C
           C *************************************************
           C
           C TEST TO ASSURE CORRECT SEP WITH A/C BEHIND
000341            NSET(3,KCOL)=NSET(3,KCOL)-NTEST
000344            NSET(4,KCOL)=NSET(4,KCOL)-NTEST
000347            NSET(5,KCOL)=NSET(5,KCOL)-NTEST
000352            NSET(7,KCOL)=NSET(7,KCOL)-NTEST
           C COMM TO DELAY SUCCESSIVE A/C AT MERGE
000355            XNNN=FLOAT(NSET(2,KCOL))/SCALE
000362            NNN=XNNN+15.001
000365            JCELS(2,NHDY)=JCELS(2,NHDY)+1
000371            JCELS(2,NNN)=JCELS(2,NNN)+1
000375            JCELS(2,29)=JCELS(2,29)+1
           C CHECK SUCCESSIVE A/C FOR CORRECT SEPARATION
000376        130 IF(NQ(IG).LE.1) GO TO 300
000402            NKCOL=NSET(MXX,KCOL)
000406        135 SPACE1=FLOAT(NSET(3,NKCOL)-NSET(3,KCOL))/SCALE
000416            SPACE2=FLOAT(NSET(4,NKCOL)-NSET(4,KCOL))/SCALE
           C ACCEPTABLE SEPARATION=ACCSPC
000425            NKCAT=FLOAT(NSET(2,NKCOL))/SCALE+.0001
000434            ACCSP1=PLANE(NKCAT+11,KCAT)
000440            ACCSP2=PLANE(NKCAT,KCAT)
000444            ACCSP3=PLANE(11,KCAT)
000447            IF(ACCSP3.GT.ACCSP2) ACCSP2=ACCSP3
000452            NTEST1=(SPACE1-ACCSP1)*SCALE
000456            NTEST2=(SPACE2-ACCSP2)*SCALE
000462            NTEST=NTEST1
000463            IF(NTEST2.LT.NTEST1) NTEST=NTEST2
```

```
000466          IF(NTEST.GE.0) GO TO 300
         C
         C ************************************************
         C
         C SEPARATION NOT GOOD,DELAY A/C
000470     140 NSET(3,NKCOL)=NSET(3,NKCOL)-NTEST
000474          NSET(4,NKCOL)=NSET(4,NKCOL)-NTEST
000477          NSET(5,NKCOL)=NSET(5,NKCOL)-NTEST
000502          NSET(7,NKCOL)=NSET(7,NKCOL)-NTEST
         C COMM TO DELAY A/C IN APPROACH DUE TO ERROR
000505          XNNN=FLOAT(NSET(2,KCOL))/SCALE
000512          NNN=XNNN+15.001
000515          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000521          JCELS(2,NNN)=JCELS(2,NNN)+1
000525          JCELS(2,29)=JCELS(2,29)+1
         C MORE A/C TO CHECK
000526          IF(NSET(MXX,NKCOL).EQ.9999) GO TO 300
000533          KCOL=NKCOL
000534          KCAT=NKCAT
000535          NKCOL=NSET(MXX,NKCOL)
000540          GO TO 135
         C ALL SEPARATIONS OF APPROACHING A/C CK
         C
         C ************************************************
         C
         C
         C WAVE OFFS--PUT BACK INTO APPROACH ACCORDING TO LOGIC
         C
000541     250 CALL RMOVE(MLE(IG),IG,NSET)
         C POSITION COMM TO WAVE OFF A/C
000546          NNN=ATRIB(2)+15.001
000551          JCELS(2,NHDY)=JCELS(2,NHDY)+1
000555          JCELS(2,NNN)=JCELS(2,NNN)+1
000561          JCELS(2,30)=JCELS(2,30)+1
         C REDEFINE A/C WAVED OFF
000562          IW=20
000563          KCATWO=ATRIB(2)+0.0001
000566          ATRIB(3)=ATRIB(3)+PLANE(19,KCATWO)-TNOW
000573          ATRIB(4)=ATRIB(3)+PLANE(10,KCATWO)
000577          ATRIB(5)=ATRIB(5)+PLANE(19,KCATWO)
000603          ATRIB(7)=ATRIB(7)+PLANE(19,KCATWO)
000607          IF(KDAY.GT.1.OR.NHDY.GT.2) GO TO 270
000622          WRITE(NPRNT,260)(ATRIB(J),J=1,IM)
```

```
000634      260  FORMAT(* WAVE OFF--------*,5X,7F10.4)
           C
           C*************************************************
           C
           C DETERMINE POSITION ON APPROACH
000634      270 ICHECK=4
000635          HOLDTM=0.0
000636          CALL APPRCH(IM,IG,NSET)
000643          ICHECK=0
000644          IF(HOLDTM.GT.60.) HOLDTM=60.
           C DEFINE WAVE OFF AND REPLACE IN FILE 3 OR 4. THE APPROACH FILE
000651           KCAT=ATRIB(2)+0.0001
000654          ATRIB(3)=ATRIB(3)+HOLDTM+TNOW
000657          XXXX=TNOW+60.
000661          IF(ATRIB(3).GT.XXXX) ATRIB(3)=XXXX
000664          ATRIB(4)=ATRIB(3)+PLANE(10,KCAT)
000671          ATRIB(5)=ATRIB(5)+HOLDTM
000673          ATRIB(7)=ATRIB(7)+HOLDTM
           C ADD DELAY TO NEW MERGE TIME
           C PUT WAVE OFF INTO APPROACH
000674          CALL FILEM(IG,NSET)
000675          RETURN
           C
           C ***********************************************
           C
           C GENERATE NEXT MERGE EVENT
000676      300 KCOL=MLE(IG)
000702          IF(KCOL.LE.0) GO TO 500
000703          ATRIB(1)=FLOAT(NSET(3,KCOL))/SCALE
000710          ATRIB(2)=FLOAT(IG)
000711          DO 305 I=3,IM
000713          ATRIB(I)=0.0
000715      305 CONTINUE
           C PLACE INTO EVENT FILE
000717          CALL FILEM(1,NSET)
000720      500 RETURN
000721          END
```

```
              SUBROUTINE OTPUT(NSET)
000003        DIMENSION NSET(12,1)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCROR,NEP,VNQ(100),KOF,KLF,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003          COMMON HOLDTM,TESTTQ,DEMAND,SEECK,SEEDL,SEEDM,ICHECK,LFLAG
000003            COMMON NBRCRD,NCAT,NCHRCT,KDAY,NHDY,LDAY,LOGIC,NHR,KH
000003        COMMON RATE(10),PLANE(20,7),ACINSY(7),DTLVO(7),PRBCAT(10,7)
000003              COMMON NSTACK,DELMAX,XK1,XK2,XK3,XK4,MCOL(6),PRIMAX(6),C(7)
000003        COMMON MAXCOL
       C
       C
       C ******************************************************
       C
000003        WRITE(NPRNT,10)
000007     10 FORMAT(//1H ,*////////////////////////////////////////////////////////////
             1////////////////////////////////////////////////////////////////////
             2*)
000007        NSTRIP=1
000010        NDMDT=SUMA(30,1)
000012        IF(LFLAG.EQ.0) LTEST=LOGIC-1
000016        IF(LFLAG.EQ.1.AND.LOGIC.EQ.2) LTEST=3
000026        IF(LFLAG.EQ.1.AND.LOGIC.EQ.3) LTEST=2
000036        IF(NRUNS.EQ.2) LTEST=3
000041        SEP=3.0
000043        WRITE(NPRNT,20) NSTRIP,NDMDT,LTEST,LFLAG,SEP
000060     20 FORMAT(//1H , 4X,*CURRENT DAY DATA ON *,I1,* RUNWAY*, 4X,
             1 *TOTAL DEMAND=*,I10, 4X,*LOGIC=*,I2, 4X,*LFLAG=*,I2, 4X,
             2F4.1,* MILE SEPARATION AT MERGE*)
000060        WRITE(NPRNT,30) LDAY,NHR
000070     30 FORMAT(//1H ,10X,*NUMBER OF DAYS SIMULATED=*,I4,10X,
             1*NUMBER OF MINUTES PER DAY=*,I5)
000070        DLYQUE=0.0
000071        DO 40 J=1,6
000074     40 DLYQUE=DLYQUE+SUMA(J,1)
000101        DLYAPP=0.0
000102        DO 50 J=7,12
000103     50 DLYAPP=DLYAPP+SUMA(J,1)
000110        DLYTOT=DLYQUE+DLYAPP
```

