Design for the Future in Terminal Air Traffic Control

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A methodology has been developed for the analysis of the capacity of terminal area airspace and the associated airports. The methodology is of assistance in assessing the value of improvements in airway layout, navaid equipment, and airport improvements. To illustrate, examples are shown of application of the methodology. In one example, an increase of the complexity of airspace use, resulting from traffic growth and new aircraft, is shown to be 6 times whereas the traffic increases only about 2.5 times. A second example indicates an annual savings of 6500 hr of operating delay due to adding parallel runways.

The airspace is analyzed with a model of airspace operation to determine the complexity of control of the airspace. The effect of increasing traffic demand, changing aircraft types, and changing the airway layout is shown. The aircraft approach and departure paths for each airport are analyzed to find any conflict with adjacent airports and any limitations on maneuver areas. Weather analyses of adjacent airports are analyzed to find the extent of simultaneous use of conflicting procedures. The airport runways are analyzed to evaluate their hourly capacity. The annual capacity of individual airports and the airport system is computed with validated models. These models incorporate pertinent operational factors including airspace conflict and overloading. Since the methodology uses models that evaluate delay to operations, cost benefit analyses can be accomplished on improvements in airspace and airport use and design.

Introduction

DURING 1967, New York's three major airports handled over one million air operations. In 1980, the area's major airports should be prepared to handle over 1,600,000 operations, according to a recent Federal Aviation Agency (FAA) forecast. In addition, for 1980, it is predicted that over six million general aviation aircraft operations will occur at other general aviation airports in the New York region.

Events of the summer of 1968 have left no doubt in aviation circles that airport and airspace congestion is a serious current problem. Yet in 1980, management will undoubtedly have to accommodate not only the growth at the major airports, but in addition, a sizable proportion of the six million other competitors for airspace positive control or advisory service.

Other metropolitan areas will also show large increases. In these areas, the increases may have a more drastic effect on local control procedures than will the added load in New York, for today New York has the only multiple airport complex operating at near maximum rates. Thus, New York will have "more of the same" whereas Chicago, Boston, Los Angeles, Washington, and so on are all moving toward a "loaded" multiple airport situation and the complexity of airspace management already evident in New York.

Current events are proving without doubt that when congestion begins occurring regularly, it is not easily eliminated. The corrections involve years of effort—new runways and airports, new airborne and ground based navaid and control equipment. Many elements of the aviation community must cooperate to accomplish the corrections. Thus, good long-range planning, encompassing the entire aviation community, is needed to avoid serious congestion, if possible, or to overcome it when it occurs.

How does one forecast the overloading of airspace and airport facilities? This paper describes the application of techniques and methodologies useful for such forecasts.

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These techniques can be used to:

1) provide a quantitative evaluation of any change in traffic handling capability, resulting from modifications to the air route structure in the terminal area (The change would be indicated by a reduction or increase in the complexity of air traffic control. This may be useful in sectorization design.)

2) provide a detailed understanding of arrival and departure paths into all IFR airports in the region (those equipped for instrument operations), and reveal interairport conflicts and the number of hours per year such conflicts will exist

3) determine the capacities, and the operating rates and delays, occurring at each airport in the airspace, due to overloading

4) indicate the benefit of a rules change, such as in lateral spacing

5) form a basis for flow control application

6) pinpoint the bottleneck points in the terminal area (ATC) air traffic control system

Description of Techniques

The techniques for analysis have been developed over a period of several years. In application, they are relatively economical of time and money, since they do not involve heavy personnel commitments as in real-time simulation programs. Their use does require an extensive background in air traffic control and airport operation, or detailed knowledge and information on many items, such as 1) origination and destination of air traffic and the preferential routes; 2) types of aircraft in use at present and in the future; 3) performance characteristics of the aircraft relative to climb, descent, and runway use; 4) existing airspace operation; 5) approach and departure paths desired for each combination of runway at each airport, and any local peculiarities due to noise considerations or obstruction problems; 6) weather data compiled for proper data processing, for each airport; 7) staged airport development programs for each airport.

Figure 1 indicates a likely sequence of use of the techniques which are described in the following paragraphs. The procedure works from the known present situation into the future terminal area and airport design.

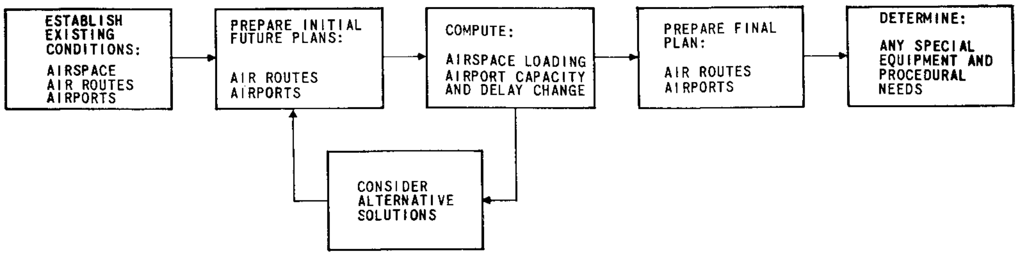

Fig. 1 Procedure to optimize terminal area traffic flow and capacity.

