To the Graduate Council:

I am submitting herewith a thesis written by Raymond Joseph Ricco, Jr., entitled "A Computerized Simulation of Airport Configurations." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Computer Science.

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A COMPUTERIZED SIMULATION OF AIRPORT CONFIGURATIONS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Raymond Joseph Ricco, Jr.

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ABSTRACT

The recapitulation of Federal Aviation Administration (FAA) regulations in the first chapter certainly points out the need for a computerized simulation for use in design of optimal airport configurations for construction of new airports and modifying existing airports. The simulation further enables an airport manager to meet, or check to see if he has met the FAA requirements. The simulation is also highly useful for the purposes of enabling an airport operator to more readily fill out the required FAA forms and thus evaluate the efficiency of his operation. The purpose of this study is to develop an algorithm that will simulate probable, and economically feasible optimum solutions to delays, at existing and planned airports, caused to aircraft by the airport's runway, taxiway, and apron configurations. The key words to employ in storing or retrieving this abstract from an automated library files system for the purposes of a literature search are: simulation, airport, delay, runway, taxiway, and apron.

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NOMENCLATURE

ANDE	The annual delay to arrivals and departures totaled over a one-year period
Capacity	The operating level, expressed as the rate of aircraft movements, which results in a given level of delay
HAC	The hourly arrival movement rate at which an average delay of four minutes occurs
HDC	The departure movement rate at which an average delay of four minutes occurs
Hourly Capacity	The movement rate per hour at a selected delay level
IFR	Instrument flight regulations
PANCAP	Practical annual capacity
Population	The actual mixture of aircraft classes making up a movement rate
Runway Rating	The average runway occupancy time for a given population of landing aircraft on a given runway
Runway Use	The function of a runway configuration with respect to arrivals and departures
T&G	The amount of touch and go operations at a particular airport
VFR	Visual flight regulations

INTRODUCTION

Since the Federal Aviation Administration is the regulatory agency for aviation matters, this simulation was done in such a manner as to satisfy or stay within the range of the affiliated FAA requirements.

Chapter I covers FAA regulations concerning airport runway, taxiway, and apron construction, and an explicit definition of what acceptable delay levels are for good economic operation of an airport.

Chapter II presents a detailed explanation of capacity, its effect upon airport operations, and the equations needed for calculation of the various capacitances for the different airport configurations.

Chapter III states a detailed definition of delay and its interaction with airport capacity and airport demand. The chapter also illustrates the calculations of annual delay, daily delay, peak hourly delay, and hourly delay.

Chapter IV covers the actual implementation of the computerization of the problem, and the conclusions the investigator obtained from the simulation.

Before implementing the automation of the algorithm the investigator conducted a manual test run and found that it took approximately 320 man-hours for him to obtain an optimum solution. It was discovered that automation reduced

this time to under five minutes with an average central processing unit time of 30 seconds. This proves the need for automation of this procedure.

CHAPTER I

FEDERAL AVIATION ADMINISTRATION REGULATIONS

It is an FAA regulation that for National Airport Plan (NAP) purposes, airport runways may be considered to have reached capacity when delays to departures average four minutes during the normal peak two-hour period of the week [1].[1] At specific runways used by small aircraft only, this departure delay level is two minutes for the peak hour of the week. Airport facility development must come before "four-minute" or "two-minute" capacity is reached. However, airport facility cost must be correspondingly low in order to justify development at lower delay levels, thus providing a satisfactory benefit/cost basis for its construction.

As runway demand increases, delays at an airport rise much more sharply than increased demand. This increase in delay is exponential in comparison to demand and capacity. An airport generally has a wide range of capacities throughout the year. This range must be taken into account when determining delay.

Thus, in order to determine the total delay at an airport, it is necessary to evaluate the capacities of all runways being used during visual flight regulations (VFR)

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[1]Numbers in brackets refer to similarly numbered references in the bibliography.

and instrument flight regulations (IFR) conditions. These capacities must be considered along with the hourly distribution of demand throughout the year.

The annual capacity of a single runway airport configuration will exceed 150,000 operations with suitable taxiway facilities. An airport runway system that is primarily used by locally based aircraft will probably attain an annual demand of more than 150,000 operations if its based aircraft total is over 200. However, the development of an additional runway based on capacity requirements may be considered for airports with a current demand level below 150,000; if construction is nominal[2] and if the traffic is increasing.

Runways

When construction costs are four times the nominal values, additional facilities should not be planned until runway demand equals capacity [1].

The following criteria should be applied in determining the need for an additional runway to enhance capacity [1]:

---

[2]For the purpose of this study, "nominal cost for all associated construction is considered to be $50 per linear foot for runways serving small aircraft, $150 per linear foot for runways serving twin-engine aircraft, and $300 per linear foot for runways serving all aircraft." This is an FAA guideline [1].

A. A parallel runway may be justified when the demand is forecast to reach the existing runway capacity within five years.

B. A new short parallel runway may be justified at an airport forecast to have, within five years, a demand greater than 60% of existing runway capacity, providing the gross cost for the facility is nominal.

C. An airport having 75,000 operations consisting of 30,000 or more transport-type aircraft may be planned for a short parallel runway to serve small aircraft if the gross cost for this facility is less than $50 per linear foot for all taxiways and runways.

D. When airport demand reaches or is expected to reach 75% or more of the capacity of the existing parallel runway configuration within a five-year period, a parallel runway can be extended to increase capacity providing the cost is nominal.

E. Although intersecting or open "V" runways are not generally recommended for the purpose of increasing capacity, consideration of terrain, noise, or obstructions may make these layouts feasible.

A new parallel runway at an airport will add substantial VFR capacity. In IFR weather the magnitude of the

increase depends on whether or not the operations on one runway can be controlled independently from operations on the other. The capacity for close parallel runways[3] is about 50 IFR operations per hour, whereas under VFR conditions the capacity of close parallels is about double that of a single runway [9]. If the runways are separated by more than 3,500 feet, the IFR capacity for handling arrivals independently from departures is about 70 operations per hour. Additional close parallel runways will not increase IFR capability unless simultaneous instrument approach capability is provided [9]. With this capability, IFR capacity can be increased to its maximum [9].[4]

Besides additional runways, runway length has an important bearing on capacity. Depending on runway length and the aircraft type that operate into the airport, the benefit of extending a runway for the purpose of delay reduction may range from substantial to nil. Short runways intended to serve air carriers but incapable of handling a large portion of the aircraft can adversely affect capacity. On the other hand, short runways to serve general aviation operations independently from air carriers not only add to the overall airport capacity, but will augment safety by permitting more effective segregation of traffic.

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[3]Close parallels are parallels separated by 3,500 feet [9].

[4]This is 140 operations per hour regardless of the number of runways at the airport [9].

Taxiways

The addition of taxiway facilities to the runway configuration increases airport operational efficiency by allowing the runway to realize its maximum capacity potential. However, there is the problem of whether standard taxiways should be built in two directions if operations are predominantly from one direction.[5] Taxiing delays can be an appreciable portion of the total delay at moderate airport movement rates and may even result in a negative overall benefit at an otherwise more efficient airport layout. At high movement rates, the taxi delays are appreciable, but not as much as those caused by the runways themselves. The following criteria should be followed when planning taxiway improvements for capacity purposes [1]:

A. Taxiway turnarounds at both ends of the runway are recommended for the fundamental airport provided the cost of the turnarounds is not prohibitive.

B. Parallel taxiways, assuming reasonableness of cost, may be justified when any one of the following criteria is reached within a five-year period:

    1. There are four instrument approaches during the normal peak hour.

---

[5]This is covered in further detail in the section on taxiway delays.

2. The annual operations total 50,000 or more.
3. The normal itinerant operations total 20 per peak hour.
4. The hourly total operations are:
   a. Thirty operations per normal peak hour for runways serving more than 90% small aircraft and where there are less than 20% touch and go (T&G) operations;
      40 operations per normal peak hour where there are more than 20% T&G operations.
   b. Thirty operations per normal peak hour for runways serving 60 to 90% small aircraft.
   c. Twenty operations per normal peak hour for runways serving 40 to 100% large aircraft.

If construction costs are more than twice average costs, the above activity levels must be increased by 25% to justify parallel taxiway development.

C. Exit taxiways beyond a basic layout of one at each runway end and one in between are justified if the demand is forecast to exceed 40% of the runway capacity providing the costs are average, and at 75% of the capacity if the costs are high. A sufficient number of exits should be planned

so that additional exits would not be required within five years following the completion of construction.

Aprons

Holding aprons and bypass taxiways also enhance airport capacity. These facilities seldom, if ever, constitute restraints on the attainment of full airport capacity within the existing airport property since land areas are normally always available to permit their construction. However, the need for these facilities should be determined sufficiently in advance to prevent bottlenecks and delays that would occur due to lack of these facilities. The following criteria should be applied in determining the need for holding aprons and bypass taxiways, once a parallel taxiway has been justified [1]:

A. When activity is forecast to reach 30 total peak hour operations within the NAP period [1], or 20,000 annual itinerant operations, or 75,000 total operations, a holding apron should be planned, giving due consideration to the following factors:

   1. Mixture of types of aircraft (obtained from Table 1, Appendix A).[6]
   2. The intensity of activity.

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[6]All tables appear in Appendix A.

3. The airport layout.

4. Location of navigational aids.

B. If the traffic density is such that more than four holding positions appear to be necessary then another solution of the problem must be found.

Future requirements for general aviation parking apron positions can be estimated from current needs in proportion to the growth in general aviation operations. Current requirements would not generally exceed the number of itinerant operations during the normal peak hour of the week. The normal peak hour of the week for the total traffic can be estimated from the annual operations by use of Figure 1, Appendix B.[7] The normal peak hour itinerant general aviation aircraft can then be estimated by multiplying the total peak hour operations by the portion of itinerant general aviation operations at the airport.[8]

If land values are not increasing rapidly, adequate property interests for airport development should be included in the NAP at the same time the airport is planned.

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[7] All figures appear in Appendix B.

[8] FPAR = CPAR/GGAO, where FPAR = future parking apron requirements, CPAR = current parking apron requirements, and GGAO = growth in general aviation operations.

However, where land values are expected to increase at more than 6% per year,[9] property interests may be included in the NAP three to five years in advance of the airport development forecasted.

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[9]This increase in land value is compounded annually and is an FAA guideline.

CHAPTER II

CAPACITY

Capacity is defined as an operating level, expressed as the rate of aircraft movements, which results in a given level of delay. The two major divisions of runway capacity are hourly and annual runway capacity. Hourly runway capacity is defined as that movement rate of aircraft which results in a reasonably acceptable average delay to operations. The delay levels considered as reasonably acceptable are as follows:[10]

Hourly Runway Capacity

VFR Departures

A. Four minutes average delay where class A&B aircraft constitute more than 10% of the population.

B. Three minutes average delay where class A&B aircraft constitute 1 to 10% of the total population.

C. Two minutes where less than 1% of the population consists of class A&B aircraft.

---

[10]For a definition of aircraft in each of the classes discussed in this unit, refer to Table 1.

VFR Arrivals

One minute average delay to all aircraft.

IFR Arrivals or Departures (During IFR Weather)

Four minutes average delay to arrivals or departures, whichever comes first.

Annual Runway Capacity

Annual runway capacities are based on having certain assumed distributions of demand, and these distributions are [1]:

A. For airports serving 90% or more class D&E aircraft, the activity level during the peak hour of the week is 20% of the peak daily traffic.

B. For airports serving 70% class D&E aircraft, the activity level during the peak hour of the week is 15% of the peak daily traffic.

C. For airports serving 50% class D&E aircraft, the activity level during the peak hour of the week is 12.5% of the peak daily traffic, if local operations are 30% or more of the traffic.

D. For airports serving 50% class D&E aircraft, the activity level during the peak hour of the week is 10% of the peak daily traffic, if local operations are less than 30% of the traffic.

E. For airports serving 40% or less class D&E aircraft, the activity level during the peak hour of the week is 87% of the peak daily traffic.

The basic procedure for determining capacity is as follows [2]:

A. Analyze the operations forecast for the location, establish the anticipated aircraft mix, and select the nearest mix type from Table 1.

B. Select the layout from Table 2 which most closely represents the future operational configuration of the airport.

C. If no adjustments are necessary, practical annual capacity (PANCAP), IFR, and VFR hourly capacities are taken directly from Table 2 for the selected layout and mix.

D. If adjustments to the assumptions are necessary, they will occur in:

1. Variation in forecast mix.
2. Variation in layout combinations and use of runways due to strong winds.
3. Variation in the amount of training activity conducted at the airport.
4. Variation in percent of IFR/VFR weather.

Practical Annual Capacity

In determining the PANCAP for configurations in Table 2, a set procedure is followed:

A. Determining the IFR and VFR capacities for each mix.

B. Adjust the IFR capacity by dividing it by D_I, where D_I is equal to IFR demand as a percent of VFR demand multiplied by b.[11]

C. Compare VFR with the adjusted IFR, divide by the larger of the two to obtain the percent of maximum and thus find the weighting factor.[12]

D. The adjusted IFR and the VFR capacities are changed to reflect the weighting factor and the percent of VFR and IFR weather, and are then added together to obtain the weighted hourly capacity (WHC).

Weighted Hourly Capacity Calculations

$$WHC = \frac{(I_a \times WF_I \times 10\%) + (V \times WF_V \times 90\%)}{(WF_I \times 10\%) + (WF_V \times 90\%)}$$

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[11] Multiplication factor, b, is obtained from Table 3.

[12] The weighting factor is taken from Table 4.

where

V = VFR hourly capacity,

I_a = IFR hourly capacity adjusted to demand,

WF_V or WF_I = weighting factor for VFR or IFR, respectively. (One of these numbers is unity in every equation. Normally, WF_V is one, since VFR capacity is almost always greater than adjusted IFR capacity

WHC = weighted hourly capacity.

Practical Annual Capacity Calculation

Using the WHC determined for each mix, the PANCAP is calculated by adjusting WHC for a certain peaking factor and for assumed training activities.

$$PANCAP = WHC \times P \times TG$$

where

PANCAP = practical annual capacity,

WHC = weighted hourly capacity,

P = multiplication to adjust for peaking,[13]

TG = correction factor for touch and go activity.[14]

---

[13]Obtained from Table 5.

[14]Obtained from Table 5.