```
000112        WRITE(NPRNT,60) DLYQUE,DLYAPP,DLYTOT
000123     60 FORMAT(//1H ,10X,*DELAY IN QUEUES=*,F10.1,
             110X,* DELAY ON APPROACHES=*,F10.1,
             210X,* TOTAL DELAY=*,F10.1)
000123        COMM=0.0
000124        DO 70 J=16,22
000127     70 COMM=COMM+FLOAT(JCFLS(2,J))
000140        WRITE(NPRNT,80) COMM
000146     80 FORMAT(//1H ,10X,*TOTAL NUMBER OF COMMUNICATIONS=*,F15.1)
000146        WRITE(NPRNT,10)
000152        RETURN
000153        END
```

```
                                                   IDENT   RANK
                               000013    PROGRAM LENGTH

                                         BLOCKS

                      000000   000013    PROGRAM*   LOCAL

                                         ENTRY POINTS

                                            000001 RANK

                                                   ENTRY   RANK
       000000  22011613555555000001      +         VFD 42/0HRANK,18/1
       000001  00000000000000000000      RANK      DATA    0
       000002  5120000011 +                         SA2     RANNO
                         56110                     SA1     B1
                              10622                BX6     X2
       000003  0301000007 +                        ZR      X1,RANDOM
                         24606                     NX6     B0,X6
       000004  0331000001 +                        NG      X1,RANK
                         6120777717                SB2     -60B
       000005  27621                               PX6     B2,X1
                    43273                          MX2     59
                         16662                     BX6     -X2+X6
                              54620                SA6     A2
       000006  0400000001 +                        ZR      B0,RANK
       000007  5110000012 +              RANDOM    SA1     RANMLT
                         42612                     DX6     X1*X2
                              54620                SA6     A2
       000010  24606                               NX6     B0,X6
                    0400000001 +                   ZR      B0,RANK
                           0000011 +     REL       EQU     **1+1
       000011  17171274321477413155      RANNO     DATA    17171274321477413155B
       000012  20000000000000553645      RANMLT    DATA    20000000000000553645B
       000013                                      END

                               011671     UNUSED STORAGE            25 STATEMENTS         5  SYMBOLS
```

```
                                             IDENT   RANL
                           000013     PROGRAM LENGTH

                                      BLOCKS

                  000000   000013     PROGRAM*   LOCAL

                                      ENTRY POINTS

                                         000001 RANL

                                                 ENTRY   RANL
     000000  22011614555555000001     +          VFD 42/0HRANL.18/1
     000001  00000000000000000000     RANL       DATA    0
     000002  5120000011 +                        SA2     RANNO
                       56110                     SA1     B1
                            10622                 BX6     X2
     000003  0301000007 +                        ZR      X1.RANDOM
                       24606                      NX6     B0.X6
     000004  0331000001 +                        NG      X1.RANL
                       6120777717                SB2     -60B
     000005  27621                                PX6     B2.X1
                  43273                           MX2     59
                       16662                     BX6     -X2+X6
                            54620                SA6     A2
     000006  0400000001 +                        ZR      B0.RANL
     000007  5110000012 +             RANDOM     SA1     RANMLT
                       42612                     DX6     X1*X2
                            54620                 SA6     A2
     000010  24606                                NX6     B0.X6
                  0400000001 +                   ZR      B0.RANL
                         0000011 +    REL        EQU     **1+1
     000011  17171274321477413155     RANNO      DATA    17171274321477413155B
     000012  20000000000000553645     RANMLT     DATA    20000000000000553645B
     000013                                      END

                           015535      UNUSED STORAGE           25 STATEMENTS          5  SYMBOLS
```

```
                                    IDENT   RANM
                     000013    PROGRAM LENGTH

                               BLOCKS

              000000   000013    PROGRAM*   LOCAL

                             .   ENTRY POINTS

                                   000001 RANM

                                              ENTRY   RANM
    000000  22011615555555000001     +        VFD 42/0HRANM,18/1
    000001  00000000000000000000     RANM     DATA    0
    000002  5120000011 +                       SA2     RANNO
                      56110                    SA1     B1
                            10622              BX6     X2
    000003  0301000007 +                       ZR      X1.RANDOM
                      24606                    NX6     B0.X6
    000004  0331000001 +                       NG      X1.RANM
                      6120777717               SB2     -60B
    000005  27621                              PX6     B2.X1
                43273                          MX2     59
                      16662                    BX6     -X2+X6
                            54620              SA6     A2
    000006  0400000001 +                       ZR      B0.RANM
    000007  5110000012 +             RANDOM   SA1     RANMLT
                      42612                    DX6     X1*X2
                            54620              SA6     A2
    000010  24606                              NX6     B0.X6
                0400000001 +                   ZR      B0.RANM
                       0000011 +     REL       EQU     **1+1
    000011  17171274321477413155     RANNO    DATA    17171274321477413155B
    000012  20000000000000553645     RANMLT   DATA    20000000000000553645B
    000013                                    END

                     015535    UNUSED STORAGE          25 STATEMENTS        5  SYMBOLS
```

```
C
C***********************************************************************
C
C INPUT DATA
C
         6          7          19         1
  31.    55.    40.    39.    10.    27.    38.    30.    26.    55.
    1.95      1.95      1.95      1.95      1.95      1.95      1.95
    1.49      1.49      1.49      1.49      1.49      1.49      1.49
   1.36      1.36      1.36      1.36      1.36      1.36      1.36
   1.20      1.20      1.20      1.20      1.20      1.20      1.20
   1.04      1.04      1.04      1.04      1.04      1.04      1.04
   1.01      1.01      1.01      1.01      1.01      1.01      1.01
  .95       .95       .95       .95       .95       .95       .95
   1.12      1.04      1.00      0.89      0.78      0.76      0.73      8
   2.4       2.3       10.8      9.7       20.6      19.82     19.08
   1.3       1.0       0.9       0.8       0.7       0.7       0.6       10
   .50       .45       .50       .48       .57       .61       0.66
   1.65    1.65      1.65      1.65      1.65      1.65      1.65
   1.31     1.31      1.31      1.31      1.31     1.31      1.31
   1.16     1.16     1.16     1.16      1.16      1.16      1.16
  1.04     1.04     1.04     1.04     1.04     1.04     1.04
   .92      .92       .92      .92       .92         .92      .92
   .87      .87       .87       .87      .87      .87        .87
   .85      .85      .85        .85      .85      .85       .85
  3.7      3.3      11.7       10.5      9.2       8.8       8.5
    5.        0.         1.        8.       17.
    7.        0.         1.       15.       32.
    3.        0.         1.       12.       24.
    6.        0.         1.       10.       22.
    2.        0.         1.        2.        5.
    1.        0.         1.        8.       17.
    2.        0.         1.       11.       24.
    3.        0.         1.        8.       18.
    4.        0.         1.        7.       14.
    7.        0.         1.       15.       32.
WEWILHELM       1  7171970    5
   14    10    30    13   200     7    10    30    1000.0
   28    28    28    28    28    28    28    28    28    28
    1     1     3     3     1     1     1     1     1     1
    1     1     2     2     1     1     1     1     1     1
    0.0       -.8        .8        .36
     .0       -.7        .7        .35
     .0       -.5        .5        .2
```