Transition Airspace Analysis—TRANSAIR Model

Transition airspace would be defined as that airspace within an area that is large enough to incorporate aircraft climbout and descent paths to and from all the major airports in a terminal area. For example, in the New York area we would consider that this would include an area of about 100-miles square and to an altitude of approximately 40,000 ft.

There is an essential requirement that the transition airspace capacity be known because we must insure that any one airport's capacity is not further limited by that of the surrounding airspace. In other words, there is no point in developing super airports within a terminal area, unless the surrounding airspace and control procedures are adequate to handle the airport traffic.

In the terminal airspace there are many arrival and departure routes for each airport to be considered. Many points of conflict between aircraft can occur at the intersections of the air routes. A measure of the extent of conflicts which is useful in determining terminal area capacity will be described.

Before describing the technique of measurement, some background comments on air traffic control are useful. In the process of air traffic control the conflicts between aircraft are resolved by three methods:

1) avoidance of intersection conflicts in the planning of published routes

2) stratification of aircraft routes by assigning published "above," "at," or "below" altitude restrictions on certain routes at the intersections

3) use of short-term vectoring and/or altitude restrictions by air traffic controllers when a possible conflict is observed

The effects of the use of these methods introduce various complexities in the terminal airspace. To achieve 1 or 2 usually results in aircraft having to fly extra air-miles with economic penalties. In addition, 2 gives rise to an extra workload on pilots. Short-term control 3 involves a workload level on both controllers and pilots.

A measure of complexity (hence workload) is therefore a clue to the capacity of an intersection. If we can establish that a certain intersection gives rise to many control and economic problems in today's airspace we can suspect that it is close to, has reached, or has exceeded its natural capacity.

If the character of future demand (that is, changes in types of aircraft, numerical increases, etc.) can be forecast, the effect on the ATC system resulting from technological change or from increased activity caused by additional airports can also be determined.

Figure 2 shows a route for aircraft departing from Kennedy Airport (JFK), and a route for aircraft arriving at LaGuardia Airport (LGA). These routes intersect at point A where there may be conflict between the aircraft climbing out and those descending.

A computer program has been prepared (labeled TRANSAIR) using as inputs a description of the airway routes, the rate of traffic flow and aircraft type on each route, the climb and descent performance of those aircraft types, and requirements relative to level out for en route flight. This computer program was developed and applied to the New York area as part of airport system analyses for the Port of New York Authority. It can also be applied to less complex areas. Figure 3 indicates the results of the computer analysis of point A of Fig. 2 for two loadings of the intersection. Note that the diagram indicates the number of aircraft occupying each altitude and whether the aircraft are climbing, descending, or leveled out. The computation is based on the optimum or desired flight path, and thus is based on traffic distribution before control or altitude restrictions are exercised.

From Fig. 3, we have a typical picture of the traffic through an intersection over a time period (normally about 4 hr of the peak traffic). From this we can proceed to determine the workload involved to handle the traffic at this intersection. To get at the workload, a complexity rating has been devised which assigns different ratings to the various maneuvers. For example, two aircraft passing through an intersection at the same flight level en route to the same airport will have a low complexity rating of, say, $\frac{1}{2}$. Another aircraft passing through the intersection, followed by an aircraft descending to the same airport, will have a somewhat higher complexity rating of 3, since the control effort will be greater. An aircraft in descent to one airport, going through the same intersection as one in descent to another airport, will have a still higher complexity rating of 7, since the controller must again give more attention and possibly more activity to the latter pair. Thus, the complexity rating is an approximation of the complexity of traffic control at the intersection, resulting from an empirical rating system that is related to controller workload. For the situation in Fig. 2, the complexity rating rises from 148 with the 1965 traffic load, to 265 with the 1975 conditions, reflecting the increase in numbers of aircraft by 1975 and the differing aircraft performance characteristics for that period.

The airspace analysis assumes unrestricted flow (no holding) into and out of the airports. That is to say that,

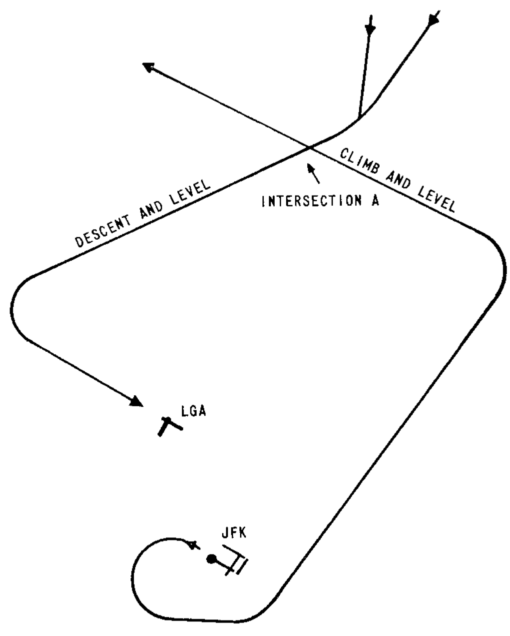

Fig. 2 Example of route intersection.