Runway Capacity

The following procedure is how to obtain a detailed analysis of runway capacity:

General Capacity Determination

A. Determine the forecast aircraft population for the airport in percent of classes A, B, C, and D&E aircraft.[15]

B. Determine the number and type of exits.[16]

C. Determine the percent of T&G operations.[17]

D. Determine the ratio of arrivals to departures during peak hours by:

$$M_S = A_L + D_T \qquad A_L = M_S \left(\frac{R}{1+R}\right)$$

$$R = \frac{A_L}{D_T} \qquad D_T = M_S \left(\frac{1}{1+R}\right)$$

where

A_L = number of arrivals per hour,

D_T = number of departures per hour,

M_S = total movements per hour,

R = ratio of arrivals to departures.

---

[15] These classes are explained in Table 1.

[16] Obtained from Figures 2 and 3.

[17] One T&G equals two operations.

E. Determine the percent of time to the nearest 1% that each runway combination is used by analyzing the wind rose and/or data from the tower chief.[18]

F. Using the above information one can then determine the hourly and annual capacities of the runway configuration.

Specific Capacity Determination

A. For runway configurations where exit rating is used, apply the following procedure [1]:

1. For general purposes and for examining the maximum runway capability to which an airport may be developed, an exit rating of one should be assumed.

2. Determine the number of right-angled, angled, and standard taxiways[19] existing on runways used for arrivals or mixed operations. For runways serving predominantly small aircraft, count only those exits that fall between 800 feet from the landing threshold to 5,000 feet, unless four-engine jet aircraft are operated on the runway, in

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[18]The author used data that were supplied to the FAA by tower chiefs.

[19]Right-angled taxiways are taxiways having angles of 60° or sharper, while angled taxiways are those from 31 to 59°, and standard exits are 30° or flatter.

which case exits up to 8,000 feet should be counted. For runways serving predominantly large aircraft, the exits from 1,000 to 6,000 feet should be counted.[20]

3. Using runway length and number of exits[21] determine the exit rating from Figures 2 and 3.
4. The capacity for runways with various exit ratings can then be determined from the capacity curves.

B. At airports where there are T&G operations, and the exit rating is other than one, Figure 4 is used to determine the new exit rating to be used with the runway capacity curves.

C. The runway capacity curves, Figures 5 through 12, may now be used to determine the capacity for any runway configuration. If airport population falls in between the values shown on these graphs, Figures 13 and 14 are used to determine the proper interpolation point. Normally, the closest population fit is adequate.

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[20]Exits up to 8,000 feet should be counted if four-engine jets are present.

[21]When dealing with a large number of exits, it is sometimes useful to reduce the number counted in the following manner: three right-angled equal two angled equal one standard exit taxiway.

D. The hourly runway capacity determined for the VFR condition should be converted for the percentage of T&G operations by the use of Figure 4. Instrument flight regulations runway capacity is not corrected for T&G activity, since this activity normally disappears in IFR weather.

E. Another factor to be determined is the ratio of arrivals to departures. For ratios of 1.1 or greater,[22] apply the procedure described in the section on ratio corrected runway capacity.

F. To evaluate the effect of runway length or other runway use restrictions on capacity, the following procedures are used. (Runway length, noise restrictions, or obstructions may limit the utility of certain runways. The capacities obtained from the following must be adjusted to take these factors into account.)[23]

1. For VFR-parallel runways, VFR-open "V" runways with operations away from the apex, and IFR-independent parallel runways if more than 50% of the aircraft are restricted from

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[22] That is, arrivals during the peak hours are 10% greater than departures.

[23] No correction to the capacity curves needed if the shorter runway is greater than 80% of the length of the longer runway.

using one of the runways; then determine the capacity from the appropriate graph (Figures 5 through 12) and multiply by 0.05/P, that is:

$$C_c = C \times (0.05/P)$$

where

C_c = corrected capacity,

C = uncorrected runway configuration capacity,

P = portion of the population that must use the predominant runway.

2. For VFR-two intersecting runways, VFR-three intersecting runways, IFR-close parallels, and IFR-open "V" runways with operations toward the apex where more than 50% of the aircraft are required to use one runway because of restrictions; both the single runway capacities for the runway capacity being studied must be determined. That is,

$$C_C = C - C_D(2P - 1)$$

where

C_C = corrected capacity,

C = uncorrected runway configuration capacity,

C_D = difference between C and single runway capacity.[24]

P = portion of aircraft using predominant runway.[25]

3. Since in IFR weather most small aircraft do not fly, the VFR runway capacity is all that needs to be evaluated in most cases. As a guide, the IFR runway capacity does not have to be determined except for the following VFR populations [1]:
   a. When D&E is less than 50%, when A&B is less than 50%, and A is less than 20%.
   b. When A&B is 60% or greater, and A is less than 20%.

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[24] Single runway capacity is obtained from Figure 5.

[25] The solution to runway use restrictions for open "V" runways with operations toward the apex in VFR conditions is found in Figure 10. This figure can be used directly when the restriction results in departures being diverted to the arrival runway. However, if the arrival runway has restricted use, then the above method is used.

c. When D&E is less than 30%, when A = 20%.

d. When D&E is less than 20%, when A = 40%.

e. When D&E is less than 5%, when A = 60%.

The above will hold for all but close parallel runways. For that case, the IFR runway capacity when D&E, in VFR, is less than 80% of the activity must be determined.

4. If IFR runway capacity is more critical than VFR runway capacity, the following procedure must be applied.

Maximum VFR Runway Capacity

$$MVFRRC = \frac{110(IFRRC)}{D_I}$$

where

IFRRC = IFR runway capacity,

$D_I = \sum$ (percent VFR demand) x b,[26]

110 = $\sum$ (percent VFR demand) + 10%, which is constant.

This is the maximum VFR runway capacity that can be used and still not result in an excessively congested IFR situation.

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[26]Multiplication factor, b, is taken from Table 3.

Maximum IFR Runway Capacity

$$MIFRRC = \frac{D_I(VFRRC)}{110}$$

where

VFRRC = VFR runway capacity,

D_I and 110 were defined previously.

This is the maximum IFR runway capacity that can be used and still not result in an excessively congested VFR situation.

A. Single runway capacity is determined by finding the hourly runway capacity in each direction of operation for VFR and, if necessary, for IFR.[27]

B. Determining the capacity for two intersecting runways or open "V" runways is accomplished by determining the capacities and the percentage of time the following configurations are used:[28]

   1. Single runways.
   2. Operations toward the intersection.
   3. Operations away from the intersection, and departures toward the intersection, while arrivals are away from it, or vice versa.

---

[27]This is accomplished by the use of Figures 5 and 11, respectively.

[28]For VFR capacities, Figures 9 and 10 are used; for IFR capacities, Figures 11 and 12 are used.

Use single runway capacity when it is greater than the capacity of intersecting runways.

C. The capacity for three intersecting runways is computed in a manner similar to the above except the capacity of three intersecting runways[29] is also computed in addition to the capacity of two intersecting and single runways, while there will also be more combinations of two intersecting runway uses.

D. Specific procedures in addition to the two intersecting runways case are:

1. Evaluate only those combinations of two intersecting runways having substantially different capacities. Disregard all runways used less than 2% of the time [2].

2. In many instances the capacity of two intersecting runways will be greater than that for three intersecting runways. "If this occurs, the final runway capacity is the capacity of two intersecting runways for the portion of time that the higher capacity of intersecting runways is available [10]." In other words, the capacity of three intersecting runways should be used only for the

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[29]For VFR capacities, Figure 9 is used in the determination, while Figure 11 is used to find the IFR capacities.

portion of time that it gives a greater capacity than any usable two runway configurations. Also, in those cases where a single runway has higher capacities than intersecting runways, use the single runway capacity.

E. The computation of the capacity for parallel runways with no crossing problem[30] is performed in a manner similar to the single runway calculation, although there may be a much greater IFR adjustment required for close parallels.

F. To determine the capacity of parallel runways with crossing problems, the following must be done [2].

1. Determine the necessary capacity for each direction of operation.
2. The remainder of the calculation is similar to that of a single runway. This computation should be done for VFR only; however, this does not preclude the use of the IFR curves to determine if the maximum VFR runway capacity should be adjusted by the IFR runway capacity.

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[30]Figure 7 is used for VFR capacities, while Figure 11 is used to find IFR capacities.

3. The maximum IFR runway capacity should be assumed as not being affected by the crossing taxiways.

Arrival to Departure Ratio Correction

Runway capacity can be determined directly from the graphs without significant error when the ratio of arrivals to departures (R) during the peak hours of the week is within the range of 0.6 through 1.1. For ratios above this range, arrival capacity can be a controlling condition in a capacity determination; then the following procedures should be applied:

A. Determine the maximum arrival capacity for runways having arrivals only or mixed operations.[31]

B. Determine the number of arrivals for the runway combination being evaluated, using the arrival/departure ratio as follows:

Maximum Arrival Demand

$$MAD = RC/(\frac{1}{R} + 1)$$

where

RC = runway capacity or IFR capacity + VFR capacity.

---

[31]To obtain these capacities, one uses Figures 6 and 11, respectively.

If MAD exceeds MAC,[32] then runway capacity should be adjusted to reflect this limitation as follows:

Ratio Corrected Runway Capacity

$$RCRC = RC \times (MAC/MAD).$$

Under VFR conditions, the foregoing calculations may have to be adjusted[33] if arrivals are conducted simultaneously on more than one runway and exit ratings are greater than one. When adjusting arrival capacity do not exceed the capacities outlined in Figure 6 for an exit rating of one for open "V" or intersecting runways.

Runway Rating

Runway rating is defined as the average runway occupancy for a given population of aircraft landing on a runway. The basic information required to obtain the runway rating for any class of aircraft is:

A. Runway altitude above mean sea level in feet.

B. Runway length in feet.

C. Number and kind of turnoffs along the runway.

D. Distance from runway threshold to each turnoff in feet.

---

[32] MAC stands for maximum arrival capacity.

[33] When maximum arrival demand is greater than maximum arrival capacity, the runway capacity must be adjusted downward, and the opposite is required when MAD is less than MAC.

Basically, the technique consists of calculating a corrected runway length.

Corrected Runway Length Calculation

$$CRL = RL \times CF$$

where

RL = runway length in feet,

CF = correction factor.[34]

From this, an exit rating is determined by runway length and turnoff design, then the exit rating is used in determining the runway rating.[35]

If turnoffs exist on either side of the runway, the ultimate destination of the landings must be considered. Furthermore, a runway may have a combination of types of turnoffs. In such cases the following procedures are to be applied:

A. Use the exit range table that corresponds to the predominant types of turnoffs in the general area of the applicable exit range.

---

[34]The correction factor is found from Figure 15 by using runway altitude and aircraft class.

[35]It is necessary to use Tables 6, 7, and 8 to find the exit range for a particular aircraft class, then returning to the original data to find the number of exits within the range, and then using this value to obtain an exit rating and a runway rating from Table 9.

B. When right-angle turnoffs predominate: One high-speed turnoff equals two angled or three right-angled turnoffs.

C. If high-speed turnoffs predominate, then: One right-angle turnoff equals two-thirds angled turnoff, or one-third high-speed turnoff.

In this latter case, some interpolation is necessary when determining both the exit and the final runway rating. To obtain a final average R_R for use in determining capacities, the average R_R must be derived for all classes, weighed by the percentage of each class for each runway.

$$R_R = (\text{percent A} \times R_R \text{ for A}) + (\text{percent B} \times R_R \text{ for B}) + (\text{percent C} \times R_R \text{ for C}) + (\text{percent D} \times R_R \text{ for D}) + (\text{percent E} \times R_R \text{ for E})$$

where

R_R = runway rating,

percent A = percent class A aircraft,

percent B = percent class B aircraft,

percent C = percent class C aircraft,

percent D = percent class D aircraft,

percent E = percent class E aircraft.

The results of these computations are then fed back into the system to be used in the computation of the corrected capacitances.

CHAPTER III

DELAY

Delay is defined as the amount of time an arrival or departure is late. When the arrival rate (A_t) at an airport rises above the acceptance rate (C) at time (t_0) not all aircraft can be accommodated, and a backlog, or queue, begins to develop, which eventually equals the number of aircraft represented by the cross-hatched area above line C in Figure 16. To be exact, the length of the queue in aircraft at any time (t), for the range $t_0 \leq t \leq t_2$, is calculated by:

$$Q_t = \int_{t_0}^{t} [\, A_t - C \,]\, dt$$

where t_0 is the time at which the queue starts to build up. The delay to an aircraft arriving at time t, is simply the time it takes to work through the queue in existence at that time.

$$W_t = \frac{Q_t}{C}$$

or equivalently,

$$W_t = \frac{1}{C} \left(\int_{t_0}^{t} [\, A_t - C \,]\, dt \right).$$

Total Delay Calculation

The total delay, D, is computed by the following:

$$D = \int_{t_0}^{t_2} [A_t \cdot C] \, dt$$

where

D = total delay to an aircraft at a certain time,

A_t = aircraft arrival rate,

W_t = aircraft arrival delay.

Daily Delay Calculation

The total delays per day are computed by:

$$D_d = \sum_{t=1}^{24} [N_t \cdot W_t]$$

where N_t is the number of aircraft per hour delayed.

The delay, W_t , reaches a maximum at t_2 , the time when the arrival rate has again returned to the level of the acceptance rate. This occurs because the excess of aircraft arriving for landing or takeoff over the acceptance rate has been accumulating throughout the time period from t_0 to t_2. Delays will return to zero only when the queue hatched areas of Figure 16 are equal. There is no simple relationship between the arrival rate during a particular time period and average delays during that hour. Instead, average delays

depend on the pattern of arrivals for landing or takeoff and on the acceptance rate.

Annual Delay Calculation

The annual delay is simply the summation of all the total daily delays.

$$D_a = \sum_{d=1}^{365} D_d$$

where D_d is the total daily delays found by

$$D_d = \sum_{t=1}^{24} [\, N_t \cdot W_t \,].$$

Delay Calculations for Planned Airports

The foregoing methods of delay calculation are excellent for use at an existing airport, when the delay caused to the movements per hour is known.[36] However, when this is not the case, the following procedure should be followed:

A. Determine the aircraft population.

B. Determine IFR and VFR arrival and departure capacities.[37]

C. Calculate the arrival to departure ratio.

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[36]This also implies a knowledge of the number of movements per hour.

[37]These capacities are obtained from Figures 5 through 12.

D. Compute the number of arrivals and departures by:

$$A_L = CO \times R$$

where

A_L = number of arrivals,

CO = capacity operations per hour,

R = ratio of arrivals to departures,

and

$$D_T = CO - A_L ,$$

where

D_T = number of departures.