```
 .0        -.5       .5      .18
 .0        -.45      .45     .15
 .0        -.4       .4      .15
 .0        -.4       .4      .15
2.0        0.5       3.5     0.50
1.3        0.5       2.8     0.50
1.2        0.5       2.7     0.50
1.1        0.5       2.6     0.50
1.0        0.5       2.5     0.50
1.0        0.5       2.5     0.50
1.0        0.5       2.5     0.50
0    1     0    7    0.0    2000.0        12345
    -1
     1     0.0       2.0
     1     5.       12.
     1   600.       12.
     1  600.       13.
     0
0    1     0    7    0.0    2000.0        12345
    -1
     1     0.0       2.0
     1     5.       12.
     1   600.       12.
     1  600.       13.
     0
0    1     0    7    0.0    2000.0        12345
    -1
     1     0.0       2.0
     1     5.       12.
     1   600.       12.
     1  600.       13.
     0
0    1     0    7    0.0    2000.0        12345
    -1
     1     0.0       2.0
     1     5.       12.
     1   600.       12.
     1  600.       13.
     0
0    1     0    7    0.0    2000.0        12345
    -1
     1     0.0       2.0
     1     5.       12.
     1   600.       12.
```

```
          1 600.        13.
          0
C SUBROUTINE OTPUT PRINTOUT FOR 1.5 MILE SEPARATION
      SEP=1.5
C PLANE ARRAY FOR 1.5 MILE SEPARATION
  .98       .98       .98       .98       .98       .98       .98
  .75       .75       .75       .75       .75       .75       .75
  .68       .68       .68       .68       .68       .68       .68
  .60       .60       .60       .60       .60       .60       .60
   .52      .52       .52       .52       .52       .52       .52
   .50       .5        .5       .5        .5        .5        .5
    .48      .48      .48        .48      .48       .48       .48
   .56       .52       .50       .45      .39        .38       .36
   2.4       2.3       10.8      9.7      20.6      19.82     19.08
   1.3       1.0       0.9       0.8      0.7       0.7       0.6         10
   .50       .45       .50       .48      .57       .61       0.66
   .82       .82       .82       .82      .82       .82        .82
   .66       .66       .66       .66      .66       .66       .66
  .58       .58       .58        .58      .58       .58       .58
  .52       .52       .52       .52       .52       .52       .52
  .46       .46        .46      .46       .46       .46        .46
  .44       .44        .44      .44       .44       .44       .44
  .43      .43        .43       .43       .43       .43       .43
  3.7       3.3       11.7      10.5      9.2       8.8       8.5
C MAIN PROGRAM INITIALIZATION FOR 2 RUNWAYS WITH 6 QUEUES
      NSTACK=6
C SUBROUTINE ARRVL QUEUE ASSIGNMENT FOR A/C CAT 1 AND 2 ON 2 RUNWAYS
      IQ=8
C SUBROUTINE OTPUT PRINTOUT FOR 2 RUNWAYS
      NSTRIP=2
```

APPENDIX G

GASP Simulation Language (Version Used in Simulation)

(Processor used: CDC 6600)

```
                SUBROUTINE COLCT (XX,    N, NSET)
000006          DIMENSION NSET(12,1), XX(1)
000006          COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
               1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
               2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000006          COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
               1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
               2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000006          IF (N) 2,2,1
000007        2 CALL  ERROR(90,NSET)
000011        1 IF (N- NCLCT) 3,3,2
000015        3 SUMA(N,1)= SUMA(N,1) +XX(1)
000020          SUMA(N,2)= SUMA(N,2) +XX(1)*XX(1)
000023          SUMA(N,3) = SUMA(N,3)+1.0
000025          IF( XX(1) -SUMA(N,4)) 4, 5, 5
000027        4 SUMA(N,4)= XX(1)
000031        5 IF(XX(1) -SUMA(N,5)) 7, 7, 6
000034        6 SUMA(N,5)= XX(1)
000036        7 RETURN
000037          END
```

```
              SUBROUTINE DATAN(NSET)
000003        DIMENSION NSET(12,1)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003        IF (NOT)23,1,2
        C*****NEP IS A CONTROL VARIABLE FOR DETERMINING THE STARTING CARD
        C*****TYPE FOR MULTIPLE RUN PROBLEMS.  THE VALUE OF NEP SPECIFIES THE
        C*****STARTING CARD TYPE.
000005      2 NT=NEP
000007        GO TO (1,5,6,41,42,8,43,299,15,20),NT
000024     23 CALL ERROR(95,NSET)
000027      1 NOT = 1
000030        NRUN = 1
        C*****DATA CARD TYPE ONE
000031        READ (NCRDR,101) NAME,NPROJ,MON,NDAY,NYR,NRUNS
000051    101 FORMAT (6A2,I4,I2,I2,I4,I4)
000051        IF(NRUNS) 30,30,5
000054     30 CALL EXIT
        C*****DATA CARD TYPE TWO
000055      5 READ (NCRDR,803) NPRMS,NHIST,NCLCT,NSTAT,ID,IM,NOQ,MXC,SCALE
000103    803 FORMAT (8I5,F10.2)
000103        IF (NHIST) 41,41,6
        C*****DATA CARD TYPE THREE IS USED ONLY IF NHIST IS GREATER THAN ZERO
        C*****SPECIFY NUMBER OF CELLS IN HISTOGRAMS NOT INCLUDING END CELLS
000106      6 READ (NCRDR,103) (NCELS(I),I=1,NHIST)
000121    103 FORMAT (10I5)
        C*****DATA CARD TYPE FOUR
        C*****SPECIFY KRANK=RANKING ROW
000121     41 READ (NCRDR,103) (KRANK(I),I=1,NOQ)
        C*****DATA CARD TYPE FIVE
        C*****SPECIFY INN=1 FOR LVF, INN=2 FOR HVF
000134     42 READ (NCRDR,103) (INN(I),I=1,NOQ)
000147        IF (NPRMS) 23,43,8
000152      8 DO 9 I = 1,NPRMS
        C*****DATA CARD TYPE SIX IS USED ONLY IF NPRMS IS GREATER THAN ZERO
000154        READ (NCRDR,106) (PARAM(I,J),J=1,4)
000167    106 FORMAT(4F10.4)
000167      9 CONTINUE
```

```
         C*****DATA CARD TYPE SEVEN.  THE NEP VALUE IS FOR THE NEXT RUN.  SET
         C*****JSEED GREATER THAN ZERO TO SET TNOW EQUAL TO TBEG.
000173      43 READ (NCRDR, 104) MSTOP,JCLR,NORPT,NEP,TBEG,TFIN,JSEED
000215     104 FORMAT( 4I5, 2F10.3, I10)
000215         IF (JSEED) 27,26,27
000220      27 ISEED=JSEED
000222         RNUM = DRAND(ISEED)
000224         ISEED=0
000225         TNOW = TBEG
000226         DO 142 J=1,NOQ
000231     142 QTIME(J)=TNOW
000235      26 JMNIT = 0
         C*****INITIALIZE NSET
         C*****SPECIFY INPUTS FOR NEXT RUN
         C*****READ IN INITIAL EVENTS
000236     299 DO 300 JS = 1,ID
         C*****DATA CARD TYPE 8
         C*****INITIALIZE NSET BY JQ EQUAL TO A NEGATIVE VALUE ON FIRST EVENT
         C*****CARD
         C*****READ IN INITIAL EVENTS.  END INITIAL EVENTS AND ENTITIES WITH JQ
         C*****EQUAL TO ZERO
000240         READ (NCRDR,1110)JQ,(ATRIB(JK),JK=1,IM)
000254    1110 FORMAT(I10,(7F10.4))
000254         IF(JQ) 44,15,320
000257      44 INIT=1
000260         CALL SET(1,NSET)
000263         GO TO 300
000265     320 CALL FILEM(JQ,NSET)
000270     300 CONTINUE
         C*****JCLR BE POSITIVE FOR INITIALIZATION OF STORAGE ARRAYS.
000274      15 IF( JCLR )20,20,10
000276      10 IF(NCLCT)23,110,116
000300     116 DO 18 I = 1,NCLCT
000302         DO 17 J =1,3
000303      17 SUMA(I,J) = 0.
000311         SUMA(I,4) = 1.0E20
000313      18 SUMA(I,5)= -1.0E20
000317     110 IF (NSTAT)23,111,117
000321     117 DO 360 I=1,NSTAT
000323         SSUMA(I,1) = TNOW
000325         DO 370 J = 2,3
000327     370 SSUMA(I,J) = 0.
000335         SSUMA(I,4) = 1.0E20
```