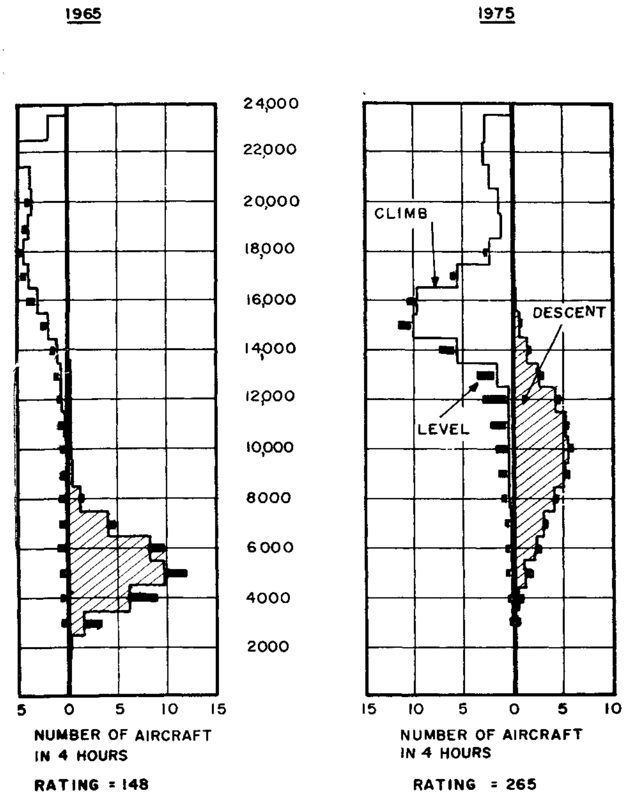

Fig. 3 Aircraft distribution by altitude through intersection A.

although the airspace layout should provide for holding, the operation of the TRANSAIR program does not include the added complexity of holding aircraft. Instead, since it is used as a gage, it first uses a traffic demand not greater than airport capacity at a selected average delay level—usually 4 min. This delay level may result in minor holding or delay maneuvers, but confined to airspace areas designed to accommodate it. If the TRANSAIR analysis shows overloading of the airspace at the selected traffic demand, then it follows that either the airspace use should be redesigned or congestion (holding) will be caused by the overloaded condition. Holding increases workload as each aircraft is kept in the system longer. Thus, a deteriorating airspace control situation can readily occur, for which the only quick solution is to limit traffic demand, i.e., use restrictive flow control.

To give an additional indication of the type of results achieved, Figs. 4–7 are of interest. Figure 4 shows the New York area airspace as it existed in 1965. The routes are schematically shown with the predominant direction of traffic flow. The 1965 traffic rate was applied to the Fig. 4 route structure to produce the results of Fig. 5, which shows the complexity ratings at intersections. The size of the circle shown at each intersection is in relation to the complexity rating of that intersection. Note that the highest complexity rating is crosshatched and this rating numerically turned out to be 564. It was of interest also that New York control personnel indicated that this was the area of greatest complexity from actual control experience.

A basis is provided by this technique for examining an air route structure to determine how much more complex the over-all control problem will become, and how complex the control problem is by intersections. This provides a basis for organizing the air route layout to minimize complexity. It also provides an indication of where the greatest control problem will be, and thus indicates the areas which may deserve special attention from an equipment or design standpoint. It provides a basis for comparing future performance with what is known today. It forms a basis for determining when transition airspace will limit regional airport capacity.

What might be expected in the future is shown in Fig. 6. The airway structure has been modified considerably, before arriving at the complexity rating distribution shown to avoid the worst problem areas as much as possible. Note that a much greater number of intersections are shown; also that the over-all size of the circles have grown larger, and that there are now eight crosshatched circles, compared to one in Fig. 5 (with each crosshatched circle representing up to 20% greater complexity). It is also of interest to compare the total complexity. For Fig. 5, the complexity of the total area is 4580 for the 45 intersections and 562 aircraft. However, in Fig. 6 there are 123 intersections, with a total complexity rating 29,420 and 1244 aircraft. Thus the

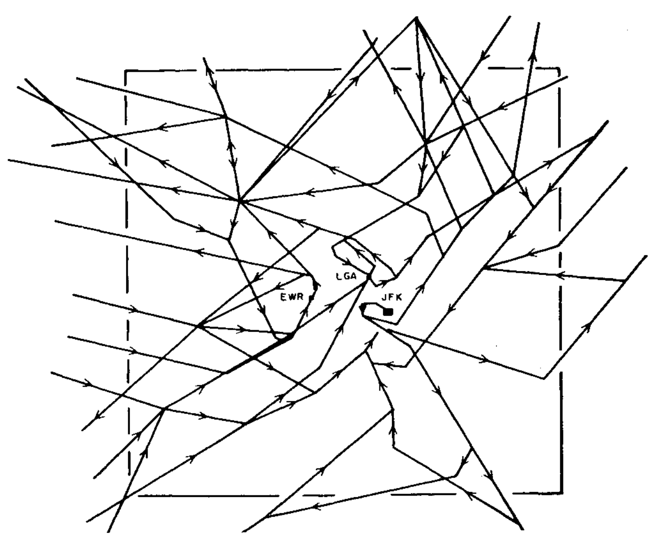

Fig. 4 New York airspace routes—1965.