E. Calculate the average delay for arrivals and departures by use of Figure 17.

F. Compute the total delay for operations per hour by:

$$D_{TH} = (L \times D_A) + (T \times D_D)$$

where

D_{TH} = total delay to all operations per hour,

L = number of arrivals,

D_A = average arrival delays,

D_D = average departure delay,

T = number of departures.

G. The total daily delay is then found by:

$$D_d = \sum_{H=1}^{24} D_H$$

where

D_H = total delay to operations per hour.

H. The total annual delay is then the sum of all the total daily delays throughout the year, or:

$$ANDE = \sum_{d=1}^{365} D_d .$$

These equations then give predictable delays for planned airports and actual delays at existing airports.

CHAPTER IV

IMPLEMENTATION AND CONCLUSIONS

The previous chapters covered the manual procedures for obtaining the required and the basic calculations, while this chapter is devoted to the automated analysis of the airport systems and the conclusions reached.

One of the first conclusions drawn was that gates and parking aprons had no real effect on airport capacity and as such, no appreciable effect on delay caused to aircraft.[38] This is especially true for the purposes of this study as it is not dealing with terminals or terminal-related problems. It was also discovered, by investigation of actual existing airport capacity information, that holding aprons and bypass taxiways enhanced airport capacity so marginally as to be useless in improving the delay situation. This was verified by an advisory circular which the investigator read on September 12, 1975 [1].

The first steps in automation of the program were as follows:

A. Convert all graphical information to a tabular form.

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[38]The FAA since the inception of this study has stated that parking aprons and gates are part of the terminal configuration and, as such, are part of the land side configuration of an airport.

B. Take all tabular information obtained and store it in the machine as reference data for the program.

Before continuing with the simulation it was necessary to determine what variables had the greatest effect on delay. The conclusion reached concerning this was that the aircraft population at a particular airport was of paramount importance because it, in turn, determines the particular airport runway configuration which is responsible for the type of runways and the runway lengths. These factors then determine the number, type, and location of exit taxiways along the runway. The runway configuration, runway length, type of runway, runway rating, and the number, type, or location of exit taxiways all contribute to determine the runway capacity of an airport and thus, that airport's capacity.

Thus, since the aircraft population determines the foregoing items, it is understandable why the aircraft mix is of such paramount importance.

The geographical location of the airport is second only in importance to aircraft population. This input is necessary because it determines the weather at the airport[39] and the actual physical runway layout.

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[39]This determines the need for a crosswind runway and the predominant weather at an airport, which have an effect on capacity.

Implementation

The first step was to read in the background data which consisted of the following information:

A. Aircraft mix.[40]

B. Geographical location.

C. Runway configuration.

D. Runway length.

E. Exit runway type.

F. Number of exit taxiways.

G. Physical location of exit taxiways.[41]

H. Percent of crosswind at the airport.

I. Runway altitude.

The above information was implemented by the program segment which follows:

```
READ (5, 1) MIX, GL, ETT, RC, NET, CW, RL, RA, PLET
1 FORMAT (6 I3, 3I5)
```

and is important because the information is used to calculate the following values:

A. Runway rating.

B. Exit rating.

C. Hourly VFR capacity.[42]

---

[40]Aircraft mix is in actuality the summation of the percentages of the various aircraft classes at the airport.

[41]That is, their physical location in relation to the runway threshold.

[42]Hourly VFR runway capacity is equivalent to the hourly VFR runway demand of the airport.

D. Hourly IFR capacity.[43]

E. Weighted hourly capacity.

F. Total movements per hour.

G. Arrival to departure ratio.

H. Number of arrivals.

I. Number of departures.

J. Practical annual capacity (PANCAP).

K. Maximum VFR hourly capacity.

L. Maximum IFR hourly capacity.

The aforementioned values are calculated by the following program segment which results in these values, which are calculated by the same program segment:

A. The true (corrected) capacity.

B. Corrected PANCAP.

C. Hourly delays to arrivals.

D. Hourly delays to departures.

E. Hourly delays to total operations.

F. Daily delay to total operations.

G. Annual delay to total operations.

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[43]Hourly IFR runway capacity is also equivalent to the hourly IFR runway demand of the airport.

```
DO 10 J = 400, 5800, 200
DO 11 K = 1, 4
DO 12 L = 1, 5
READ (5, 3) CFCLA (J, K, L)
3 FORMAT (5 F 10.6)
READ (5, 2) CFMIX (J, K)
2 FORMAT (4 F 10.6)
12 CONTINUE
11 CONTINUE
10 CONTINUE
   N = 1
   M = 400
15 IF (MIX. EQ. N) GO TO 13
14 N = N + 1
   IF (N. GT. 4) GO TO 25
16 GO TO 15
13 CONTINUE
17 IF (RA. LE. M) GO TO 18
19 M = M + 200
   IF (M. GT. 5800) GO TO 25
20 GO TO 17
18 CONTINUE
   CRL = RL * CFMIX (M, N)
21 IF (ETT. NE. 1) GO TO 22
23 CONTINUE
   IF (NET. GT. 1) GO TO 24
```

```
26 CONTINUE
   ER = 5
   GO TO 35
24 ER = 6 - NET
   GO TO 35
22 IF (ETT. NE. 2) GO TO 27
28 CONTINUE
   IF (NET. GT. 0) GO TO 29
30 CONTINUE
   ER = 5
   GO TO 35
29 ER = 5 - NET
   GO TO 35
27 CONTINUE
   ETT = 3
   IF (NET. GT. 0) GO TO 32
31 CONTINUE
   ER = 4
   GO TO 35
32 ER = 4 - NET
35 CONTINUE
   IF (CRL. GT. 2999) GO TO 46
37 CONTINUE
   RRA = 0
   RRB = 0
   RRC = 0
   IF (ER. GT. 1) GO TO 38
```

```
39 CONTINUE
   RRD = 20
   RRE = 21
   GO TO 36
38 CONTINUE
   IF (ER. GT. 2) GO TO 40
41 CONTINUE
   RRD = 27
   RRE = 28
   GO TO 36
40 CONTINUE
   IF (ER. GT. 3) GO TO 42
43 CONTINUE
   RRD = 32
   RRE = 32
   GO TO 36
42 CONTINUE
   IF (ER. GT. 4) GO TO 44
45 CONTINUE
   RRD = 39
   RRE = 40
   GO TO 36
44 CONTINUE
   ER = 5
   RRD = 44
   RRE = 46
```

```
36 CONTINUE
   READ (5, 101) PA, PB, PC, PD, PE
   101 FORMAT (5 I3)
   RR = (PA * RRA) + (PB * RRB) + (PC * RRC) +
        (PD * RRD) + (PE * RRE)
46 CONTINUE
```

This is a sample segment of how the runway rating is determined. As can be readily seen, it takes a combination of aircraft mix, runway altitude, corrected runway length, and exit rating to determine the runway rating. The next step in implementation was to determine the weighted hourly capacity, maximum hourly VFR and IFR capacities, and PANCAP; then calculate the total number of movements per hour and the total hourly arrival to departure ratio.[44]

This then finished the capacity segment of the calculation sequence, which then is followed by the delay calculation segment. This segment was handled in the same manner as that of the capacity calculation.

The final step in the implementation stage was to set up the decision making process of the simulation algorithm. This was accomplished by cross-branching through the algorithm with a standard information retrieval system. The type employed is a combination of a tree structure with

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[44]This was done by employing the equations for these values, stated in Chapter II, as part of the calculation segment of the program.

a key word type of cross-reference and various relative maximum and relative minimum correlations. The relative minimums for the purposes of this study are the aircraft population mix at an airport, runway configuration, and taxiway configuration. While the only relative maximum is that of construction costs for runways and taxiways at an airport.[45]

Absolute maximums were also employed in the correlation and decision making process:

A. Maximum runway capacity.[46]

B. Maximum delay to aircraft.[47]

C. Maximum R-T configuration.[48]

Also, the only absolute minimum is that concerning appreciable delay reduction.[49]

Therefore, the first step in the simulation was to calculate and determine the initial values of runway

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[45]This is a relative maximum due to the effects of inflation on construction costs.

[46]That is, the maximum number of aircraft a runway can handle in the arrival and/or departure mode.

[47]This is as per discussion covered in Chapter III.

[48]This is the maximum number of taxiways per runway configuration.

[49]In order for a delay reduction to be appreciable, according to the FAA, it must improve the existing delay situation by at least 25%.

capacity, aircraft delay,[50] arrival to departure ratios, airport airside configuration type, and geographical location.

The next step in the simulation was to implement the actual testing stage of the algorithm. This was accomplished by means of an alphanumeric input statement with data checking and initial access to the program being controlled by a series of alphanumeric logic statements. The actual testing for delay reduction was accomplished by taking the initially determined values of runway arrival and departure demand and holding them constant.

Then, by changing the runway length, runway configuration, or taxiway configuration either singly or in combinations thereof, the testing of these values to determine if appreciable delay reduction resulted has begun. This is done by testing the newly calculated capacitances, then by comparing them with the existing demand levels, new values of delay are determined.

After this calculation is completed the results are compared with economic constraints and the initial delay values to determine if economically feasible and appreciable

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[50]This is one of the first points that makes this a valid computerization problem in that 8,760 hourly calculations are required to calculate the total annual delay alone. The complexity is better understood when one realizes that the total hourly annual delay is the total of all hourly delays per day, which is further the total of all delays per hour. Therefore, it is readily understandable how this can become easily excessive when considered in terms of manpower time and economics.

delay reductions have occurred. If acceptable results have not been achieved, then the program does the following:

A. States that an unacceptable solution was obtained and why.[51]

B. States the type of solution attempted.

C. Branches back to the test data input location and reads in a new set of testing parameters.

If the test results are acceptable, then the program executes the following procedure:

A. States that an acceptable solution has been obtained.

B. States type of solution employed.

C. Branches back to initial test data input location and executes the procedure again to see if the most optimum result has been achieved.

The most optimum solution is one that gives the greatest delay reduction with the least amount of expense.

Conclusions

A class I airport is an airport that serves predominantly four-engine jet and air carrier type of aircraft. A class II airport is one serving twin-engine jet or class B aircraft predominantly. A class III airport is one that serves predominantly class C aircraft, while an airport

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[51] A solution is unacceptable because it was either economically unfeasible, or appreciable delay reduction was not achieved, and/or the delay still exceeded FAA maximum requirements.

handling mainly class D&E type of aircraft is a class IV airport. From the simulation the following conclusions resulted for the sample airports used in each class.

Class IV Airports[52]

The conclusions reached as a result of the simulation for class IV airports are as follows: The first attempted solution was that of varying solely the runway length. It was found that this was an excellent solution as far as delay reduction was concerned, but was economically unfeasible. However, the most optimum solution was found to be that of slightly lengthening the runway and providing additional taxiway facilities simultaneously.[53] The final conclusion was that for class IV airports, changing the runway configuration was too excessive in cost.

Class III Airports

For class III airports, while lengthening the runways was an economically feasible solution, it failed to appreciably reduce the existing delay. The next conclusion was that changing the taxiways and runways consecutively produced an appreciable delay reduction and was quite

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[52]The case of each airport class was handled by choosing a representative airport of each class from FAA statistics illustrating the fact that a delay problem existed at the airport.

[53]In order to increase the number of taxiways it is necessary to lengthen the runway as the number of taxiways is a function of runway length.

economical. It was further found that while varying the runway configuration produced an appreciable delay reduction, it was economically unfeasible. The most economical solution for the airport[54] used in this study was to have one runway devoted to arrivals with the other runway being devoted to departures. This was the most optimum because it provided a very appreciable delay reduction at almost no financial expense to the airport operators.

Class II Airports

For class II airports it was found that solely increasing runway length had no appreciable effect on delay when held within economic constraints. It was also found that while increasing runway length and the number of taxiways resulted in appreciable delay reduction, the necessary expansion was so large that it became economically unfeasible.

The most optimum solution for class II airports was found to be that of a runway configuration change. This change was to either convert existing parallel runways, or simply add an independent runway[55] parallel to the existing runway configuration, into a parallel runway configuration

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[54]The airport chosen was an average class III configuration employing a dual runway situation, while that chosen for the class IV was a standard single runway configuration.

[55]An independent parallel runway configuration is one in which the runways are separated by 5,000 feet or more.

in which one runway was for arrivals only and the other handling departures solely. The conversion of runways was feasible economically and appreciably reduced delay, but was realistically unacceptable at some class II airports,[56] including the sample airport used in this study. Therefore, the best solution was that of adding an independent runway parallel to the existing configuration.

Class I Airports

At class I airports extending runway length and increasing the number of taxiways were ineffective because they failed to result in appreciable delay reductions. It was further established that the addition of a separate runway for arrivals or departures, or conversion of the existing configuration to such a scheme were unacceptable solutions, as they failed to produce acceptable results. This was true because a class I airport is devoted predominantly to IFR-type traffic, and these particular solutions enhance VFR capacity more than IFR capacity. Therefore, the acceptable solution was found to be that of making an adjustment to the aircraft population at the airport.

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[56]This is because of open or closed "V" type runways and intersecting runways.

This is accomplished by either adding an independent parallel runway for VFR traffic[57] or by completely banning VFR-type traffic from using the airport. The banning of a particular type of traffic is unacceptable and impractical at an airport; thus, the best solution is to construct an independent parallel runway for VFR traffic.

Therefore, it has been established that the above methods provided the best delay reduction for the sample airports. It is also evident from this that the problem is a valid computerization problem, because of the excessive number of computations and the complexity of the branching techniques through the algorithm to obtain optimum results. Although this could be done without the aid of a computer, the costs in terms of manpower and the amount of time are astronomical.

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[57]This is defined as general aviation aircraft, and class C aircraft as defined in Appendix A.

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BIBLIOGRAPHY

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APPENDICES

APPENDIX A

TABLES

For Table 1, the A, B, C, and D&E stand for various types of aircraft:

Type A means all jet aircraft normally requiring runway lengths exceeding 6,000 feet (corrected to sea level) for takeoff and/or landing.

Type B means: (1) piston and turboprop aircraft having a normal loaded weight in excess of 36,000 pounds; (2) jet aircraft not included in class A, but having a normal loaded weight in excess of 25,000 pounds.

Type C means: (1) piston and turboprop aircraft having a normal loaded weight greater than 8,000 pounds and less than 36,000 pounds; (2) jet aircraft having a normal loaded weight greater than 8,000 pounds, but less than 25,000 pounds.

Type D means all light twin-engine piston and turbo-prop aircraft having a normal loaded weight less than 8,000 pounds, and some high-performance single-engine light aircraft.