```
000337      360 SSUMA(I,5) = -1.0E20
000343      111 IF(NHIST)23,20,118
000345      118 DO 380 K = 1,NHIST
000347          DO 380 L = 1,MXC
000350      380 JCELS(K,L) = 0
          C*****PRINT OUT PROGRAM IDENTIFICATION INFORMATION
000361       20 WRITE (NPRNT,102) NPROJ,NAME,MON,NDAY,NYR,NRUN
000401      102 FORMAT (1H1,29X,22HSIMULATION PROJECT NO.,I4,2X,2HBY,2X,
               1 6A2//,30X,4HDATE,I3,1H/,I3,1H/,I5,12X,10HRUN NUMBER,I5//)
          C*****PRINT PARAMETER VALUES AND SCALE
000401          IF(NPRMS ) 60,60,62
000404       62 DO 64 I=1,NPRMS
000406       64 WRITE (NPRNT,107) I,(PARAM(I,J),J=1,4)
000427      107 FORMAT(20X,14H PARAMETER NO.,I5,4F12.4)
000427       60 WRITE (NPRNT,1107) SCALE
000435     1107 FORMAT (//47X,8H SCALE =F10.4)
000435          PRINT 995, NPRMS,NHIST,NCLCT,NSTAT,ID,IM,NOQ,MXC
000461      995 FORMAT(//2X,I5,6H=NPRMS,2X,I5,6H=NHIST,2X,I5,6H=NCLCT,2X,
               1 I5,6H=NSTAT,2X,I5,3H=ID,5X,I5,3H=IM,5X,I5,4H=NOQ,4X,
               2 I5,4H=MXC)
000461          IF (NHIST) 994, 994, 993
000464      993 PRINT 996, (NCELS(K), K=1,NHIST)
000477      996 FORMAT (/, 8(2X,I5, 6H=NCELS))
000477      994 PRINT 997, (KRANK(K), K=1,NOQ)
000512      997 FORMAT (/, 8(2X,I5, 6H=KRANK))
000512          PRINT 998, (INN(K), K=1,NOQ)
000525      998 FORMAT( /, 8(2X,I5, 6H=INN  ))
000525          PRINT 999, MSTOP,JCLR,NORPT,NEP,TBEG,TFIN,JSEED
000547      999 FORMAT (/, 2X,I5, 6H=MSTOP, 2X,I5, 5H=JCLR, 2X,I5, 6H=NORPT,2X,I5,
               1 4H=NEP,4X,F10.3,5H=TBEG,2X,F10.3,5H=TFIN,2X,I5,6H=JSEED)
000547          RETURN
000550          END
```

```
                SUBROUTINE ERROR(J,NSET)
000005          DIMENSION NSET(12,1)
000005          COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
               1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
               2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000005          COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
               1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
               2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000005          WRITE(NPRNT,100) J
000012          JEVNT=101
          C*****PRINT FILING ARRAY NSET
000013          CALL MONTR(NSET)
000016          WRITE(NPRNT,101)
          C*****PRINT NEXT EVENT FILE
000022          CALL PRNTQ(1,NSET)
          C*****PRINT SUMMARY REPORT UP TO PRESENT
000025          CALL SUMRY(NSET)
000030      100 FORMAT(///36X16HERROR EXIT, TYPE,I3,7H ERROR.)
000030      101 FORMAT(1H1,41X16HSCHEDULED EVENTS//)
000030          NFOOL=0
000031          IF(NFOOL)3,4,3
000033        3 RETURN
000034        4 STOP
000036          END
```

```
              SUBROUTINE FILEM (JQ,NSET)
000005        DIMENSION NSET(12,1)
000005        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000005        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
        C*****TEST TO SEE IF THERE IS AN AVAILABLE COLUMN FOR STORAGE
000005        IF (MFA - ID ) 2,2,3
000007      3 WRITE (NPRNT,4)
000013      4 FORMAT (//24H OVERLAP SET GIVEN BELOW/)
000013    100 CALL ERROR (87,NSET)
        C*****PUT ATTRIBUTE VALUES IN FILE
000016      2 DO 1 I = 1,IM
000021        DEL =.000001
000023        IF (ATRIB(I)) 5,1,1
000025      5 DEL = -.000001
000027      1 NSET(I,MFA)=SCALE*(ATRIB(I)+DEL)
        C*****MFEX IS FIRST ENTRY IN FILE WHICH HAS NOT BEEN COMPARED WITH ITEM
        C*****TO BE INSERTED
000042        MFEX = MFE(JQ)
000044        MLEX=MLE(JQ)
        C*****MLEX IS LAST ENTRY IN FILE WHICH HAS NOT BEEN COMPARED WITH ITEMS
        C*****TO BE INSERTED.
        C*****KNT IS A CHECK CODE TO INDICATE THAT NO COMPARISONS HAVE BEEN MADE
000046        KNT = 2
        C*****KS IS THE ROW ON WHICH ITEMS OF FILE JQ ARE RANKED
000047        KS = KRANK(JQ)
        C*****PUTTING AN ENTRY IN FILE JQ
        C*****NXFA IS THE SUCCESSOR COLUMN OF THE FIRST AVAILABLE COLUMN FOR
        C*****STORING INFORMATION
        C*****THE ITEM TO BE INSERTED WILL BE PUT IN COLUMN MFA
000051      8 NXFA = NSET(MX,MFA)
000055        IF(NQ(JQ)) 9,10,9
        C*****IF INN(JQ) EQUALS  1) FILE IS LVF, 2) FILE IS HVF, 3) FILE IS FIFO
        C*****4) FILE IS LIFO
000057      9 IF (INN(JQ)-1) 100,11,6
000063      6 IF(INN(JQ)-3) 19,13,16
000067     10 NSET(MXX,MFA)=KLE
000074        MFE(JQ) = MFA
        C*****THERE IS NO SUCCESSOR OF ITEM INSERTED.  SINCE ITEM WAS INSERTED
```

```
        C*****IN COLUMN MFA THE LAST ENTRY OF FILE JQ IS IN COLUMN MFA.
000075     17 NSET(MX,MFA) = KOL
000102        MLE(JQ) = MFA
        C*****SET NEW MFA EQUAL TO SUCCESSOR OF OLD MFA.  THAT IS NXFA.  THE
        C*****NEW MFA HAS NO PREDECESSOR SINCE IT IS THE FIRST AVAILABLE COLUMN
        C*****FOR STORAGE.
000103     14 MFA = NXFA
000105        IF (MFA-KOF) 237,238,238
000107    237 NSET(MXX,MFA) = KLE
        C*****UPDATE STATISTICS OF FILE JQ
000114    238 XNQ = NQ(JQ)
000117        ENQ(JQ) = ENQ(JQ)+XNQ*(TNOW-QTIME(JQ))
000124        VNQ(JQ) = VNQ(JQ) + XNQ*XNQ*( TNOW-QTIME(JQ))
000132        QTIME(JQ) = TNOW
000134        NQ(JQ) = NQ(JQ) + 1
000136        IF (NQ(JQ) -MAXNQ(JQ)) 239,239,240
000142    240 MAXNQ(JQ)= NQ(JQ)
000145    239 MLC(JQ)= MFE(JQ)
000150        RETURN
        C*****TEST RANKING VALUE OF NEW ITEM AGAINST VALUE OF ITEM IN COLUMN
        C*****MLEX
000151     11 IF(NSET(KS,MFA)-NSET(KS,MLEX))12,13,13
        C*****INSERT ITEM AFTER COLUMN MLEX.  LET SUCCESSOR OF MLEX BE MSU.
000161     13 MSU = NSET(MX,MLEX)
000165        NSET(MX,MLEX) = MFA
000171        NSET(MXX,MFA) = MLEX
000174        GO TO (18,17),KNT
        C*****SINCE KNT EQUALS ONE A COMPARISON WAS MADE AND THERE IS A
        C*****SUCCESSOR TO MLEX, I.E., MSU IS NOT EQUAL TO KOL.  POINT COLUMN
        C*****MFA TO MSU AND VICE VERSA.
000202     18 NSET(MX,MFA) = MSU
000207        NSET(MXX,MSU) = MFA
000212        GO TO 14
        C*****SET KNT TO ONE SINCE A COMPARISON WAS MADE.
000213     12 KNT = 1
        C*****TEST MFA AGAINST PREDECESSOR OF MLEX BY LETTING MLEX EQUAL
        C*****PREDECESSOR OF MLEX.
000214        MLEX = NSET(MXX,MLEX)
000220        IF(MLEX-KLE) 11,16,11
        C*****IF MLEX HAD NO PREDECESSOR MFA IS FIRST IN FILE.
000222     16 NSET(MXX,MFA) = KLE
000227        MFE(JQ) = MFA
        C*****SUCCESSOR OF MFA IS MFEX AND PREDECESSOR OF MFEX IS MFA. (NOTE AT
```