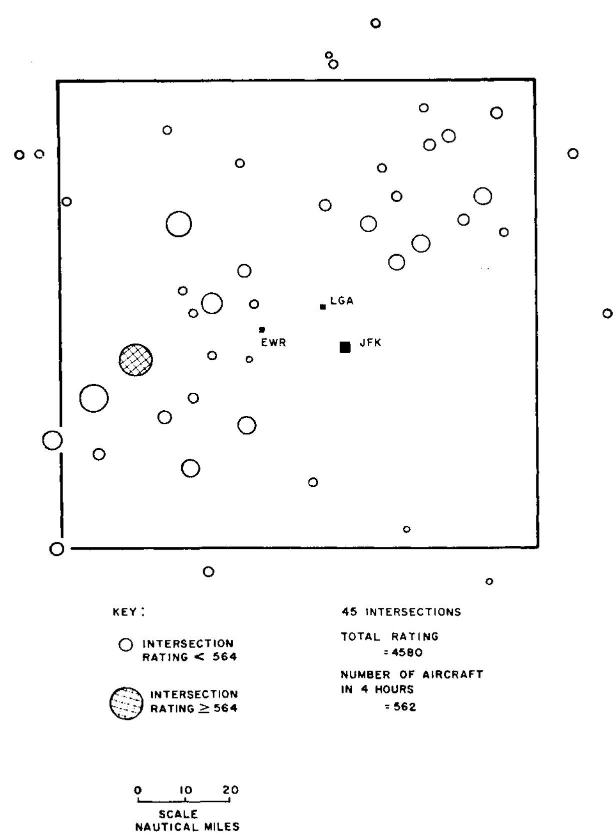

Fig. 5 New York area complexity ratings—1965 demand and existing route structure.

over-all complexity of control will increase about 6 times while the number of aircraft is increasing about 2.5 times.

Figure 7 shows the serious overloading of numerous intersections that would occur as a result of the 1975 demand adhering to the current air route structure, with some minor modifications.

Approach Departure (AD) Path Analysis

Approach and departure paths in the vicinity of the individual airports must have a more detailed examination than that given in the gross examination of TRANSAIR. This is accomplished by actually laying out approach and departure paths to and from each airport for every combination of runway use.

To determine the combinations of runways which must be considered, the airport configuration, with any restrictions due to noise or obstructions, traffic, etc., is observed and studied to assign wind directions to combinations of runway use. Figure 8 is an illustration of such an analysis using a 15-knot crosswind criteria and a maximum crosswind angle of 80°. Figure 8 indicates the use of multiple runways to the maximum extent to minimize single runway use. This illustration would vary for each airport configuration.

Once the runway combinations are known, IFR approach and departure paths are laid out for most efficient use of these combinations. Figure 9 is an illustration of a portion of the approach and departure paths laid out for one of many combinations of runways used in the New York area. The combinations of runways used at each airport are those which are most commonly used today.

From Fig. 9 it is possible to determine items that will restrict capacity such as 1) unusual lengths of straight-in approach path; 2) unusual length of single lane and altitude restricted departure paths (for example, the Teterboro Airport outbounds); 3) conflicts that cannot be resolved by altitude or lateral separation.

Once the items that may restrict capacity have been determined, it is essential to find the percentage of times they occur. Where interairport conflict occurs, weather analysis is performed for two airports simultaneously. Computer programs have been prepared to accomplish the weather analyses for either single or dual airports. Figure 10 is an example of analysis for coincidence of weather at two airports. For example, at Airport X runway combination 4 would occur simultaneously with the use of runway combination B at Airport Y for 11 hr. The AD path analysis,

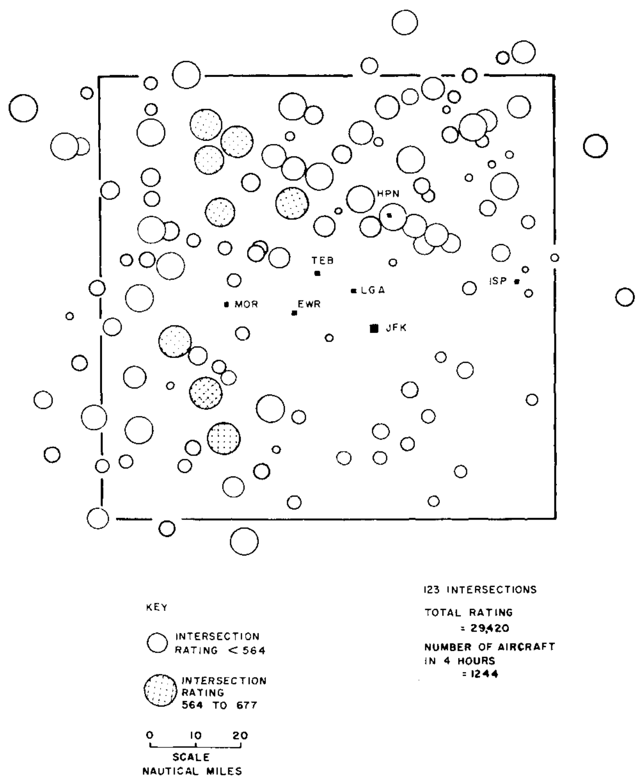

Fig. 6 New York area complexity ratings—1975 demand with improved route structure.