Type E means all single-engine aircraft with the exception of the Mustang, Bonanza, and Debonair, and small short takeoff and landing (STOL) aircraft, some of which may have two engines.

The following conditions were assumed in setting up Table 2:

A. An annual weather condition of 90% VFR and 10% IFR was assumed in calculating the weighted hourly capacity (WHC) and PANCAP.

B. The numbers in the mix column for each configuration in Table 2 were taken from Table 1.

C. The percent of daily activity during the peak hour of the day is defined as the peaking factor. This factor greatly influences annual capacity and varies with the type of aircraft mix in operation at a particular airport.

   1. For mix 1 the peaking factor is 13%, with 60% touch and go assumed.
   2. For mix 2 the peaking factor is 12.5%, with 30% touch and go assumed.
   3. For mix 3 the peaking factor is 9.5%, with 10% touch and go assumed.
   4. For mix 4 the peaking factor is 8.7%, with 15% touch and go assumed.

Understanding of these two tables is of paramount importance in order to readily understand the remaining tables.

TABLE 1

AIRCRAFT MIX

Mix No.	Percent Type A	Percent Type B	Percent Type C	Percent Type D&E
1	0	0	10	90
2	0	30	30	40
3	20	40	20	20
4	60	20	20	0

Source: Federal Aviation Administration, "Airport Capacity Criteria Used in Planning the National Airport Plan" (Federal Aviation Administration-Department of Transportation AC 150/5060-1A, Washington, D. C., January, 1968), Appendix III, p. 4.

TABLE 2

AIRPORT CAPACITIES FOR LONG RANGE PLANNING PURPOSES

Runway Configuration Description	Mix	PANCAP	Practical Hourly Capacity IFR	VFR
(A) Single Runway	1	215,000	53	99
(Arrivals/Departures)	2	195,000	52	76
	3	180,000	44	54
	4	170,000	42	45
(B) Close Parallels	1	345,000	64	198
(IFR-Dependent)	2	330,000	63	152
	3	295,000	55	108
	4	280,000	54	90
(C) Independent IFR	1	425,000	79	198
(Approach/Departure)	2	300,000	79	152
	3	355,000	79	108
	4	330,000	74	90
(D) Independent IFR	1	430,000	105	198
(Arrivals/Departures)	2	390,000	104	152
	3	360,000	83	108
	4	340,000	84	90
(E) Independent Plus One	1	600,000	117	297
Close Parallel	2	525,000	115	228
	3	475,000	99	162
	4	450,000	96	135
(F) Independent Plus	1	665,000	156	307
Simultaneous	2	595,000	153	236
Departure Runway	3	540,000	146	162
	4	525,000	133	139
(G) Independent Parallels	1	665,000	156	307
Plus Divergent	2	595,000	153	236
Runways	3	475,000	146	162
	4	450,000	133	139
(H) Independent Parallels	1	770,000	128	395
Plus Two Close	2	660,000	126	304
Parallels	3	590,000	110	216
	4	560,000	103	180
(I) Independent Parallels,	1	1,050,000	177	505
Close Parallels, Plus	2	930,000	174	392
Divergent Runways	3	790,000	155	269
	4	770,000	153	229

TABLE 2 (continued)

Runway Configuration Description	Mix	PANCAP	Practical Hourly Capacity IFR	VFR
(J) Widely Spaced Open "V" with Independent Operations	1	425,000	79	193[a]
	2	340,000	79	136
	3	310,000	74	94
	4	310,000	74	84
(K_1) Open "V" with Dependent Operations Away from the Intersection	1	420,000	71	198
	2	335,000	70	135
	3	300,000	63	94
	4	295,000	60	84
(K_2) Open "V" with Dependent Operations Toward the Intersection	1	235,000	57	103
	2	220,000	56	86
	3	215,000	50	66
	4	200,000	50	53
(L_1) Two Intersecting at Near Threshold	1	375,000	71	175
	2	310,000	70	125
	3	275,000	63	83
	4	255,000	60	69
(L_2) Two Intersecting in Middle Threshold	1	220,000	61	99[b]
	2	195,000	60	76[b]
	3	195,000	53	58
	4	190,000	47	52
(L_3) Two Intersecting at Far Threshold	1	220,000	55	99[b]
	2	195,000	54	76[b]
	3	180,000	46[b]	58
	4	175,000	42[b]	57
(M) Three Intersecting	1	375,000	71	175
	2	310,000	70	125
	3	275,000	63	83
	4	255,000	60	69
(N_1) Parallel and Intersecting, Intersection Points at Ends (Near)	1	590,000	124	274
	2	505,000	122	201
	3	455,000	107	137
	4	425,000	103	114
(N_2) Parallel and Intersecting, Intersection Points at Ends (Far)	1	465,000	114	193
	2	430,000	107	152
	3	390,000	93	112
	4	365,000	83	97

TABLE 2 (continued)

Runway Configuration Description	Mix	PANCAP	Practical Hourly Capacity IFR	VFR
(O_1) "Z" Configuration and Parallel[b] with Both Intersecting (at Ends)	1	465,000	87	217
	2	430,000	87	167
	3	390,000	87	118
	4	365,000	81	99
(O_2) "Z" Configuration and Parallel[c] with Both Intersecting (in the Middle)	1	465,000	87	217
	2	430,000	87	167
	3	390,000	87	118
	4	365,000	81	99
(P_1) "Z" Configuration and Parallel[d] with Both Intersecting (at Ends)	1	475,000	116	217
	2	430,000	114	167
	3	395,000	96	118
	4	375,000	92	99
(P_2) "Z" Configuration and Parallel[d] with Both Intersecting (in the Middle)	1	475,000	116	217
	2	430,000	114	167
	3	395,000	96	118
	4	375,000	92	99

[a] Crossing problem effects capacity.

[b] Indicates single runway capacity.

[c] Close parallels.

[d] Independent parallels.

TABLE 3

CORRECTION FACTOR, b

Aircraft Mix Type	Multiplication Factor, b
A	1.0
B	1.0
C	0.7
D&E	0.015
	at 100% VFR, 0.05

TABLE 4

RUNWAY CAPACITY WEIGHTING TABLE

Percent of Maximum Capacity	Weight
91% or more	1
81% to 90%	2
66% to 80%	4
51% to 65%	8
40% to 50%	12

Maximum capacity is that equaled plus exceeded 10% or more of the time. Since delay to operations arises very rapidly with increasing operating rate, it is necessary to give greater weight to lower capacities when evaluating airport capacity.

TABLE 5

CORRECTION FOR TOUCH AND GO

Aircraft Mix Type	Multiplication Factor, b	Correction Factor, T&G
A	1,830	1.250
B	2,350	1.115
C	3,250	1.040
D&E	3,750	1.000

TABLE 6

EXIT RANGES FOR RUNWAYS HAVING RIGHT-ANGLE TURNOFFS

Corrected Runway Length (feet)	Aircraft Class				
	A	B	C	D	E
≤ 2,999				1,050 to 2,999	800 to 2,999
3,000 to 4,299			1,700 to 4,299	1,150 to 4,299	900 to 3,400
4,300 to 5,399		2,300 to 4,600	1,900 to 4,550	1,250 to 4,400	950 to 3,500
5,400 to 6,199	3,800 to 6,199	2,350 to 4,700	2,100 to 4,650	1,450 to 4,450	950 to 3,600
6,200 to 6,999	3,900 to 6,900	2,500 to 4,800	2,400 to 4,700	1,600 to 4,500	950 to 3,700
7,000 to 7,999	4,200 to 7,500	2,700 to 4,900	2,500 to 4,900	1,700 to 4,550	950 to 3,800
8,000 to 8,999	4,400 to 7,600	2,900 to 5,000	2,650 to 5,000	1,750 to 4,600	1,000 to 3,900
9,000 to 9,999	4,600 to 7,700	3,100 to 5,300	2,750 to 5,150	1,800 to 4,700	1,100 to 4,000
10,000 to 10,999	4,900 to 8,100	3,300 to 5,700	2,850 to 5,350	1,900 to 4,750	1,200 to 4,100
11,000 to 11,999	5,100 to 8,400	3,500 to 6,400	2,900 to 5,550	2,000 to 4,750	1,250 to 4,200
≥ 12,000	5,300 to 8,600	3,700 to 7,400	3,000 to 5,750	2,150 to 4,800	1,300 to 4,300

TABLE 7

EXIT RANGES FOR RUNWAYS HAVING ANGLED TURNOFFS

Corrected Runway Length (feet)	Aircraft Class				
	A	B	C	D	E
≤ 4,299			1,500 to 4,000	1,000 to 3,850	750 to 2,900
4,300 to 5,399		1,900 to 4,400	1,700 to 4,200	1,050 to 3,900	800 to 3,050
5,400 to 6,199	3,500 to 5,800	2,200 to 4,500	1,900 to 4,350	1,200 to 3,950	800 to 3,150
6,200 to 6,999	3,650 to 6,400	2,350 to 4,600	2,150 to 4,450	1,300 to 4,000	800 to 3,300
7,000 to 7,999	3,850 to 7,100	2,500 to 4,750	2,300 to 4,600	1,400 to 4,150	850 to 3,400
8,000 to 8,999	3,950 to 7,300	2,700 to 4,900	2,400 to 4,750	1,400 to 4,250	900 to 3,500
9,000 to 9,999	4,050 to 7,500	2,800 to 5,100	2,500 to 4,900	1,450 to 4,350	1,000 to 3,600
10,000 to 10,999	4,250 to 8,000	3,000 to 5,500	2,550 to 5,050	1,500 to 4,400	1,050 to 3,700
11,000 to 11,999	4,350 to 8,300	3,100 to 6,050	2,600 to 5,200	1,600 to 4,400	1,100 to 3,800
≥ 12,000	4,500 to 8,600	3,250 to 7,000	2,700 to 5,400	1,700 to 4,450	1,150 to 3,900

TABLE 8

EXIT RATINGS FOR RUNWAYS HAVING HIGH-SPEED TURNOFFS

Corrected Runway Length (feet)	Aircraft Class				
	A	B	C	D	E
≤ 5,399		1,700 to 3,850	1,100 to 3,250	850 to 2,400	700 to 1,700
5,400 to 6,199	2,700 to 4,500	1,800 to 3,900	1,300 to 3,400	950 to 2,500	700 to 1,850
6,200 to 6,999	2,900 to 5,000	1,900 to 4,100	1,450 to 3,600	1,000 to 2,600	700 to 2,000
7,000 to 7,999	3,050 to 5,500	2,000 to 4,300	1,600 to 3,800	1,050 to 2,900	750 to 2,150
8,000 to 8,999	3,200 to 5,900	2,100 to 4,500	1,700 to 4,000	1,050 to 3,200	800 to 2,300
9,000 to 9,999	3,350 to 6,100	2,200 to 5,650	1,750 to 4,200	1,100 to 3,300	900 to 2,400
10,000 to 10,999	3,500 to 6,400	2,300 to 4,800	1,750 to 4,200	1,150 to 3,350	950 to 2,500
11,000 to 11,999	3,650 to 6,600	2,400 to 4,950	1,800 to 4,250	1,200 to 3,400	1,000 to 2,600
≥ 12,000	3,800 to 6,800	2,500 to 5,100	1,800 to 4,300	1,250 to 3,400	1,000 to 2,700

TABLE 9

RUNWAY RATING VERSUS RUNWAY LENGTH AND EXIT RATING

Corrected Runway Length (feet)	A					B					C					D					E				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
≤ 2,999																20	27	32	38	44	21	28	32	38	46
3,000 to 4,299											30	35	38	42	50	22	28	33	39	45	25	29	34	40	49
4,300 to 5,399						36	38	40	48	58	32	36	39	44	52	24	29	34	39	46	27	30	35	42	51
5,400 to 6,199	42	46	59	59	66	37	39	41	51	59	33	38	41	49	55	25	39	35	40	47	28	31	36	44	54
6,200 to 6,999	43	47	51	59	68	38	40	42	53	60	34	39	43	51	56	26	31	36	41	49	29	32	37	45	56
7,000 to 7,999	44	47	52	60	71	39	41	43	55	63	35	41	45	53	57	27	32	37	43	51	30	33	38	47	57
8,000 to 8,999	45	48	53	61	75	39	42	45	57	65	36	42	47	54	59	28	33	38	44	53	31	34	34	49	58
9,000 to 9,999	45	49	54	64	78	40	44	49	59	68	37	43	48	55	61	29	34	39	45	55	32	36	40	50	59
10,000 to 10,999	45	50	55	66	80	40	46	50	60	70	38	44	48	56	63	31	35	40	46	57	33	37	41	51	60
11,000 to 11,999	46	52	58	68	83	41	47	51	62	71	39	45	49	57	66	33	37	41	46	59	34	39	43	52	61
≥ 12,000	46	53	60	70	85	41	48	52	63	73	40	46	49	58	68	35	40	42	47	62	35	40	45	53	64

APPENDIX B

FIGURES

The figures presented in this appendix are necessary for proper operation of the algorithm to determine capacity and demand.

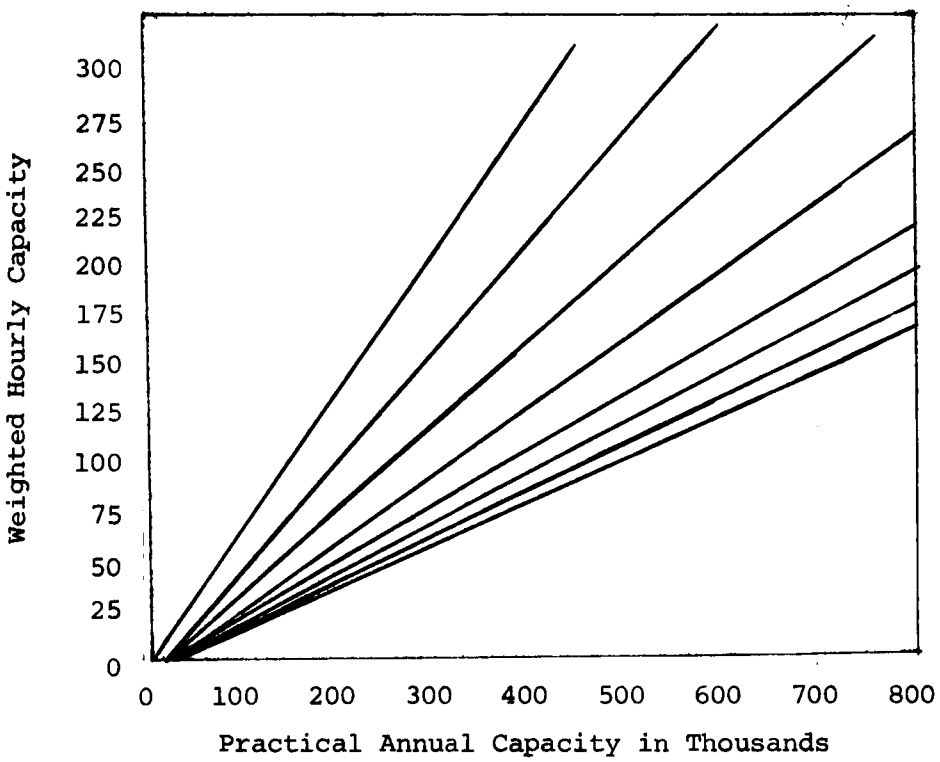


Figure 1. Hourly versus annual capacity.