```
              C*****THIS POINT MLEX = MFEX IF LVF WAS USED).
000230           26 NSET(MX.MFA) = MFEX
000235              NSET(MXX.MFEX) = MFA
000240              GO TO 14
              C***** FOR HVF OPERATION TRY TO INSERT ITEM STARTING AT BEGINNING OF
              C*****FILE JQ.
              C*****TEST RANKING VALUE OF NEW ITEM AGAINST VALUE OF ITEM IN COLUMN
              C*****MFEX.
000241           19 IF(NSET(KS.MFA)-NSET(KS,MFEX))20,21,21
              C*****IF NEW VALUE IF LOWER, MFA MUST BE COMPARED AGAINST SUCCESSOR OF
              C*****MFEX.
000251           20 KNT = 1
              C*****LET MPRE = MFEX AND LET MFEX BE THE SUCCESSOR OF MFEX.
000252              MPRE = MFEX
000254              MFEX = NSET(MX.MFEX)
000257              IF (MFEX-KOL) 19,24,19
              C*****IF NEW VALUE IS HIGHER, IT SHOULD BE INSERTED BETWEEN MFEX AND ITS
              C*****PREDECESSOR.
              C*****IF KNT = 2, MFEX HAS NO PREDECESSOR.  GO TO STATEMENT 16.  IF KNT
              C*****= 1, A COMPARISON WAS MADE AND A VALUE OF MPRE HAS ALREADY BEEN
              C*****OBTAINED ON THE PREVIOUS ITERATION.  SET KNT = 2 TO INDICATE THIS.
000261           21 GO TO (22,16),KNT
000267           22 KNT = 2
              C*****MFA IS TO BE INSERTED AFTER MPRE.  MAKE MPRE THE PREDECESSOR OF
              C*****MFA AND MFA THE SUCCESSOR OF MPRE.
000270           24 NSET(MXX.MFA) = MPRE
000275              NSET(MX.MPRE) = MFA
              C*****IF KNT WAS NOT RESET TO 2, THERE IS NO SUCCESSOR OF MFA.  POINTERS
              C*****ARE UPDATED AT STATEMENT 17.  IF KNT = 2, IT WAS RESET AND THE
              C*****SUCCESSOR OF MFA IS MFEX.
000300              GO TO (17,26), KNT
000306              END
```

```
              SUBROUTINE FIND (XVAL,    MCODE, JQ, JATT, KCOL, NSET)
000011        DIMENSION NSET(12,1), XVAL(1)
000011        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000011        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
        C*****CHANGE VALUE TO FIXED POINT WHEN SEARCHING NSET
000011        DEL= 0.00001
000012        IF (XVAL(1)) 30, 40, 40
000013     30 DEL= -DEL
000014     40 NVAL= SCALE*(XVAL(1) +DEL)
        C*****THE COLUMN WHICH IS THE BEST CANDIDATE IS KBEST
000020        KBEST=0
        C*****THE NEXT COLUMN TO BE CONSIDERED AS A CANDIDATE IS NEXTK
000021        NEXTK=MFE(JQ)
000023        IF(NEXTK) 16,1,2
000024     16 CALL ERROR(89,NSET)
000026      1 KCOL=KBEST
000033        RETURN
        C*****MGRNV IS +1 FOR GREATER THAN SEARCH AND -1 FOR LESS THAN SEARCH
        C*****NMAMN IS +1 FOR MAXIMUM AND -1 FOR MINIMUM
        C*****FOR SEARCH FOR EQUALITY THE SIGN OF MGRNV AND NMAMN ARE NOT USED
000034      2 GO TO (11,12,13,14,11),MCODE
000045     11 MGRNV=1
000046        NMAMN=1
000047        GO TO 20
000050     12 MGRNV=1
000051        NMAMN=-1
000052        GO TO 20
000053     13 MGRNV=-1
000054        NMAMN=1
000055        GO TO 20
000056     14 MGRNV=-1
000057        NMAMN=-1
000060     20 IF(MGRNV*(NSET(JATT,NEXTK)-NVAL)) 4,21,66
        C*****WHEN EQUALITY IS OBTAINED TEST FOR MCODE=5, THE SEARCH FOR A
        C*****SPECIFIED VALUE
000067     21 IF(MCODE-5) 4,15,4
000071     66 IF (MCODE-5) 6,4,6
000073      6 IF(KBEST) 16,8,7
```

```
000075          7 IF(NNAMN*(NSET(JATT,NEXTK)-NSET(JATT,KBEST))) 4,4,8        FIND 430
000106          8 KBEST=NEXTK                                                 FIND 440
000110          4 NEXTK=NSET(MX,NEXTK)                                        FIND 450
000114            IF(NEXTK-7777)20,1,1                                        FIND 460
000117         15 KCOL=NEXTK                                                  FIND 470
000120            RETURN                                                      FIND 480
000121            END                                                         FIND 490
```

```
              SUBROUTINE GASP(NSET)
000003        DIMENSION NSET(12,1)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003        NOT = 0
000004      1 CALL DATAN(NSET)
        C*****PRINT OUT FILING ARRAY
000005        JEVNT = 101
000006        CALL MONTR (NSET)
000010        WRITE (NPRNT,403)
000014    403 FORMAT(1H1,38X,24H**INTERMEDIATE RESULTS**//)
        C*****OBTAIN NEXT EVENT WHICH IS FIRST ENTRY IN FILE 1. ATRIB(1) IS EVE
        C*****TIME. ATRIB(2) IS EVENT CODE
000014     10 CALL RMOVE(MFE(1),1,NSET)
000021        TNOW = ATRIB(1)
000023        JEVNT = ATRIB(2)
        C*****TEST TO SEE IF THIS EVENT IS A MONITOR EVENT
000025        IF(JEVNT - 100)13,12,6
000030     13 I = JEVNT
        C*****CALL PROGRAMMERS EVENT ROUTINES
000032        CALL EVNTS (I,NSET)
        C*****TEST METHOD FOR STOPPING
000034        IF (MSTOP) 40,8,20
000037     40 MSTOP = 0
        C*****TEST FOR NO SUMMARY REPORT
000040        IF (NORPT) 14,22,42
000042     20 IF(TNOW-TFIN)8,22,22
000045     22 CALL SUMRY(NSET)
000046        CALL OTPUT (NSET)
        C*****TEST NUMBER OF RUNS REMAINING
000050     42 IF(NRUNS-1)14,9,23
000053     23 NRUNS = NRUNS - 1
000055        NRUN = NRUN + 1
000056        GO TO 1
000056     14 CALL ERROR(93,NSET)
000061      6 CALL MONTR(NSET)
000063        GO TO 10
        C*****RESET JMNIT
```

```
000065        12 IF(JMNIT)14,30,31                                                        GASP 430
000067        30 JMNIT = 1                                                                GASP 440
000070           GO TO 10                                                                 GASP 450
000071        31 JMNIT = 0                                                                GASP 460
000072           GO TO 10                                                                 GASP 470
            C*****TEST TO SEE IF EVENT INFORMATION IS TO BE PRINTED                       GASP 480
000073         8 IF(JMNIT)14,10,32                                                        GASP 490
000075        32 ATRIB(2) = JEVNT                                                         GASP 500
000077           JEVNT = 100                                                              GASP 510
000100           CALL MONTR(NSET)                                                         GASP 520
000101           GO TO 10                                                                 GASP 530
            C*****IF ALL RUNS ARE COMPLETED RETURN TO MAIN PROGRAM FOR INSTRUCTIONS       GASP 540
000103         9 RETURN                                                                   GASP 550
000104           END                                                                      GASP 560
```