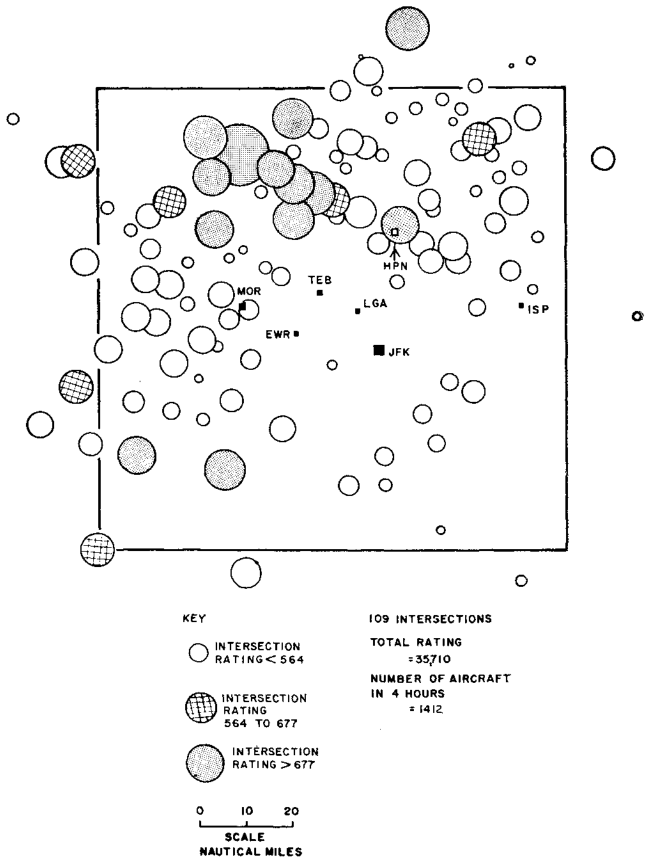

Fig. 7 New York area complexity ratings—1975 demand with revised route structure.

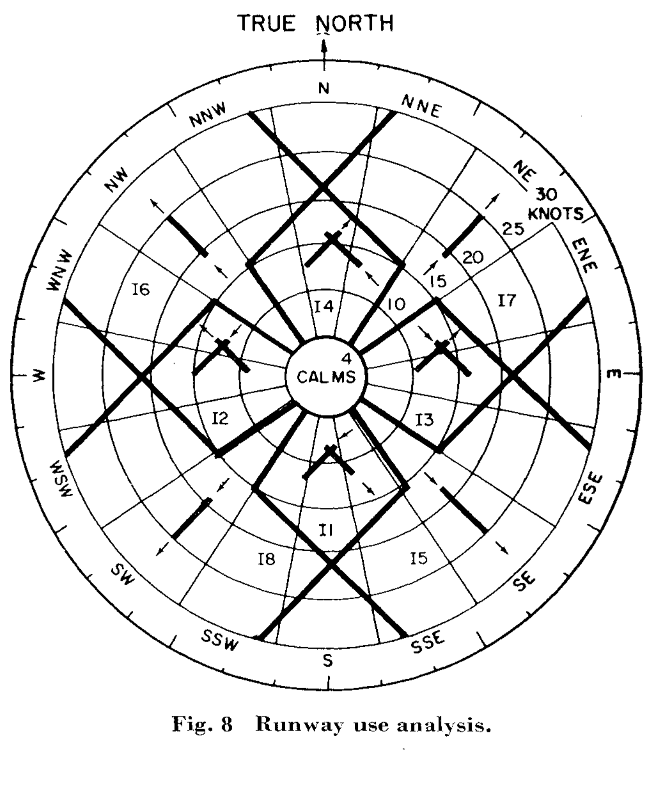

Fig. 8 Runway use analysis.