Note: The peaking factor is based on hourly distribution for the busiest day of the week.

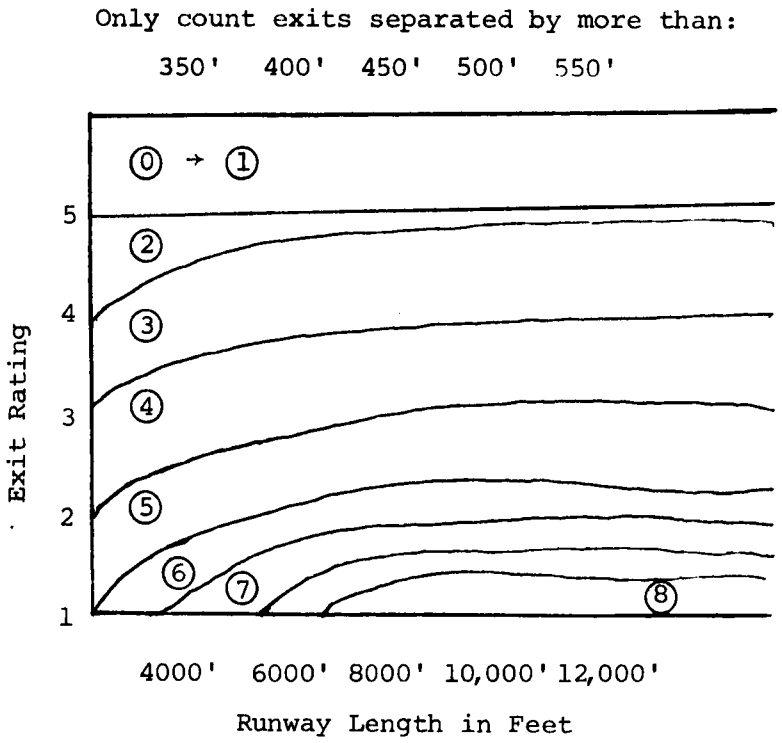
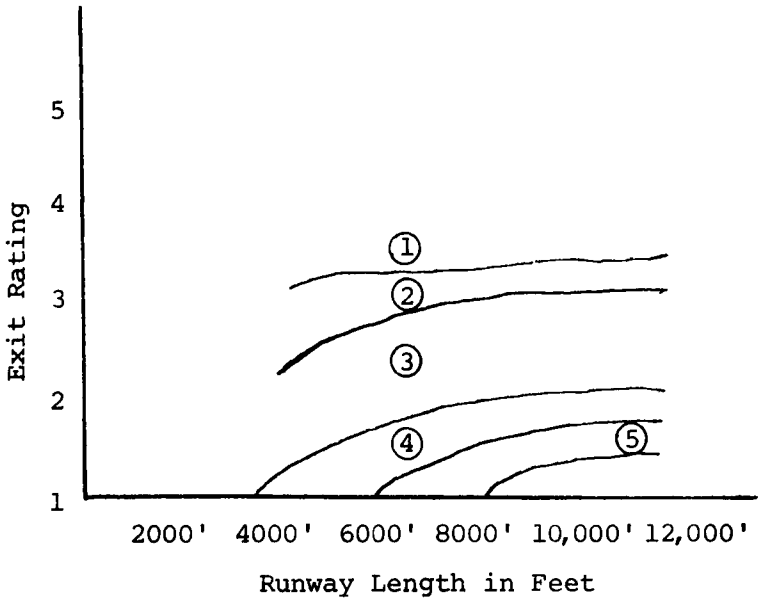


Figure 2. Exit rating, right-angled exits.

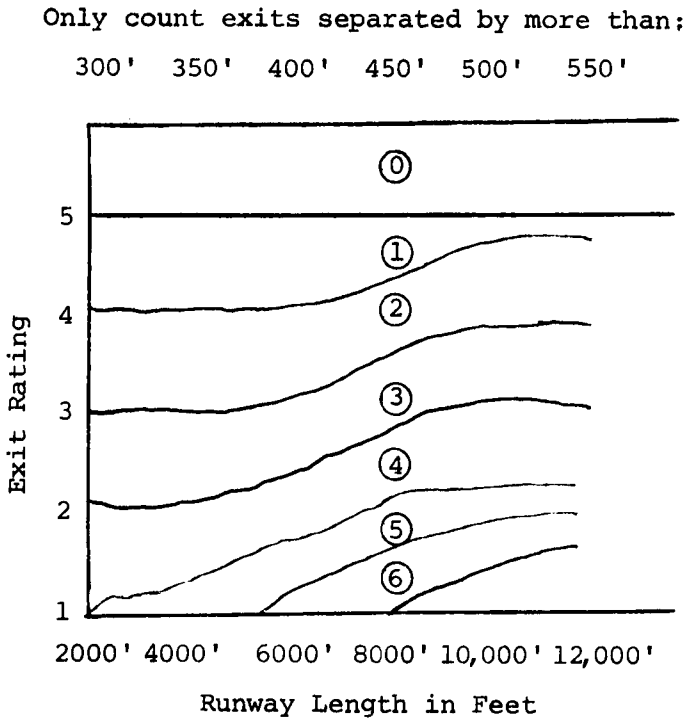
Note: Number in circle = number of exits.



a) Standard exits

Figure 3. Exit rating, standard and angled exits.

Note: Number in circle = number of exits.



b) Angled exits

Figure 3. (continued)

Note: Number in circle = number of exits.

(A) Single runways, parallel, or open "V" with operations away from intersection

(B) All other configurations

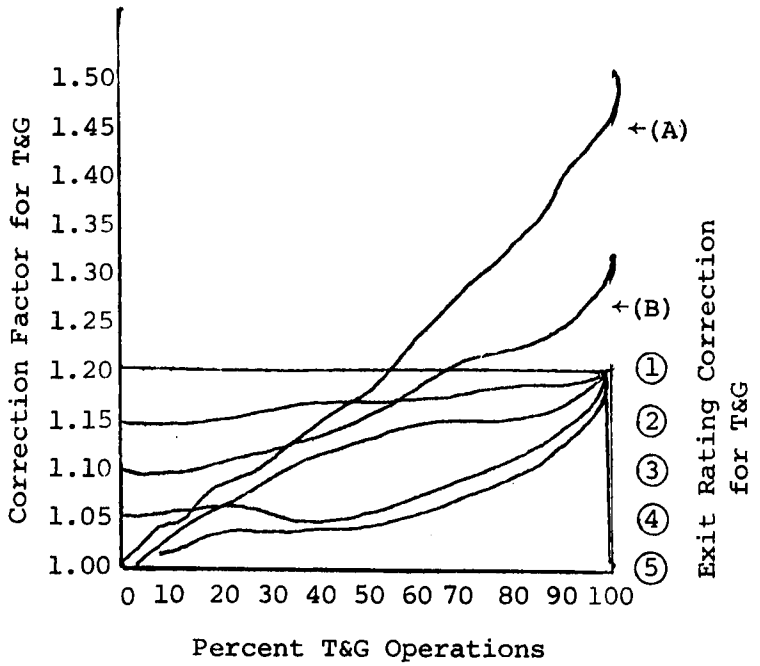


Figure 4. Touch and go correction factors (for VFR use only).

Note 1: Number in circle = existing exit rating.

Note 2: If the percent of T&G's are not known or cannot be approximated, but there are training activities at the airport, use the following values: at 90% class E aircraft population one has 60% non-airline T&G; at 80 to 90% class D&E aircraft population one has 50% non-airline T&G and 30% airline T&G; at 60 to 80% class D&E aircraft population one has 40% non-airline T&G and 20% airline T&G; at 40 to 60% class D&E aircraft population one has 30% non-airline T&G and 10% airline T&G; at 40% class D&E aircraft population one has 20% non-airline T&G.

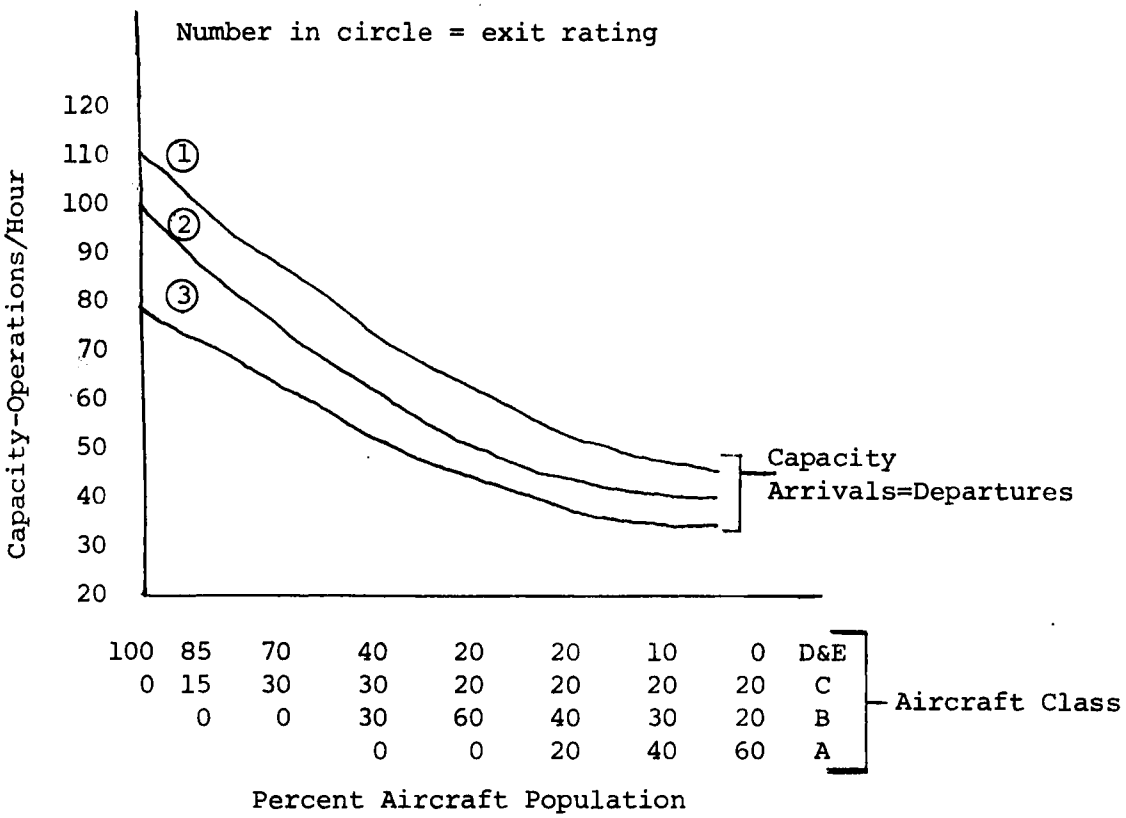


Figure 5. Single runway capacity, VFR.

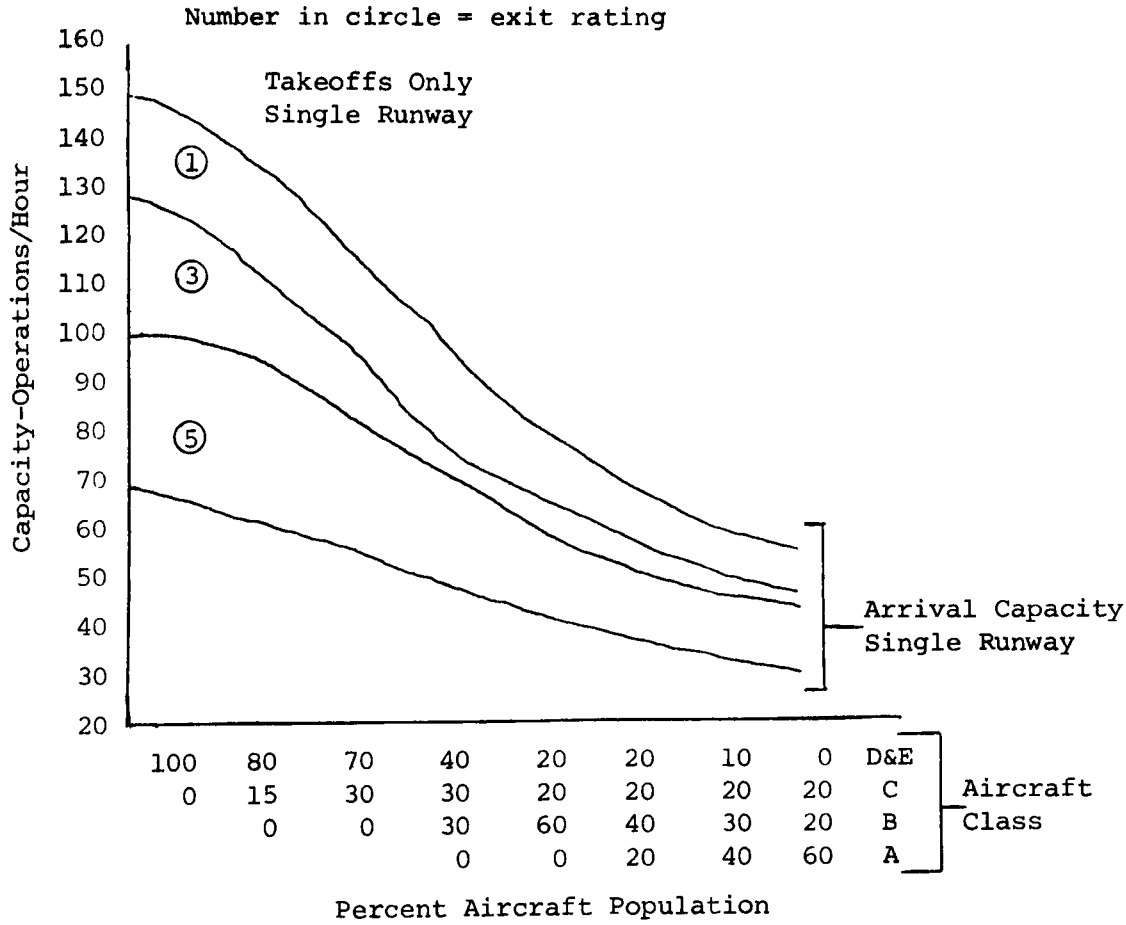


Figure 6. Single runway, arrival and departure capacity, VFR.