```
                 SUBROUTINE HISTO (XX, A, W, N, NSET)
000010           DIMENSION NSET(12,1), XX(1), A(1), W(1)
000010           COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000010           COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000010         5 IF (N-NHIST) 11,11,2
000012         2 CALL ERROR(96, NSET)
000014       250 FORMAT(19H ERROR IN HISTOGRAM,I4//)
000014           CALL EXIT
000015        11 IF(N)2,2,3
           C*****TRANSLATE X1 BY SUBTRACTING A IF X.LE.A THEN ADD 1 TO FIRST CELL
000022         3 X= XX(I) -A(I)
000024           IF (X)6,7,7
000025         6 IC = 1
000026           GO TO 8
           C*****DETERMINE CELL NUMBER IC. ADD 1 FOR LOWER LIMIT CELL AND 1 FOR
           C*****TRUNCATION
000027         7 IC= X/W(I) +2.
000033           IF (IC - NCELS(N) - 1) 8,8,9
000037         9 IC = NCELS(N)+2
000042         8 JCELS(N,IC) = JCELS(N,IC) + 1
000047           RETURN
000050           END
```

```
              SUBROUTINE MONTR(NSET)
000003        DIMENSION NSET(12,1)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
        C*****IF JEVNT .GE. 101, PRINT NSET
000003        IF (JEVNT - 101) 9,7,9
000005      7 WRITE (NPRNT,100) TNOW
000013        DO 1000 I=1,ID
000016    100 FORMAT(1H1,10X31H**GASP JOB STORAGE AREA DUMP AT,F10.4,
             1 2X,12HTIME UNITS**//)
000016   1000 WRITE (NPRNT,101) I,(NSET(J,I),J=1,MXX)
000041    101 FORMAT(I5,12I9)
000041        RETURN
000042      9 IF(MFE(1))3,6,1
        C*****IF JMNIT = 1,PRINT TNOQ,CURRENT EVENT CODE, AND ALL ATTRIBUTES OF
        C*****THE NEXT EVENT
000044      1 IF (JMNIT - 1) 5,4,3
000047      3 WRITE (NPRNT,199)
000053    199 FORMAT(///36X26H ERROR EXIT,TYPE 99 ERROR.)
000053        CALL EXIT
000054      4 MMFE =MFE(1)
000056        WRITE (NPRNT,103) TNOW,ATRIB(2),(NSET(I,MMFE),I=1,MXX)
000100    103 FORMAT (/10X23HCURRENT EVENT....TIME =,F8.2,5X7HEVENT =,F7.2,
             1/10X,17HNEXT EVENT......./(10X,12I9)//)
000100      5 RETURN
000101      6 WRITE (NPRNT,104) TNOW
000107    104 FORMAT (10X,19H FILE 1 IS EMPTY AT,F10.2)
000107        GO TO 5
000111        END
```

```
               SUBROUTINE PRNTQ (JQ,NSET)
000005         DIMENSION NSET(12,1)
000005         COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
              1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
              2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000005         COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
              1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
              2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000005         WRITE (NPRNT,100) JQ
000012         IF (TNOW - TBEG) 12,12,13
000016      12 WRITE (NPRNT,105)
000022     105 FORMAT(/35X,25H NO PRINTOUT TNOW = TBEG //)
000022         GO TO 2
        C*****COMPUTE EXPECT NO. IN FILE JQ UP TO PRESENT THIS MAY BE USEFUL
        C*****IN SETTING THE VALUE OF ID
000024      13 XNQ=NQ(JQ)
000027         X=(ENQ(JQ)+XNQ*(TNOW-QTIME(JQ)))/(TNOW-TBEG)
000037         STD=((VNQ(JQ)+XNQ*XNQ*(TNOW-QTIME(JQ)))/(TNOW-TBEG)-X*X)**0.5
000053         WRITE (NPRNT,104) X,STD,MAXNQ(JQ)
        C*****PRINT FILE IN PROPER ORDER REQUIRES TRACING THROUGH THE POINTERS
        C*****OF THE FILE
000067         LINE = MFE(JQ)
000073         IF (LINE-1) 4,1,1
000075       4 WRITE (NPRNT,102)
000101       2 RETURN
000102       1 WRITE (NPRNT,101)
000106       6 DO 77 I=1,IM
000111         ATRIB  (I) = NSET(I,LINE)
000116      77 ATRIB (I)=ATRIB (I)/SCALE
000123         WRITE (NPRNT,103) (ATRIB(I),I=1,IM)
000135         LINE = NSET(MX,LINE)
000143         IF (LINE-7777) 6,2,5
000145       5 WRITE (NPRNT,199)
000151     199 FORMAT(///36X26HERROR EXIT, TYPE 94 ERROR.)
000151     100 FORMAT(//39X25H FILE PRINTOUT, FILE  NO.,I3)
000151     101 FORMAT (/45X14H FILE CONTENTS/)
000151     102 FORMAT(/43X18HTHE FILE  IS EMPTY)
000151     103 FORMAT(20X,10F10.4)
000151     104 FORMAT(/35X,27HAVERAGE NUMBER IN FILE  WAS,F10.4,/35X,9HSTD. DEV.,
               1 18X,F10.4,/35X,7HMAXIMUM,24X,I4)
000151         STOP
000153         END
```

```
              SUBROUTINE RMOVE  (KCOLL,JQ,NSET)
000006        DIMENSION NSET(12,1),KCOLL(1)
000006        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000006        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000006        KCOL=KCOLL(1)
000007        IF (KCOL) 16,16,2
000010     16 CALL ERROR(97,NSET)
        C*****PUT VALUES OF KCOL IN ATTRIB
000012      2 DO 3 I = 1,IM
000016        ATRIB (I) = NSET(I,KCOL)
000023      3 ATRIB (I) = ATRIB(I)/SCALE
        C*****REMOVAL OF AN ITEM FROM FILE JQ.
        C*****UPDATE POINTING SYSTEM TO ACCOUNT FOR REMOVAL OF KCOL
        C*****                                          LET JL EQUAL SUCCESSOR
        C*****OF COLUMN REMOVED AND JK EQUAL PREDECESSOR OF COLUMN REMOVED.
        C*****IF JL = KOL, MLC WAS LAST ENTRY.  IF JK = KLE, MLC WAS FIRST ENTRY
        C*****MLC WAS NOT FIRST OR LAST ENTRY.  UPDATE POINTERS SO THAT JL IS
        C*****SUCCESSOR OF JK AND JK IS PREDECESSOR OF JL.
000030        DO 32 I=1,IM
000031     32 NSET(I,KCOL) = 0
000040        JL = NSET(MX,KCOL)
000044        JK= NSET(MXX,KCOL)
000050        IF (JL-KOL) 33,34,33
000052     33 IF (JK-KLE) 35,36,35
000054     35 NSET(MX,JK) = JL
000061        NSET(MXX,JL) = JK
000064        GO TO 37
        C****KCOL WAS FIRST ENTRY BUT NOT LAST ENTRY.  UPDATE POINTERS.
000065     36 NSET(MXX,JL) = KLE
000072        MFE(JQ) = JL
000073        GO TO 37
000074     34 IF (JK-KLE) 38,39,38
        C****KCOL WAS LAST ENTRY BUT NOT FIRST ENTRY.  UPDATE POINTERS.
000076     38 NSET(MX,JK) = KOL
000103        MLE(JQ) = JK
000104        GO TO 37
        C****KCOL WAS BOTH THE LAST AND FIRST ENTRY. THEREFORE, IT IS THE ONLY
        C*****ENTRY.
```