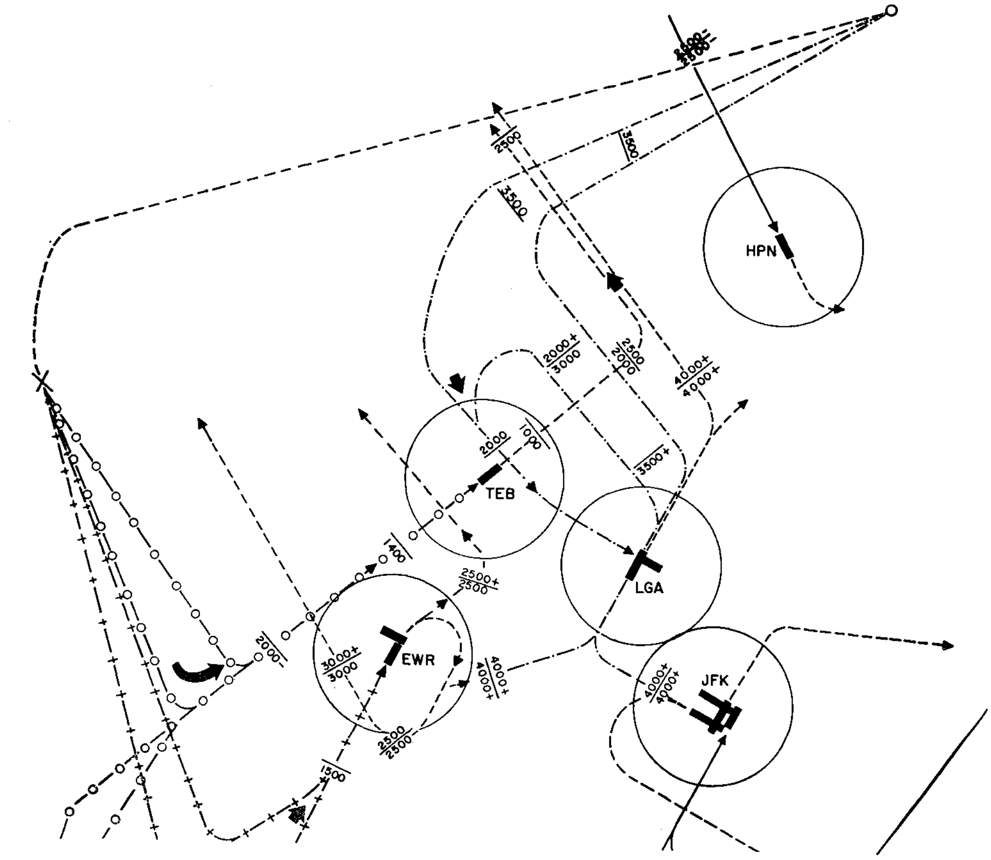

Fig. 9 Approach and departure paths.

previously described, indicated that runway combinations 4 and B were in conflict since the arrival paths crossed without adequate vertical separation. Therefore, during the 11 hr of the year when these patterns are conflicting, appropriate limits must be put on the capacity evaluation for this intersection.

Thus, through the AD path and weather analyses, runway configuration and airport use can be analyzed to provide a basis for later capacity computation.

Practical Annual Capacity and Hourly Capacity

The ultimate aim in studying terminal area operations is to maximize airport capacity and minimize delay and inefficient routing. A basis has now been laid for proceeding to capacity and delay computations.

When the airspace is studied, as described, and any other actions or restrictions determined, it is possible to reflect these findings in capacity computations. The hourly capacity (PHOCAP) computations are accomplished first.

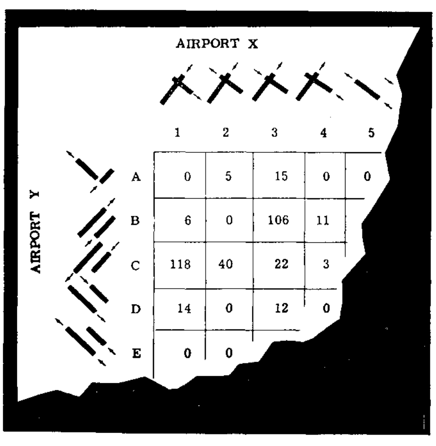

Fig. 10 Occurrence of interference, hr.

Briefly, the technique utilizes mathematical models based on queuing theory. The delay to operations (landings and takeoffs) is computed and practical capacity is selected as an operating level with reasonable delay. Figure 11 shows a typical curve plotted from a PHOCAP computer analysis to show delay vs movements. PHOCAP is generally selected at the 4-min delay level, which on Fig. 11 occurs with 56 movements per hour. Thus, the PHOCAP computed can be exceeded, but at the expense of higher delay.

The technique of computing the practical annual capacity (PANCAP) is essentially an evaluation of delay occurring during the hours when PHOCAP is exceeded and PANCAP is selected at a delay level to provide reasonable service without excessive delay over a 1-yr period. An essential point of this technique is that it can permit an accurate assessment of the interaction between airports. Since it computes capacity over a time period of 1 yr, it can be used to show the effect of interairport conflict during the appropriate times of the year. Since it is also based on a delay evaluation (just as PHOCAP), it thus can be exceeded, but at the price of higher delay.

Figure 12 can be used to illustrate additional points on capacity computation. A three-stage airport development program is shown. Table 1 indicates the PHOCAP for each stage. Note that there are a number of capacities depending

Table 1 PHOCAP in movements per hour; time period—1975

	Stage A		Stage B		Stage C	
	PHOCAP	Percent use	PHOCAP	Percent use	PHOCAP	Percent use
VFR	70	18.1	74	18.1	106	32.1
	65	12.9	68	12.9	88	52.9
	62	14.0	65	14.0		
	55	11.0	56	40.0		
	50	29.0				
IFR	56	6.0	56	6.0	60	15.0
	50	5.0	50	5.0		
	41	4.0	41	4.0		

Table 2 PANCAP in movements per hour

Stage	PANCAP	Peak hour
A	259,800	74
B	272,500	78
C	388,400	111

on which combination of runways is in use. Table 2 gives the PANCAP for this same airport, and in addition gives the average peak hour. This peak hour, given for both VFR and IFR, is defined as the average peak hour of the average peak day (which occurs 26 days/yr) to correspond with airport demand at PANCAP. It is considered important to use this average peak hour for airport design and terminal overloading, rather than any single hourly capacity criteria. Note the number of hourly capacities for a typical airport as listed in Table 1. The question of which one to use for design is answered by the use of the average peak hour based on PANCAP rather than on one of the many PHOCAP's. This peak hour is derived from a delay evaluation covering the use of all of these capacities and the many demand variations that occur over a 1-yr period.