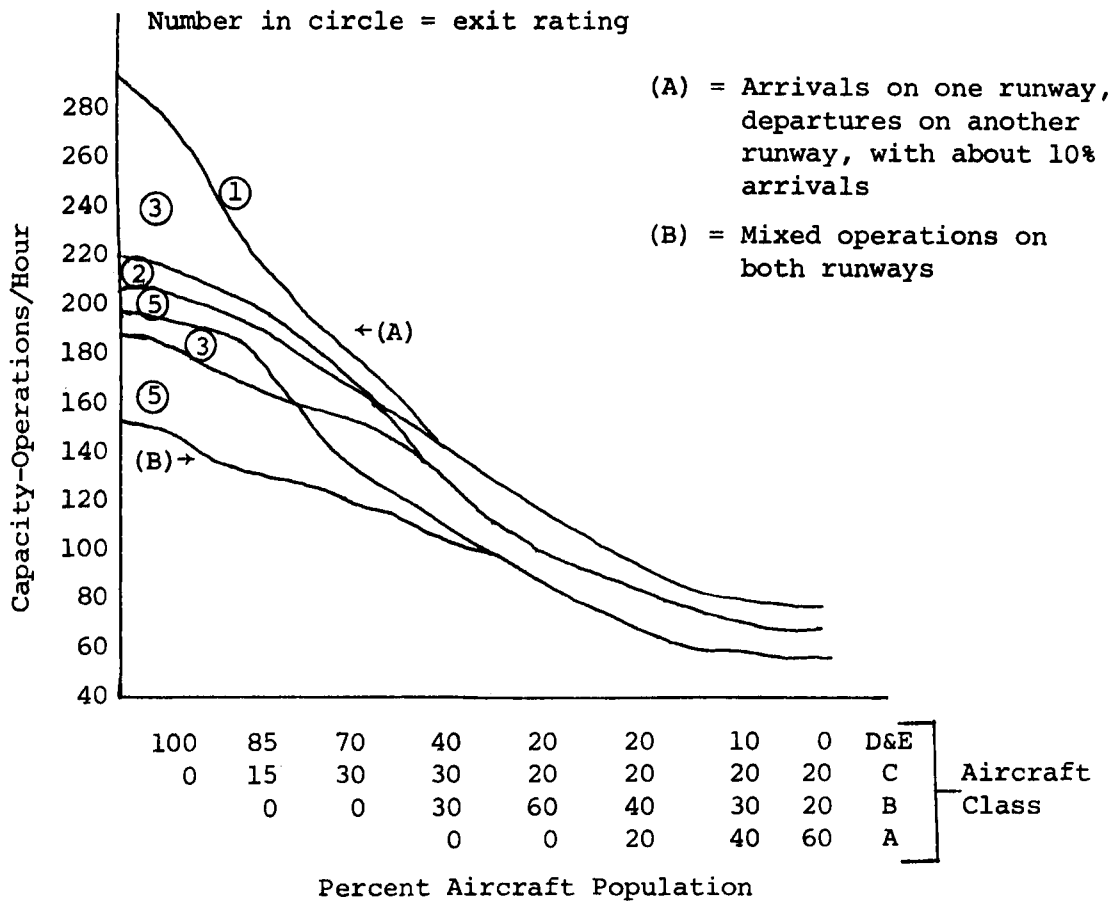


Figure 7. Parallel runway capacity, VFR.

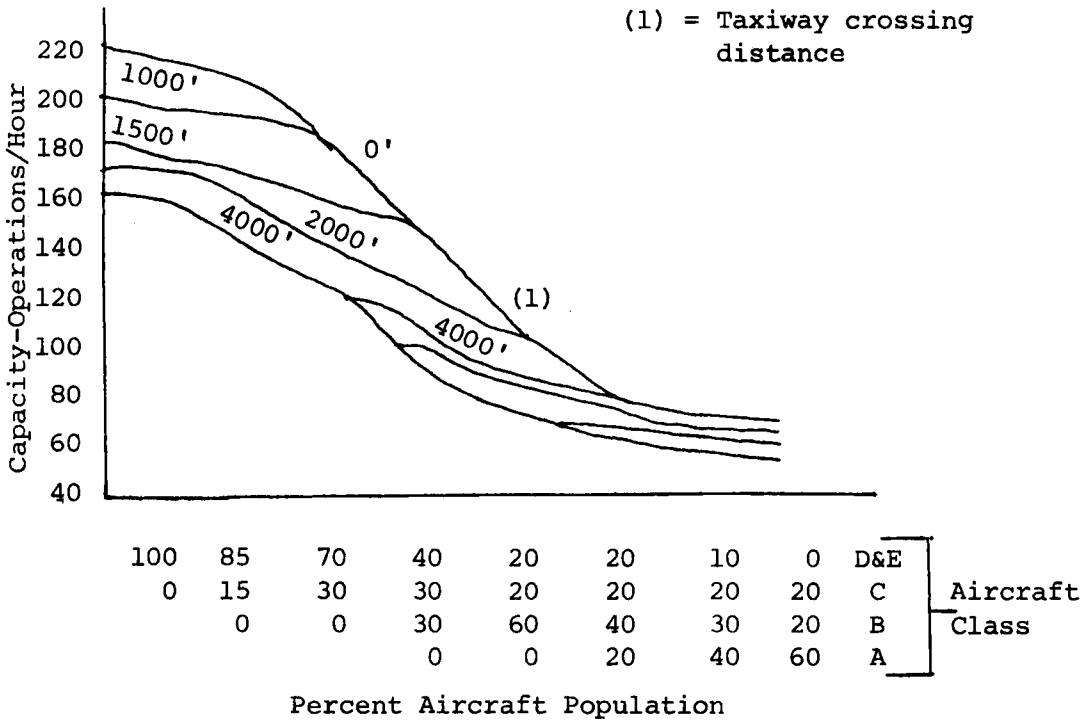


Figure 8. Capacity of parallel runways with taxiway crossing problems, VFR.

Note: This figure was based on an exit rating of one. For other exit ratings, compare the capacity with that of Figure 2; use the lower value. This figure can also be used for open "V" runways where there is a crossing problem. Apply Figure 4 for T&G correction.

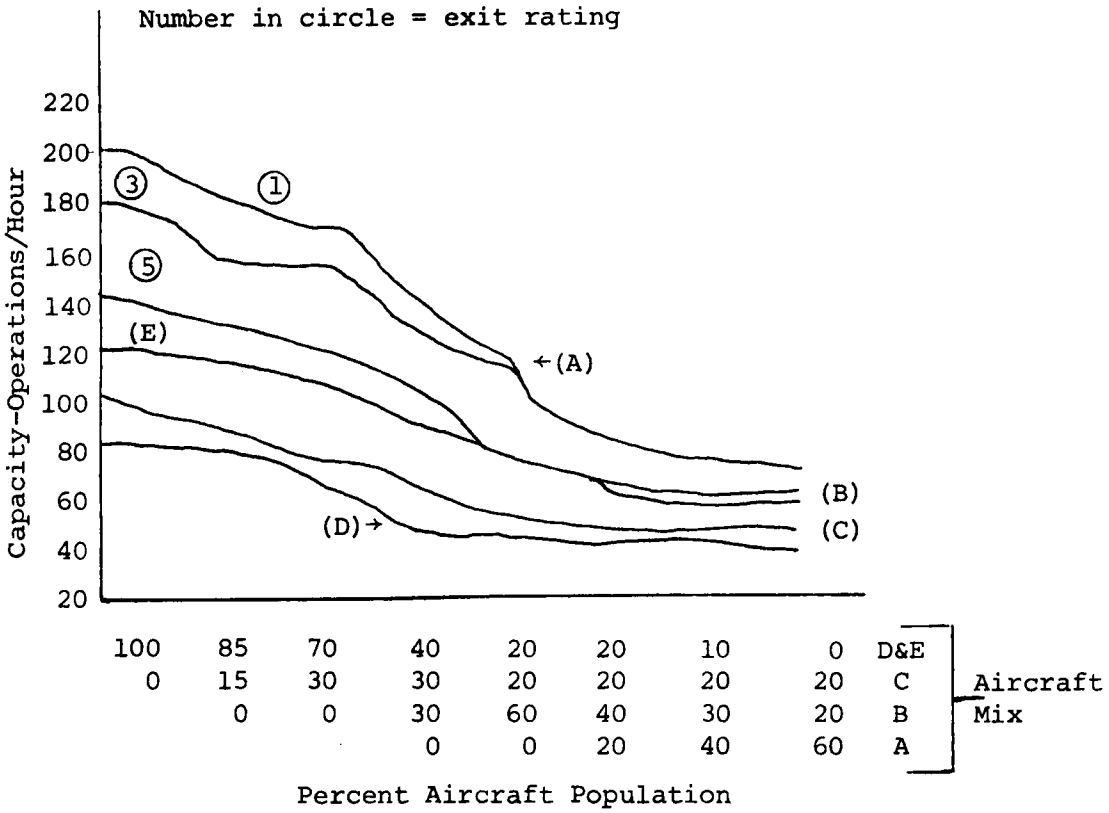


Figure 9. Two and three intersecting runways, VFR.

Note 1: Where angle between runways is less than 50, assume exit rating = 1.

Note 2: (A) = two runways intersecting at the near threshold (intersection distance = 0.0); (B) = two runways intersecting at middle (intersection distance = 0.05); (C) = two runways intersecting at far end (intersection distance = 1.0); D = all exit ratings; (E) = three intersection runways.

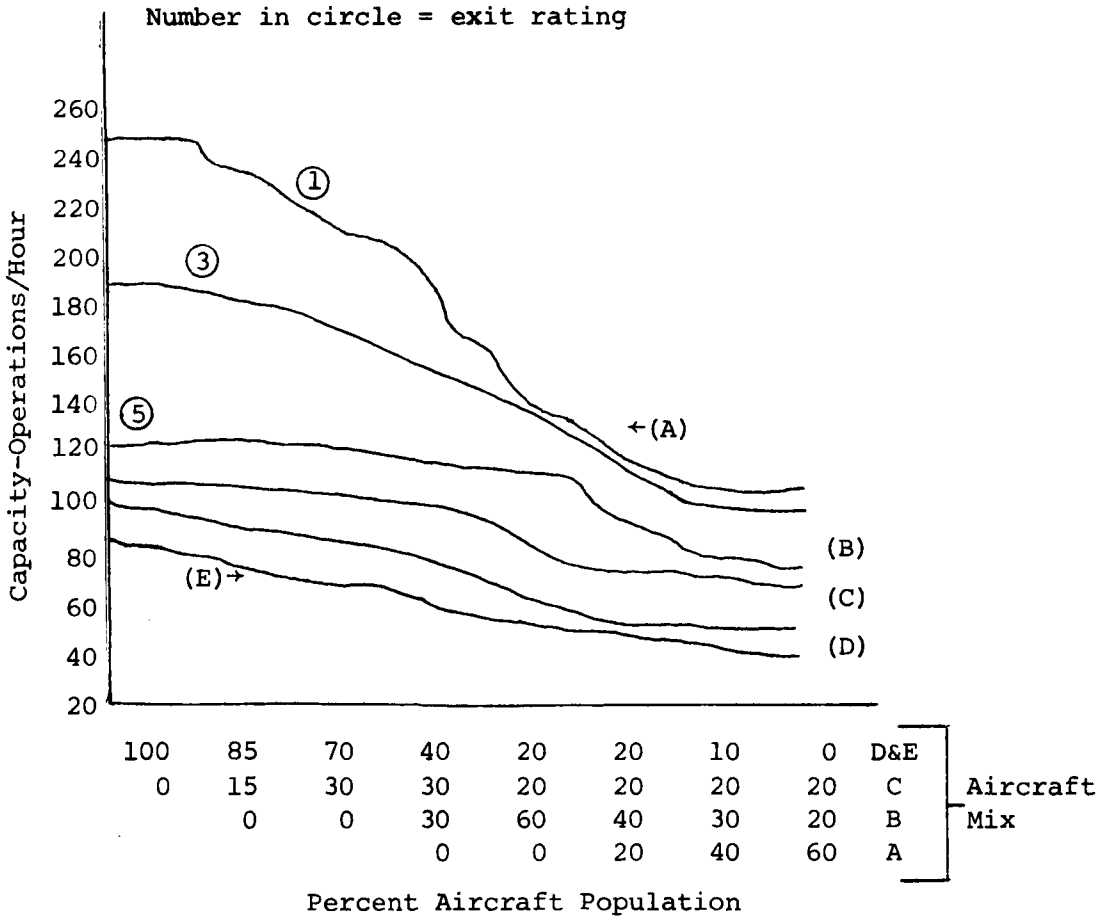


Figure 10. Open "V" runways, VFR capacity.

Note 1: Where angle between runways is less than 50, assume exit rating = 1.

Note 2: (A) = open "V" operations away from apex;
(B) = one runawy for arrivals, one for departures;
(C) = one-fourth of all departures on arrival runway;
(D) = one-half of all takeoffs on arrival runway;
(E) = open "V" operations toward apex.

Figure 11. Single, parallel, and open "V" runways, IFR capacity.

Note: (A) = mixed operations; (B) = arrivals on one runway, departures on the other; (C) = operations away from intersection; (D) = capacity requires correction when thresholds are offset; (E) = operations towards apex; (F) = departures only; (G) = mixed operations; (H) = arrivals only.