```
000105      39 MFF(JQ) = 0
000107         MLF(JQ) = 0
         C*****UPDATE POINTERS.
000111      37 NSET(MX,KCOL) =MFA
000116         NSET(MXX,KCOL ) = KLE
000122         IF (MFA-KOF) 234,235,235
000124     234 NSET(MXX,MFA) = KCOL
000131     235 MFA= KCOL
         C*****UPDATING FILE STATISTICS
000133         XNQ = NQ(JQ)
000135         IF (JQ -1)  16, 301, 302
000140     301 TNOW= ATRIB(1)
000142     302 ENQ(JQ)= ENQ(JQ) +XNQ*( TNOW -QTIME(JQ))
000150         VNQ(JQ) = VNQ(JQ) + XNQ*XNQ*( TNOW-QTIME(JQ))
000156         QTIME(JQ) = TNOW
000160         NQ(JQ) = NQ(JQ)-1
000162         RETURN
000163         END
```

```
              SUBROUTINE SET(JQ,NSET)
000005        DIMENSION NSET(12,1)
000005        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000005        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
       C*****INIT SHOULD BE ONE FOR INITIALIZATION OF FILE
000005        IF (INIT-1) 27,28,27
       C*****INITIALIZE FILE TO ZERO.  SET UP POINTERS
       C*****MUST INITIALIZE KRANK(JQ)
       C*****MUST INITIALIZE INN(JQ)****INN(JQ)=1 IS FIFO**INN(JQ)=2 IS LIFO
000007     28 KOL = 7777
000010        KOF = 8888
000011        KLE = 9999
000012        MX = IM+1
000014        MXX = IM+2
       C*****INITIALIZE POINTING CELLS OF NSET AND ZERO OTHER CELLS OF NSET
000016        DO 1 I = 1,ID
000017        DO 2 J = 1,IM
000020      2 NSET(J,I) = 0
000027        NSET(MXX,I) = I-1
000033      1 NSET(MX,I) = I + 1
000041        NSET(MX,ID) = KOF
000044        DO 3 K = 1,NOQ
000046        NQ(K)=0
000050        MLC(K)=0
000051        MFE(K)=0
000053        MAXNQ(K) = 0
000054        MLE(K)=0
000056        ENQ(K)=0.0
000057        VNQ(K)=0.
000061      3 QTIME(K)=TNOW
       C*****FIRST AVAILABLE COLUMN = 1
000065        MFA = 1
000066        INIT = 0
000067        OUT = 0.0
000070     27 RETURN
000071        END
```

```
              SUBROUTINE SUMRY (NSET)
000003        DIMENSION NSET(12,1)
000003        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCROR,NEP,VNQ(100),KOF,KLE,KOL
000003        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003        WRITE (NPRNT,21)
000007     21 FORMAT (1H1,39X,23H**GASP SUMMARY REPORT**/)
000007        WRITE (NPRNT,102) NPROJ,NAME,MON,NDAY,NYR,NRUN
000027    102 FORMAT     (30X,22HSIMULATION PROJECT NO.,I4,2X,2HBY,2X,
             1 6A2//,30X,4HDATE,I3,1H/,I3,1H/,I5,12X,10HRUN NUMBER,I5/)
000027        IF (NPRMS) 147,147,146
000032    146 DO 64 I=1,NPRMS
000034     64 WRITE (NPRNT,107) I,(PARAM(I,J),J=1,4)
000055    107 FORMAT(20X,14H PARAMETER NO.,I5,4F12.4)
000055    147 IF(NCLCT)5,60,66
000057      5 WRITE (NPRNT,199)
000063    199 FORMAT(///36X26HERROR EXIT, TYPE 98 ERROR.)
000063        CALL EXIT
000064     66 WRITE (NPRNT,23)
000070     23 FORMAT (//44X,18H**GENERATED DATA** /27X,4HCODE,4X,4HMEAN,6X,9HSTD
             1.DEV.,5X,4HMIN.,7X,4HMAX.,5X,4HOBS./)
        C*****COMPUTE AND PRINT STATISTICS GATHERED BY CLCT
000070        DO 2 I=1,NCLCT
000073        IF(SUMA(I,3))5,62,61
000075     62 WRITE (NPRNT,63) I
000103     63 FORMAT(27X,I3,10X18HNO VALUES RECORDED)
000103        GO TO 2
000105     61 XS = SUMA(I,1)
000110        XSS = SUMA(I,2)
000111        XN = SUMA(I,3)
000113        AVG = XS/XN
000114        N = XN+.001
000117        IF(N-1) 203,203,204
000121    203 STD=0.0
000122        GO TO 205
000123    204 STD=(((XN*XSS)-(XS*XS))/(XN*(XN-1.0)))**.5
000134    205 WRITE (NPRNT,24) I,AVG,STD,SUMA(I,4),SUMA(I,5),N
000154     24 FORMAT (27X,I3,4F11.4,I7)
000154      2 CONTINUE
```

```
000160       60 IF(NSTAT)5,67,4
000162        4 WRITE (NPRNT,29)
000166       29 FORMAT ( /44X,23H**TIME GENERATED DATA** /27X,4HCODE,4X,4HMEAN,6X,
               18HSTD.DEV.,5X,4HMIN.,7X,4HMAX.,3X,10HTOTAL TIME/)
          C*****COMPUTE AND PRINT STATISTICS GATHERED BY TMST
000166          DO 6 I = 1,NSTAT
000171          IF(SSUMA(I,1))5,71,72
000174       71 WRITE (NPRNT,63) I
000202          GO TO 6
000204       72 XT= SSUMA(I,1) -TBEG
000207          XS = SSUMA(I,2)
000211          XSS = SSUMA(I,3)
000212          AVG = XS/XT
000214          STD = (XSS/XT-AVG*AVG)**.5
000221          WRITE (NPRNT,30) I,AVG,STD,SSUMA(I,4),SSUMA(I,5),XT
000241       30 FORMAT (27X,I3,5F11.4)
000241        6 CONTINUE
000245       67 IF(NHIST)5,75,9
000247        9 WRITE (NPRNT,25)
000253       25 FORMAT   (/37X,37H**GENERATED FREQUENCY DISTRIBUTIONS** /27X,4HCOD
               1E,20X,10HHISTOGRAMS)
          C*****PRINT HISTOGRAMS
000253          DO 12 I=1,NHIST
000256          NCL = NCELS (I)+2
000261       12 WRITE (NPRNT,26) I,(JCELS(I,J),J=1,NCL)
000303       26 FORMAT(/1X,I2,1X,11I11/(4X,11I11))
          C*****PRINT FILES AND FILE STATISTICS
000303       75 DO 15 I = 1,NOQ
000305       15 CALL PRNTQ (I,NSET)
000313          RETURN
000314          END
```

```
              SUBROUTINE TMST(XX, T, N, NSET)
000007        DIMENSION NSET(12,1), XX(1)
000007        COMMON IO,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000007        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000007        IF (N) 2,2,1
000010      2 CALL ERROR(91,NSET)
000012      1 IF(N-NSTAT)3,3,2
000017      3 TT= T-SSUMA(N,1)
000022        SSUMA(N,1)= T
000024        SSUMA(N,2)= SSUMA(N,2) +XX(1)*TT
000027        SSUMA(N,3)= SSUMA(N,3) +XX(1)*XX(1)*TT
000031        IF (XX(1) -SSUMA(N,4)) 4, 5, 5
000034      4 SSUMA(N,4)= XX(1)
000036      5 IF( XX(1) -SSUMA(N,5)) 7, 7, 6
000041      6 SSUMA(N,5)= XX(1)
000043      7 RETURN
000044        END
```

```
                FUNCTION DRAND(IY)                                    DRND  10
000003          X=FLOAT(IY)
000004          DRAND=RANF(X)
000006          X=0.0
000010          RETURN                                                DRND  70
000011          END                                                   DRND  80
```

```
                 FUNCTION ERLNG (J)
000003           COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003           COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003           K = PARAM(J,4)
000005           IF(K-1) 8,10,10
000007         8 WRITE(NPRNT,20) J
000015        20 FORMAT(/16HK = 0 FOR ERLNG,I7)
000015           CALL EXIT
000016        10 R=1
000020           DO 2 I = 1,K
000022         2 R = R*DRAND(ISEED)
000030           ERLNG = -PARAM(J,1)*ALOG(R)
000035           IF(ERLNG-PARAM(J,2))7,5,6
000037         7 ERLNG  = PARAM (J,2)
000041         5 RETURN
000043         6 IF(ERLNG  - PARAM (J,3))5,5,4
000046         4 ERLNG  = PARAM (J,3)
000050           RETURN
000050           END
```