Annual Delay Computation

Another important tool in terminal area evaluation is the ability to compute air and ground delay to operations. Note that in Fig. 11, the variation in delay with movement rate can be determined. For example, while at 56 movements, the delay is 240 sec. This technique for evaluating delay has been extended into a computer program that assesses delay over a 1-yr period. This has proven to be a very valuable means of determining the effect of airport or terminal area improvements. Table 3 shows the change in delay due to the staged airport development program shown in Fig.

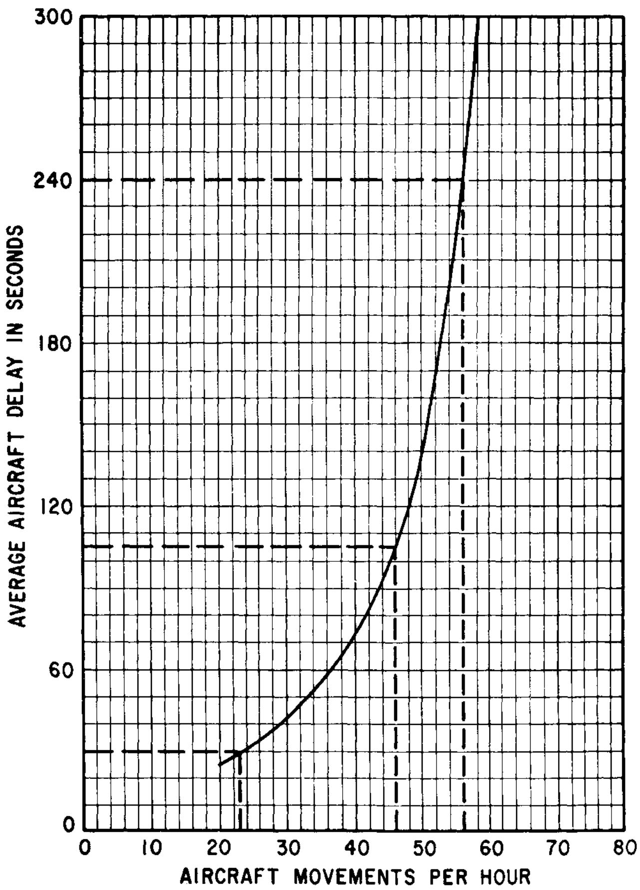

Fig. 11 PHOCAP is selected at a reasonable delay level.

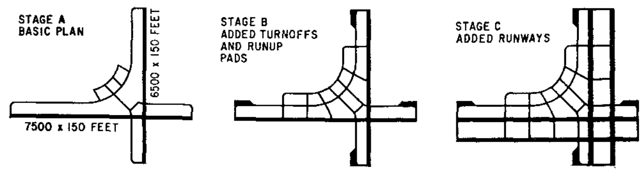

Fig. 12 Staged airport development plans.

12. Note that a basis is available for comparing investment cost with benefit.

A further example of the use of delay computation is to determine the benefit of a one-airport development program vs a two-airport development program. Figure 13 is an analysis conducted for a terminal area in which a rather extensive development program for one airport was compared to the development and use of two airports. The delay at two airports is considerably less than the delay with one airport, even when the demand is less than the PANCAP of one airport. For example, in 1970, with one airport in operation, the delay is 17,500 hr. With two airports in use, the delay drops to 11,000 hr or a saving of 6500 hr of delay per year.

Application of Techniques

To summarize the use of the techniques, assume that a new major airport must be located in a busy terminal area. This would require that adequate provisions be made for: 1) the airspace and route layout changes, and a determination of whether airspace capacity is adequate; 2) a determination of what, if any, conflicts would result between airport operations; 3) a determination of existing and future terminal area airport capacity, allowing for any airspace limitations.

Referring to Fig. 14, the first task would be a large scale, detailed, data gathering effort on existing conditions. This would cover the gathering of many statistics and also achieve, for the analysis, a thorough understanding of current airspace and airport traffic use and control procedures. The existing