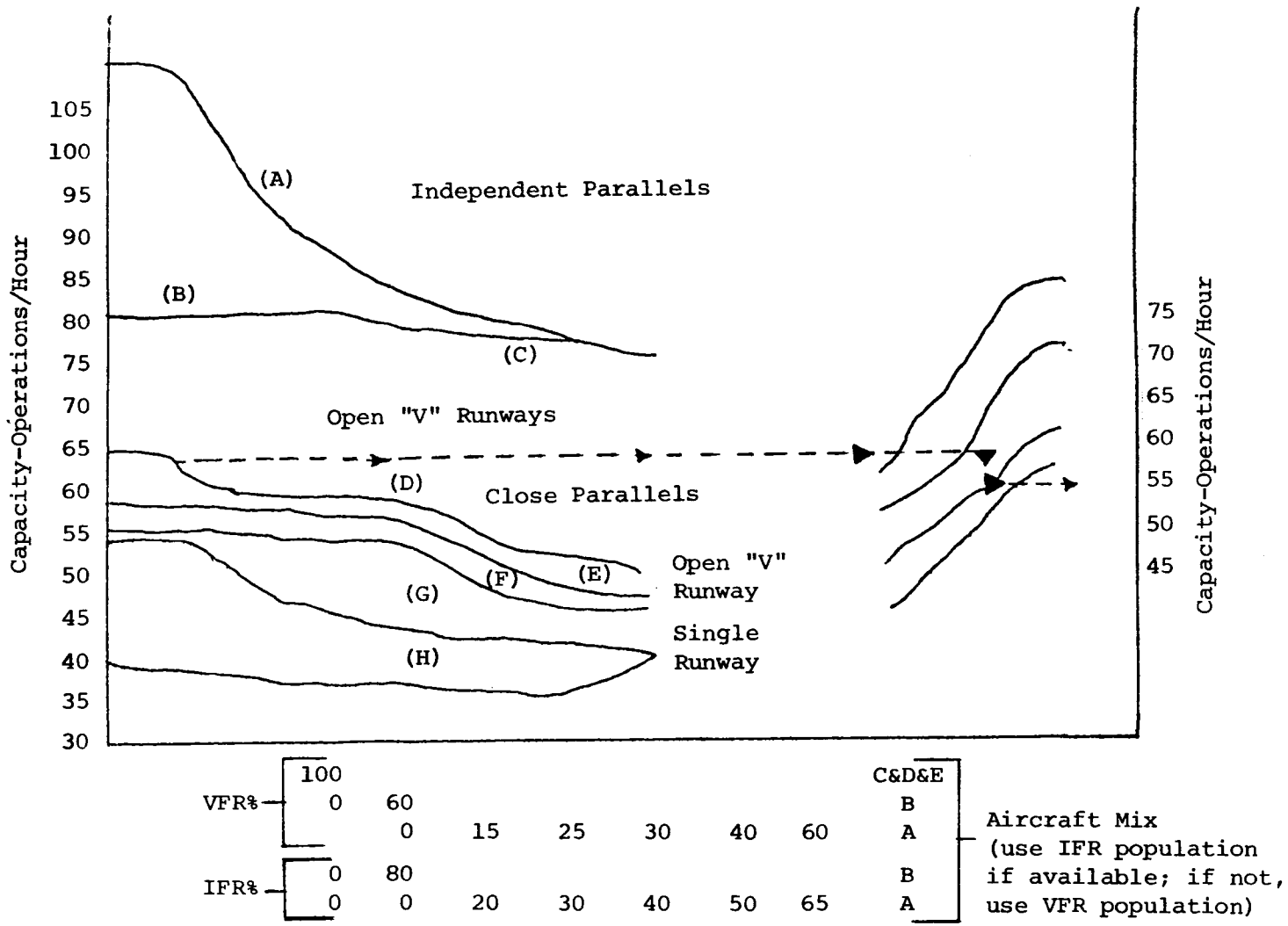

Capacity-Operations/Hour
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
(A)
Independent Parallels
(B)
(C)
Open "V" Runways
(D)
Close Parallels
(E)
(F)
(G)
Open "V"
Runway
Single
Runway
(H)
75
70
65
60
55
50
45
Capacity-Operations/Hour
VFR%
100
0
60
0
15
25
30
40
60
C&D&E
B
A
IFR%
0
80
0
0
20
30
40
50
65
B
A
Aircraft Mix
(use IFR population
if available; if not,
use VFR population)

Figure 11.

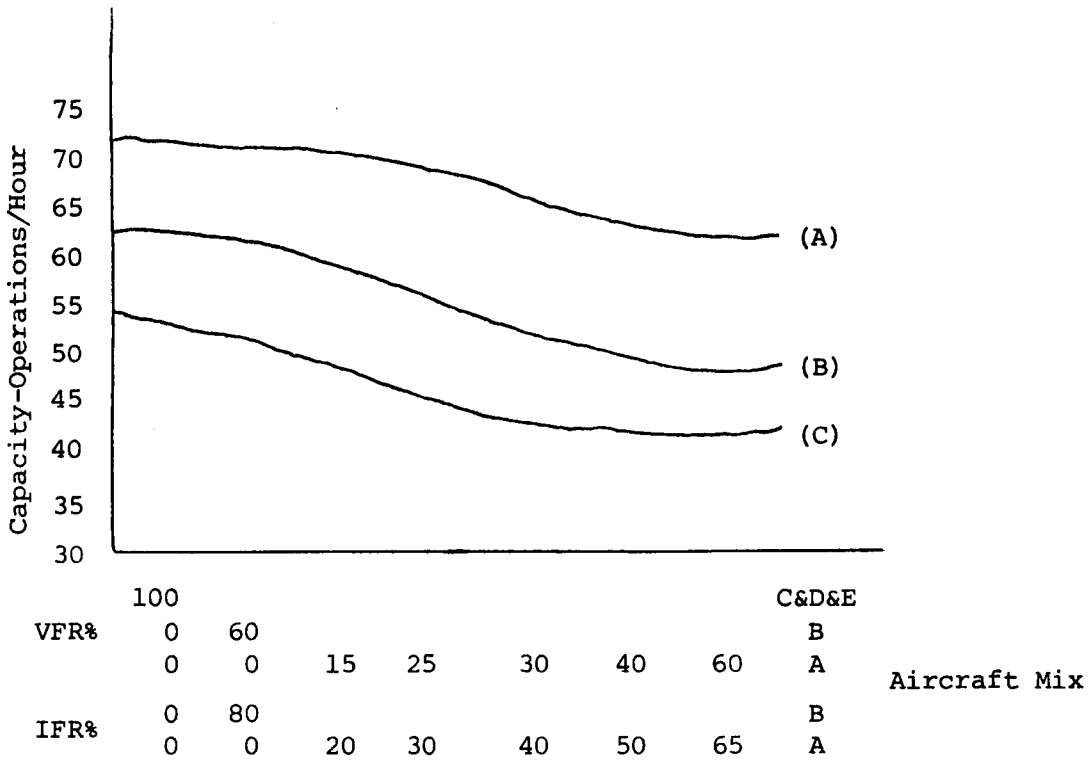


Figure 12. Intersecting runways, IFR capacity.

Note 1: For three intersecting runways, use the capacity for the predominant two runways for each operational condition. Use IFR population if available; if not, use VFR.

Note 2: (A) = intersection at end, operations away from intersection (intersection distance = 0.0); (B) = intersection in middle (intersection distance = 0.5); (C) = intersection at far end, operations toward intersection (intersection distance = 1.0).

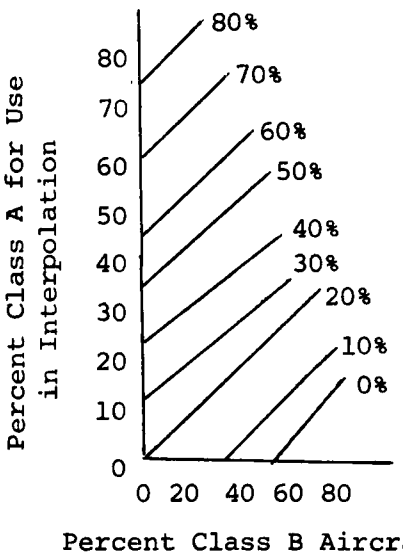


Figure 13. Class A aircraft-population interpolation, VFR.

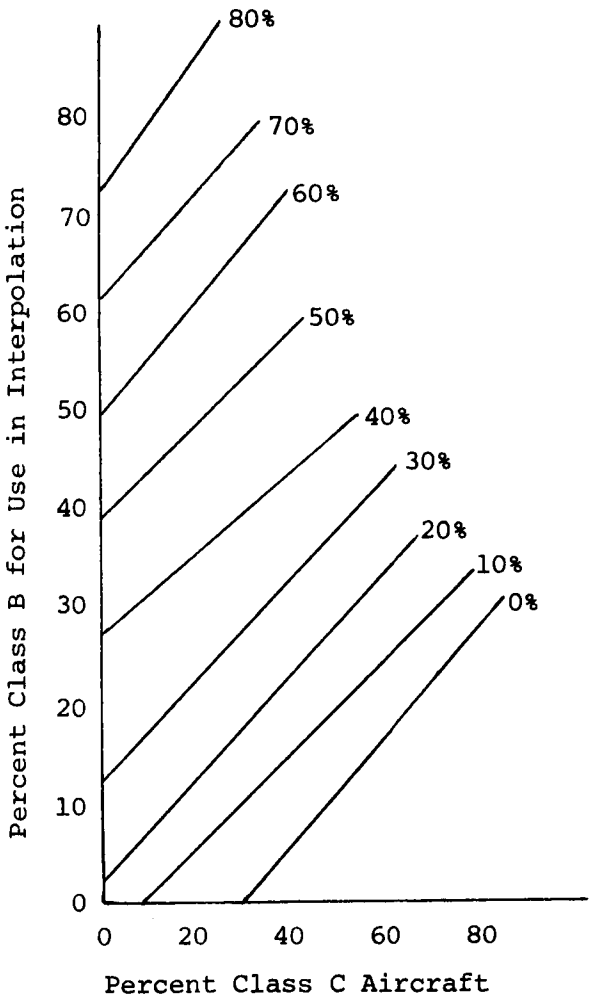


Figure 14. Class B aircraft-population interpolation, VFR.

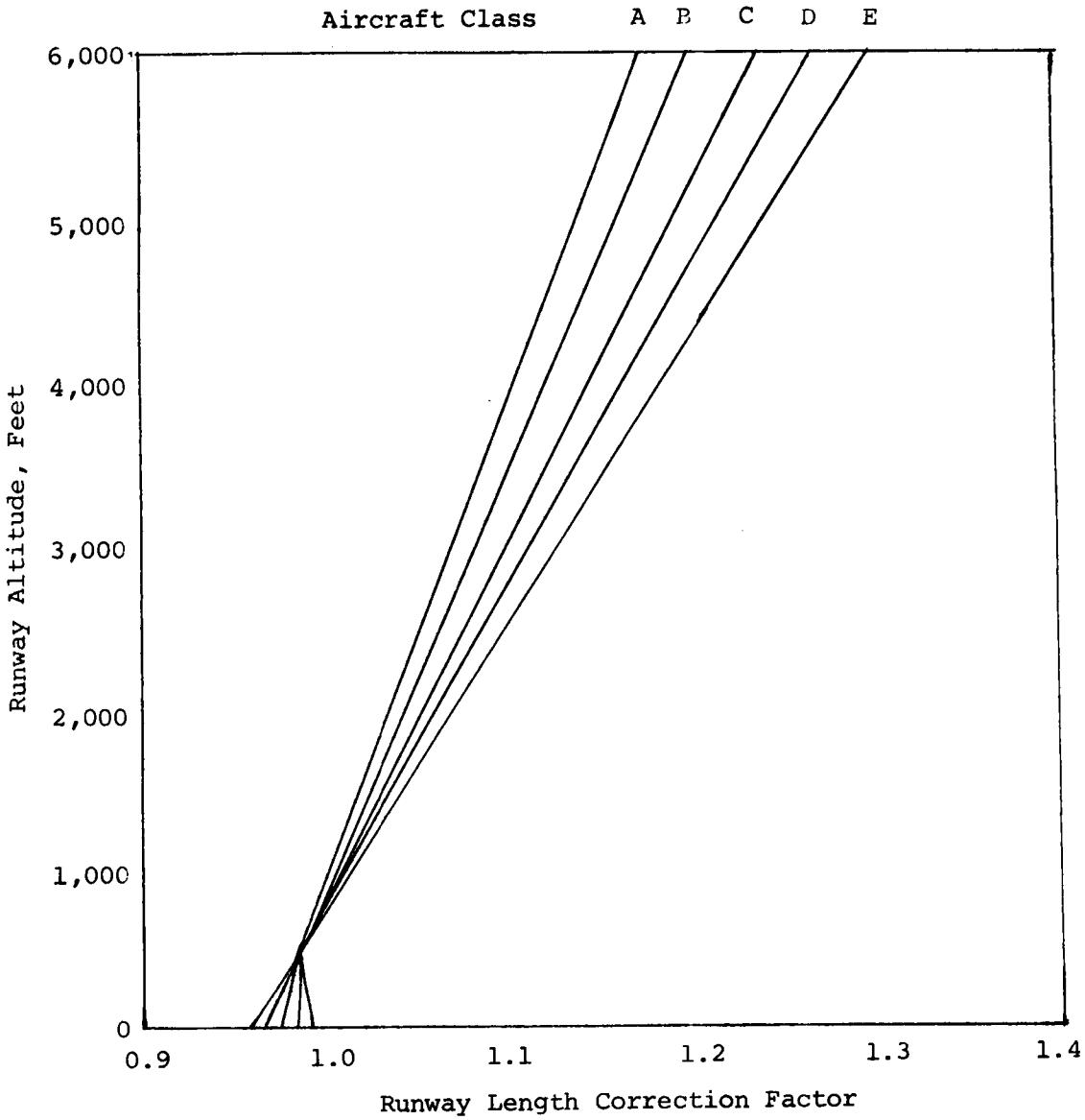


Figure 15. Effect of airport altitude on runway length factor for computing runway rating.