```
                  SUBROUTINE NPOSN(J,NPSSN)
000005            COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                 1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                 2TBEG,TFIN,MXX,NPRNT,NCROR,NEP,VNQ(100),KOF,KLE,KOL
000005            COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                 1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                 2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000005            NPSSN = 0
000005            P = PARAM (J,1)
000010          1 IF (P-6.0) 2,2,4
000013          2 Y = EXP (-P)
000017            X = 1.0
000020          3 X=X*DRAND(ISEED)
000024            IF (X-Y) 6,8,8
000027          8 NPSSN = NPSSN+1
000031            GO TO 3
000031          4 TEMP=PARAM (J,4)
000033            PARAM(J,4) = (PARAM(J,1))**.5
000037            NPSSN=RNORM(J)+.5
000044            PARAM (J,4)=TEMP
000046            IF(NPSSN)4,6,6
000047          6 KK=PARAM (J,2)
000052            KKK=PARAM (J,3)
000054            NPSSN=KK+NPSSN
000055            IF(NPSSN-KKK)7,7,9
000057          9 NPSSN = PARAM (J,3)
000061          7 RETURN
000062            END
```

```
              FUNCTION RLOGN (J)
        C*****THE PARAMETERS USED WITH RLOGN ARE THE MEAN AND STANDARD DEVIATION
        C*****OF A NORMAL DISTRIBUTION
000003        VA= RNORM (J)
000005        RLOGN=EXP(VA)
000010        RETURN
000010        END
```

```
                  FUNCTION RNORM (J)
000003            COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                 1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                 2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000003            COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                 1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                 2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000003            RA = DRAND(ISEED)
000006            RB = DRAND(ISEED)
000010            V=(-2.0*ALOG(RA))**0.5*COS (6.283*RB)
000022            RNORM  = V*PARAM (J,4) + PARAM (J,1)
000026            IF (RNORM -PARAM (J,2)) 6,7,8
000030          6 RNORM  = PARAM (J,2)
000032          7 RETURN
000034          8 IF (RNORM -PARAM (J,3)) 7,7,9
000037          9 RNORM  = PARAM (J,3)
000041            RETURN
000041            END
```

```
              FUNCTION UNFRM (A,B)                                                        UNFM  10
           C*****THIS CARD IS TO MAINTAIN THE PROPER SEQUENCING                           UNFM  20
000005        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,                 UNFM  30
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,                  UNFM  40
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNO(100),KOF,KLF,KOL                          UNFM  50
000005        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,            UNFM  60
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4UNFM  70
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR              UNFM  80
000005        UNFRM   = A+(B-A)*DRAND(ISEED)                                              UNFM  90
000013        RETURN                                                                      UNFM 100
000013        END                                                                         UNFM 110
```

```
                 FUNCTION PRODQ (JATT,JQ,NSET)
000006           DIMENSION NSET(12,1)
000006           COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
                1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
                2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLF,KOL
000006           COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
                1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
                2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000006           PRODQ = 1.
000007           IF (JQ-NOQ) 17,17,18
000011        18 CALL ERROR(84,NSET)
000013        17 IF (NQ( JQ )) 19,19,20
000017        19 PRODQ=0.
000020           RETURN
000021        20 MTEM=MFE(JQ)
000024        23 VSET=NSET(JATT,MTEM)
000030           PRODQ = PRODQ*VSET/SCALE
000033           IF (NSET(MX,MTEM) -7777) 21,22,21
000040        21 MTEM= NSET(MX,MTEM)
000044           GO TO 23
000045        22 RETURN
000047           END
```

```
              FUNCTION SUMQ (JATT,JQ,NSET)
000006        DIMENSION NSET(12,1)
000006        COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,NHIST,
             1NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,SCALE,ISEED,TNOW,
             2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(100),KOF,KLE,KOL
000006        COMMON ATRIB(10),ENQ(100),INN(100),JCELS(10,32),KRANK(100),JCLR,
             1MAXNQ(100),MFE(100),MLC(100),MLE(100),NCELS(10),NQ(100),PARAM(40,4
             2),QTIME(100),SSUMA(30,5),SUMA(30,5),NAME(6),NPROJ,MON,NDAY,NYR
000006        SUMQ = 0
000007        IF (JQ-NOQ) 17,17,18
000011     18 CALL ERROR(85,NSET)
000013     17 IF (NQ( JQ )) 19,19,20
000017     19 RETURN
000021     20 MTEM = MFE(JQ)
000024     23 VSET = NSET(JATT,MTEM)
000030        SUMQ = SUMQ + VSET/SCALE
000033        IF (NSET(MX,MTEM)-7777) 21,22,21
000040     21 MTEM = NSET(MX,MTEM)
000044        GO TO 23
000045     22 RETURN
000047        END
```

APPENDIX H

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Robert L. Radkey	Aeronautical and Astronautical Engineering Department University of Illinois B.S.A.E., University of Illinois
Gerald F. Reid	Department of Electrical Engineering Virginia Polytechnic Institute B.S.E.E., Virginia Military Institute
John M. Sauders	Department of Electrical Engineering George Washington University B.S.E.E., George Washington University M.S.E.E., George Washington University
Firman L. Schiebout	Department of Aerospace Engineering Iowa State University B.S.A.E., Iowa State University
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Richard E. Schmotzer	Department of Aerospace Engineering University of Cincinnati B.S. (Mathematics), University of Dayton

Daniel E. Staub	Department of Electrical Engineering Marquette University B.S.E.E., University of Notre Dame
Wilbert E. Wilhelm, Jr.	Department of Industrial Engineering Virginia Polytechnic Institute B.S.M.E., West Virginia University M.S.I.E., Virginia Polytechnic Institute

APPENDIX I

GUEST LECTURERS

Lecturer	Topic
Mrs. Joan Barriage Federal Aviation Administration Department of Transportation	Experiences with STOL Aircraft
Mr. Neil Blake Federal Aviation Administration Department of Transportation	What the Needs Are in Air Traffic Control in the Next 10 Years
Mr. Joseph Chambers NASA Langley Research Center	V/STOL Characteristics with Air Traffic Control
Mr. Richard Couch NASA Langley Research Center Mr. Les Britt Research Triangle Institute	Air Collision Avoidance Systems
Mr. Leo Garodz National Aviation Facilities Experiment Center Atlantic City, New Jersey	Wake Turbulence
Mr. George B. Graves NASA Langley Research Center	Air Traffic Control Problems
Mr. Keith Holsen Norfolk Approach Control	Terminal Air Traffic Control
Mr. Dominic Maglieri NASA Langley Research Center	Noise Problems in the Terminal Area
Mr. Robert Maxwell Civil Aviation Research and Development	Examples of Systems Analysis Work Done by Civil Aviation Research and Development
Mr. James Nelson Federal Aviation Administration Department of Transportation	All Weather Operations
Mr. Robert Oetting NASA-WVU Participant	Comments on Navigation and Air Traffic Control
Mr. John Reeder NASA Langley Research Center	Terminal Area Operations and All Weather Operations

Mr. Robert Schade NASA Langley Research Center	Air Traffic Control Systems
Mr. Luther W. Snyder Mr. Robert A. Russell Naval Air Test Center	Automatic Carrier Landing Systems
Mr. Robert Sturgill Professional Air Traffic Controllers Organization	Problems of Air Traffic Controllers
Mr. Thomas Walsh NASA Langley Research Center	Terminal Area Model for Air Traffic Control
Dr. Thomas Ballard NASA Langley Research Center	Fundamentals of Navigation
Mr. Donald Geoffrion Federal Aviation Administration	The Next Thirty Years-Air Traffic Control

APPENDIX J

TOURS

June 16, 1970..................................Norfolk Airport Terminal

June 17, 1970..................................Langley Air Force Base
Control Tower

July 15, 1970..................................NASA Langley Research Center