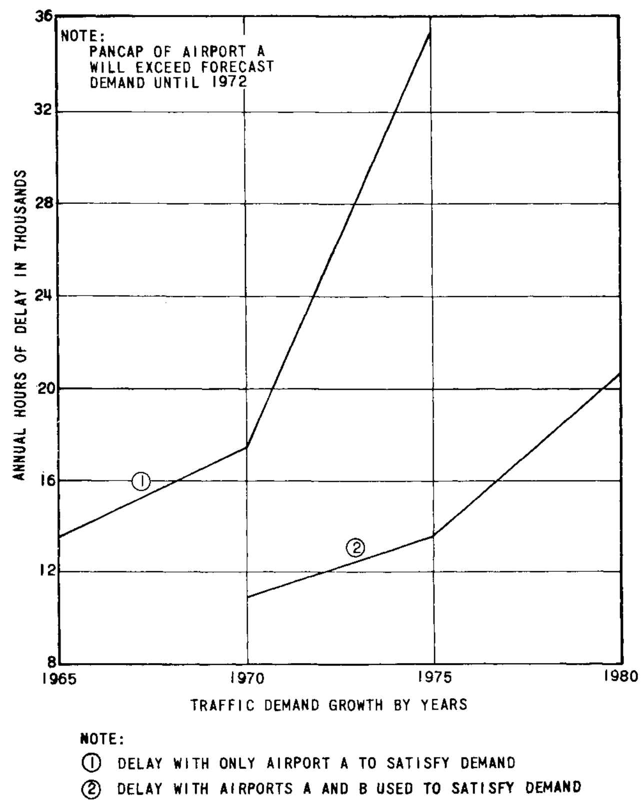

Fig. 13 Annual delay with one- and two-airport operations.

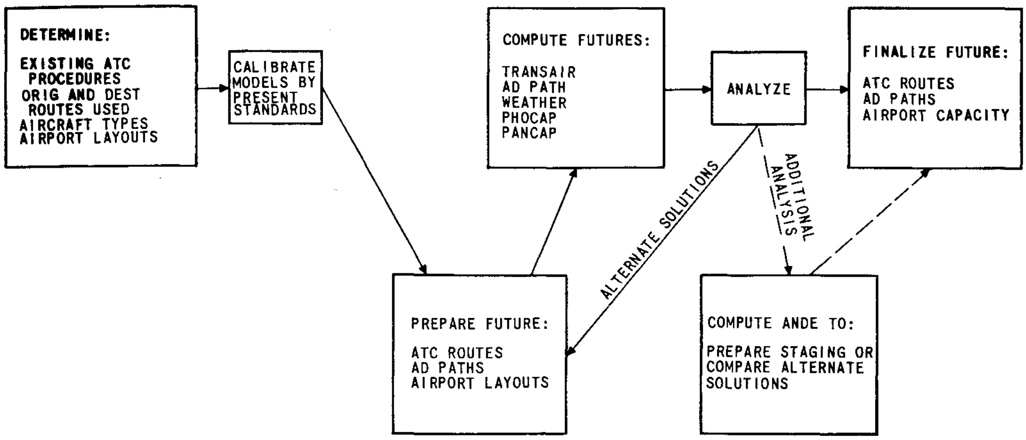

Fig. 14 Detail of procedure to optimize traffic flow and capacity.

conditions analysis would then be used to check application of the models (Fig. 14) and form a basis for comparison of the present-to-future planning.

Next, considerable effort must be given to planning the future routes, approach and departure paths, and airport development programs. In a complex terminal area, numerous combinations of degrees of airport development at the different airports could be arrived at, each one requiring a different airspace solution. The analyst must examine many possibilities and then select for detailed analysis a few combinations that offer the most promise as an airport system (say 4 or 6). The procedure of Fig. 14 is a relatively economical means of analysis but still the study size must be held to practical limits.

The basis has now been laid for application of the several computer programs to get numerical results. Once numerical results are available for analysis, it may be determined that alternate solutions should be examined because other approaches may be more fruitful. Thus, a recycling would occur with additional computer applications.

The study results are achieved without being limited, as real-time simulation tends to be, by specific control or flight equipment. Alternate solutions can be examined quite readily and at considerably lower cost than real-time simulation. Yet the study results will: 1) provide a factual base for terminal area planning and airport system capacity, and enable choices between alternate solutions; 2) provide a factual base for staging a multiairport development program to minimize delay, or to control delay at a level commensurate with other considerations, as for example, added facility cost due to multiple airport operation.

Conclusion

Airspace management is a problem; however, we have a basis for numerically describing the problem. What, then, are the potential solutions? Certainly, we cannot expect that the workload will be handled primarily by increasing the number of controllers.

The FAA National Airspace plan (NAS) will provide some capability to handle the increasing workload through the use of alphanumerics and improved displays. Experience to date with alphanumerics, such as at Atlanta, has indicated benefits to the control function, although numerical results have been slow to become available.

However, to cope with the forecasted traffic, we believe more study is needed by interdisciplinary teams (including operations researchers, mathematicians, air traffic analysts, engineering psychologists) on at least these areas:

1) airspace management and procedures on such items as sector size both as to altitude and number of fixes

2) the navigation aids needed to achieve a more dense but also flexible terminal route structure, and to minimize controller workload (reduce vectoring)

3) display and control systems to reduce and subdivide controller workload

4) an over-all effort to reduce dependence on manual operation while retaining human control and judgment

Present planning for airspace management, as reflected in NAS, stems from the 1961 Beacon report. Now, eight years later we have added knowledge on aircraft types (the 747, SST, Airbus) and projected traffic growth. A new airspace user appears most likely—V/STOL aircraft. A reassessment or updating of future planning is urgently needed.

Table 3 Annual delay analyses

Stages compared	Annual demand	Delay reduction, hr Departures	Arrivals	Dollar savings
Stage B over A	259,800	1,235	0	$ 146,850
Stage B over A	272,500	1,580	0	188,260
Stage C over B	272,500	5,041	1,402	1,101,800
Stage C over B	388,400	30,700	7,425	6,311,450

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