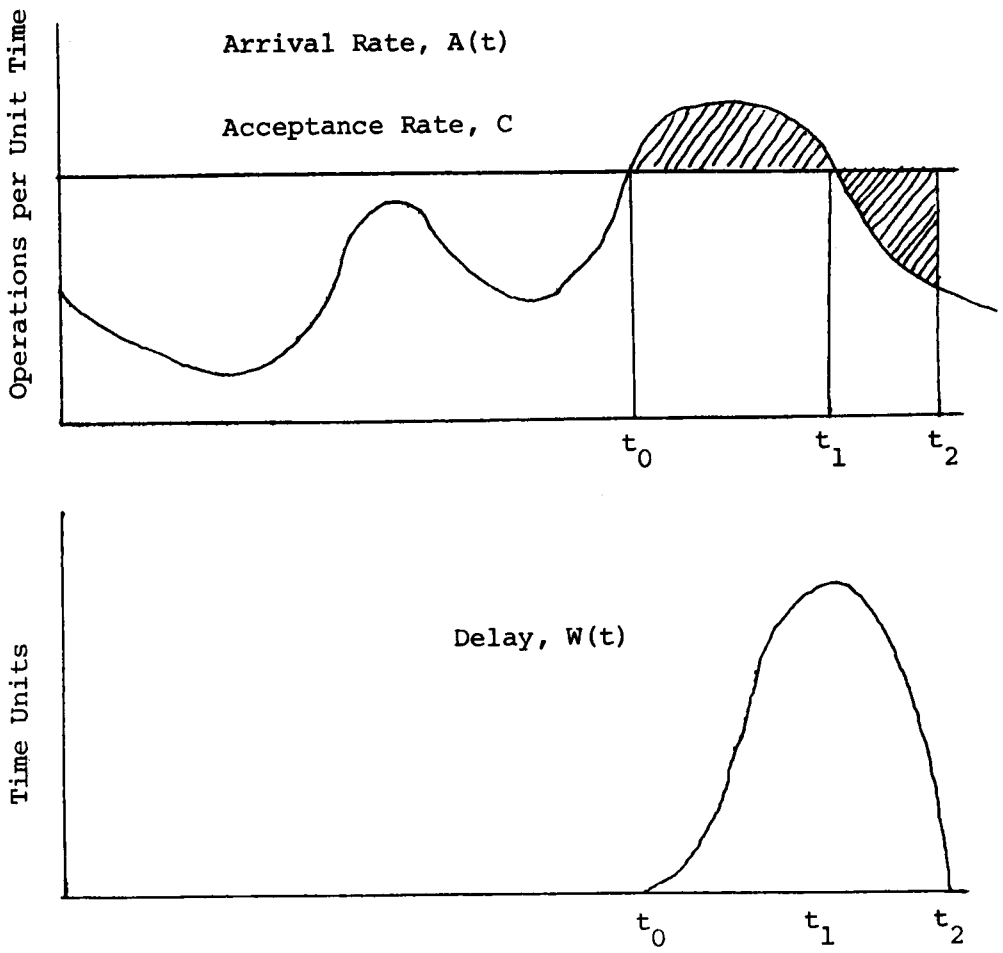


Figure 16. Simplified model, long delay equation.

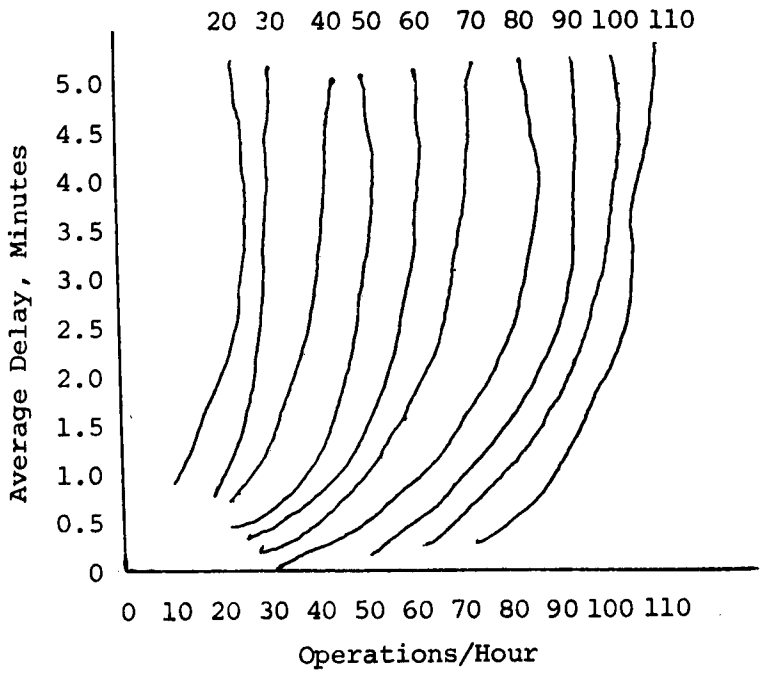


Figure 17. Average delay/operation, VFR single or parallel runways with mixed landings and takeoffs on each runway.

APPENDIX C

ALGORITHM

This unit is the computer algorithm developed by the investigator to give probable solutions to delay.

```
      INTEGER RRA(11,5), RRB(11,5), RRC(11,5), RRD(11,5)
      INTEGER GL, ETT, RC, CW, RL, RA, PLET, PANCAP, AP, IVFR
      DIMENSION CFCLA(50,4,5), CFMIX(50,4), B(4),`P(4`
      DIMENSION CFTG(4), KIFR(22,4), KVFR(22,4), KPCAP(22,4)
      DIMENSION KAD(22,4), IDAYD(8760`, IHD(24), IRRE(11,5)
      READ(5,1` MIX,GL,ETT,NET CW,RL,RA,PLET
    1FORMAT(6I3, I5`
      DO 10 J=400,5800,200
      DO 11 K=1,4
      DO 12 L=1,5
      READ(5,3` CFCLA(J,K,L)
    3FORMAT(5F10.6`
      READ(5,2) CFMIX(J,K)
    2FORMAT(4F10.6`
   12CONTINUE
   11CONTINUE
   10CONTINUE
      IT=0
   15IF(MIX .EQ. N) GO TO 13
   14N=N+1
      IF(N .GT. 4) GO TO 25
   16M=400
   13 CONTINUE
   17IF(RA .LE. M) GO TO 18
   19M=M+200
      IF(M  GT. 5800` GO TO 25
   20GO TO 17
   18CONTINUE
      CRL=RL*CFMIX(M,N)
   21IF(ETT .NE. 1` GO TO 22
   23CONTINUE
```

```
      IF(NET .GT. 1) GO TO 24
   23CONTINUE
      ER=5
      GO TO 35
   24ER=6-NET
      GO TO 35
   22IF(ETT .NE. 2) GO TO 27
   28CONTINUE
      IF(NET .GT. 0) GO TO 29
   30CONTINUE
      ER=5
      GO TO 35
   29ER=5-NET
      GO TO 35
   27CONTINUE
      ETT=3
      IF(NET .GT. 0) GO TO 32
   31CONTINUE
      ER=4
      GO TO 35
   32ER=4-NET
   35CONTINUE
      DO 36 I=1,11
      DO 37 M=1,5
      READ(5,4) RRA(I,M),RRB(I,M),RRC(I,M),RRD(I,M),IRRE(I,M)
    4FORMAT(5I3)
   37CONTINUE
   36CONTINUE
      READ(5,5) PA,PB,PC,PD,PE
    5FORMAT(5I3)
      II=ER
      IF(CRL .GT. 2999) GO TO 39
   38CONTINUE
```

```
      M=1
      GO TO 61
   39CONTINUE
      IF(CRL .GT. 4299) GO TO 41
   40CONTINUE
      M=2
      GO TO 61
   41CONTINUE
      IF(CRL .GT. 5399) GO TO 43
   42CONTINUE
      M=3
      GO TO 61
   43CONTINUE
      IF(CRL .GT. 6199) GO TO 45
   46CONTINUE
      M=4
      GO TO 61
   45CONTINUE
      IF(CRL .GT. 6999) GO TO 47
   48CONTINUE
      M=5
      GO TO 61
   47CONTINUE
      IF(CRL .GT. 7999) GO TO 49
   50CONTINUE
      M=6
      GO TO 61
   49CONTINUE
      IF(CRL .GT. 8999) GO TO 51
   52CONTINUE
      M=7
      GO TO 61
   51CONTINUE
```

```
      IF(CRL .GT. 9999) GO TO 53
   54CONTINUE
      M=8
      GO TO 61
   53CONTINUE
      IF(CRL .GT. 10999) GO TO 55
   56CONTINUE
      M=9
      GO TO 61
   55CONTINUE
      IF(CRL .GT. 11999) GO TO 57
   58CONTINUE
      M=10
      GO TO 61
   57CONTINUE
      M=11
   61CONTINUE
      READ(5,60) PA,PB,PC,PD,PE
   60FORMAT(5F7.3)
      RR=(PA*RRA(M,II))+(PB*RRB(M,II))+(PC*RRC(M,II))
      RRL=(PD*RRD(M,II))+(PE*IRRE(M,II))
      RRT=RR+RRL
      READ(5,6) AP
    6FROMAT(I3)
      IF(AP .EQ. 1) GO TO 160
   59CONTINUE
C     THIS IS AN EXISTING AIRPORT
      READ(5,7) IVFR,IFR
    7FORMAT(2I4)
   62CONTINUE
      READ(5,8) (B(KK),P(KK),CFTG(KK), KK=1,4)
    8FORMAT(3F10.5)
      DI=110*B(N)
```

```
      IAIFR=IFR/DI
      IWFV=1
      READ(5,63) MCP
   63FORMAT(I3)
      IF(MCP .LT. 91) GO TO 64
   65CONTINUE
      IWFI=1
      GO TO 75
   64CONTINUE
      IF(MCP .LT. 81) GO TO 66
   67CONTINUE
      IWFI=2
      GO TO 75
   66CONTINUE
      IF(MCP .LT. 66) GO TO 68
   69CONTINUE
      IWFI=4
      GO TO 75
   68CONTINUE
      IF(MCP .LT. 51) GO TO 70
   71CONTINUE
      IWFI=8
      GO TO 75
   70CONTINUE
      IWFI=12
   75CONTINUE
      WHC=((IWFI*IAIFR*.1)+(VFR*1.0*.9))/((IWFI*.1)+(1.0*.9))
      PANCAP=WHC*P(N)*CFTG(N)
      READ(5,9) NAH,NDH,IPOP,IRCC,ICD
    9FORMAT(5I3)
      MS=NAH+NDH
      IR=NAH/NDH
```

```
      IRC=IVFR+IFR
      MAXVFR=(110*IFR)/DI
      MAXIFR=DI*(IVFR/110)
      IF(IRCC .NE. 1) GO TO 72
   73CONTINUE
      IC=RC*(.05/IPOP)
      GO TO 74
   72CONTINUE
      IC=RC-ICD*((2*IPOP)-1)
   74CONTINUE
      MIRC=MAXVFR+MAXIFR
      MAC=.5*MIRC
      MAD=IRC/((1/IR)+1)
      IRCRC=IRC*(MAC/MAD)
      GO TO 76
  160CONTINUE
      READ(5,77)(KVFR(IJ,KL),KIFR(IJ,KL),KPCAP(IJ,KL),KD(IJ,KL),
     1IJ=1,22,J=1,4)
   77FORMAT(2I3,I8,I7)
      READ(5,78) IRUNC
   78FORMAT(I3)
      JK=1
      IF(IRUNC .NE. JK) GO TO 79
   80CONTINUE
      IFR=KIFR(JK,N)
      IVFR=KVFR(JK,N)
      NAH=KD(JK,N)*.5
      NDH=NAH
      GO TO 62
   79CONTINUE
      JK=JK+1
      IF(JK .GT. 22)  GO TO 25
   76CONTINUE
```

```
      MDC=MAC
      DO 82 LIM=1,365
      DO 83 LIN=1,24
      READ(5,81) INAH(LIN),IMAC(LIN),INDH(LIN),IMDC(LIN),NA(LIN)
   81 FORMAT(5I3)
      INA(LIM)=NA(LIN)
      WT(LIN)=(INAH(LIN)-IMAC(LIN))/IMAC(LIN)
      WT(LIN)=(INDH(LIN)-IMDC(LIN))/IMDC(LIN)
      IHD(LIN)=INAH(LIN)*(WT(LIN))
      ITHD(LIM)=IHD(LIN)
      IDD(LIM)=ITHD(LIM)*INA(LIM)
      IANDE=IDD(LIM)
   83 CONTINUE
   82 CONTINUE
      READ(5,101) COST
  101 FORMAT(F10.2)
   84 IF(MIX .NE. 1) GO TO 85
   86 CONTINUE
      CCOST=COST-200.00
      IF(CCOST .GT. 0.0) GO TO 150
   87 CONTINUE
      GO TO 151
   85 CONTINUE
      IF(MIX .GT. 2) GO TO 88
   89 CONTINUE
      CCOST=COST-150.00
      IF(CCOST .GT. 0.0) GO TO 150
   90 CONTINUE
      GO TO 151
   88 CONTINUE
      IF(MIX .GT. 3) GO TO 92
   91 CONTINUE
      CCOST=COST-100.00
      IHHD=IHD(LIN)
      IF(IHHD .EQ. 4)  GO TO 152
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153CONTINUE
   IF(CCOST .GT. 0.0) GO TO 150
 93CONTINUE
   GO TO 151
 92CONTINUE
   CCOST=COST-50.00
   IF(CCOST .GT. 0.0) GO TO 150
 94CONTINUE
151 CONTINUE
   READ(5,102) ITRL, ITER, MIXT,ITRC
102FORMAT(4I6)
   IF(ITRL .EQ. 0) GO TO 104
103ITRL=RL
104CONTINUE
   IF(ITER .EQ.0) GO TO 106
105ITER=ER
106CONTINUE
   IF(MIXT .EQ. 0) GO TO 108
109MIXT=MIX
110CONTINUE
   IF(ITRC .EQ.0) GO TO 112
113ITRC=RC
112CONTINUE
   IF(IT .GT. 1) GO TO 152
114CONTINUE
   IT=IT+1
   GO TO 18
152CONTINUE
   WRITE(6,115) ITRL,ITER,MIXT,IHHD
115FORMAT('THIS TEST RESULTED IN A VALID DELAY REDUCTION WITH
  1 A RUNWAY LENGTH OF', I6, 'AND AN EXIT RATING OF', I3, 'AND
  1 AN AIRCRAFT MIX OF', I3, 'WITH AN ACTUAL RESULTANT DELAY OF'
  1 , I2)
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      GO TO 25
  150 CONTINUE
      WRITE(6,159) CCOST,IHHD
  159 FORMAT(' THIS RESULTED IN AN UNECONOMIC SOLUTION WITH A
     1 COST OF', F6.2, 'WITH A DELAY LEVEL OF ', I3)
      WRITE(6,175)
  175 FORMAT( 'UNACCEPTABLE DELAY REDUCTION, THEREFORE THIS IS
     1 AN UNACCEPTABLE SOLUTION AND IS THUS INVALID.')
   25 CONTINUE
      STOP
      END
```

VITA

Raymond Joseph Ricco, Jr., was born in Tullahoma, Tennessee, on August 7, 1948. He attended St. Paul's Parochial School for eight years prior to entering Tullahoma High School, from which he graduated in 1966. In September, 1966, he entered Middle Tennessee State University, and in August, 1971, he received a Bachelor of Science degree in History with a strong secondary field of Computer Science. He entered the Graduate School at The University of Tennessee Space Institute in September, 1971, and accepted a research assistantship in April, 1972. He was awarded the Master of Science degree with a major in Computer Science in December, 1976.