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General Aviation Forecasts for System Planning

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Consistent, reproducible forecasting models for general aviation activity at airports are important in statewide airport planning since more than 80 percent of the operations at major airports are by general aviation aircraft. During the state airport system planning process in Iowa, current general aviation forecasting tools were evaluated and a survey was designed to study the aviation operations at several airports where continuous count data were not available. The methodology developed for forecasting annual general aviation operations, passenger enplanements, and peak-hour movements are discussed. Data for 1971, 1975, and 1976 were available from several nontowered and towered airports and indicate that general aviation operations per based aircraft declined at both classes of airports. The general aviation operation models, developed from 1975 survey data, predicted operations in 1976 within 7 percent; the differences were not statistically significant.

A primary objective for the development of state and national airport system plans is to provide for the orderly and timely development of a system of airports adequate to meet air transportation needs. Within this framework a major component of analysis is the development of aviation activity forecasts that are used to identify airport development and air navigation facility needs, airspace use, and air traffic control procedures. Annual and peak-hour operations and passenger enplanements by air carrier and general aviation aircraft are principal factors in determining these needs.

Although the greatest financial needs may occur at those airports that provide certificated air carrier service, that service is a small portion of the total airport activity. Even at the 430 major airports that have Federal Aviation Administration (FAA) control towers, the data indicate that, on the average, approximately 80 percent of all operations are by general aviation aircraft. At most of the other approximately 12 000 airports in the country, general aviation aircraft constitute the entire operational activity.

For airport system planning purposes the air-carrier activity is well documented, and a reasonable historical data base can be established at most air carrier airports. General aviation activity, however, is not well documented, and consistently applicable estimating procedures have not been established. In this paper we discuss some basic parameters and forecasting methodologies that have been used to estimate general aviation activity and discuss the forecasting procedure used in the development of the Iowa State Airport Plan (1, 2). The changes that have occurred in aviation activity and the sensitivity of the forecasting model to the changes are evaluated.

GENERAL AVIATION FORECASTING METHODOLOGIES

The absence of a satisfactory data base for general aviation operations at all sizes of airports imposes one of the greatest handicaps to the development of forecasting models. If adequate information were available, the operations at a local airport could be analyzed for correlation with community factors such as population, income per capita, employment, and gross sales; with aviation factors such as airport quality, based aircraft, and registered pilots in the county; and with regional or system characteristics such as degree of isolation. Since adequate data are not available, however, the activity forecasts in smaller communities are most frequently based on some form of trend extrapolation from national forecasts or FAA guidelines. Several of the forecasting techniques that have been used for state or national system studies are discussed here.

One forecasting approach is the use of average data offered as a guide by FAA. FAA data on operations per based aircraft, given below, combined with an estimate of based aircraft are used to forecast aircraft operations. (The metropolitan area is the area under the influence of the central city of a standard metropolitan statistical area.)

Airport Type	Annual Operation	Metropolitan Areas	Nonmetropolitan Areas
Airline served	Itinerant	600	300
	Local	600	300
General aviation only	Itinerant	400	200
	Local	600	300

A second approach uses national growth rates and is based on the forecasts of flight hours by general aviation aircraft. Forecasts of aviation flight hours by aircraft type (3) based on reported flight hours for the registered aircraft are developed annually by FAA. The hours flown forecasts are combined with the estimate of hours per flight by aircraft type and the number of aircraft by type at the airport to derive an estimate of annual operations.

One modification of the procedure involves adjustment of the state projections based on relative state and national population and increase in the number of aircraft. Specific community factors, however, are not addressed in these forecasts.

In a third forecasting approach, at least one state recognized the value of incorporating local parameters into the estimating relations, but because of time and financial constraints the data on operations could not be obtained (5). Instead, estimates of operations were obtained from the Airport Master Record (Form 5010-1) maintained by FAA. The operation data on Form 5010-1 are themselves estimates that are frequently based on data such as those given in the tabulation above or on estimates made by the local airport manager. Further, the estimates are frequently not given on the forms, and gaps in the data result.

One of the most comprehensive efforts to evaluate the relations between community factors and general aviation operations was accomplished under the sponsorship of FAA (4). An objective of that study was to develop a nonsurvey method for estimating activity at nontowered airports. One phase was concerned with models to develop total operations, and a later phase dealt exclusively with general aviation operations. Operational data were obtained from activity reports at towered facilities, from FAA survey audits conducted at tower-candidate airports, and from similar surveys conducted by the research agency at general aviation airports. Aviation characteristics and community characteristics were obtained primarily from Form 5010-1 and from the census bureau's city-county data book respectively.

More than 50 factors were considered to be potentially important in explaining variations in annual operations.

The investigators developed regression models that were reported to be statistically valid for estimating activity at nontowered airports throughout the country. As an indication of variables found to be significant in that study, the final equation for estimating general aviation itinerant operations at nontowered airports included airport land area, number of single-engine based aircraft, registered aircraft in the county, state registered aircraft per 100 000 population, hours flown, and an airport facility index that described the airport quality.

Although this modeling effort produced equations that met standard statistical tests, some reservations regarding the use of the model for system planning remain. For example, itinerant operations at an airport were predicted to decrease with an increase of airport size. Likewise, local operations were predicted to decrease with an increase in the number of single- and multi-engine based aircraft. These relations are logically inconsistent and are not borne out by the observed data. Further, the hours-flown variable used in the itinerant model must itself be estimated, even in the base year, because of nonreported flight activity. During the entire planning period we felt that the hours-flown variable would be at least as difficult to forecast as the dependent variable. Finally, when the model was used to estimate general aviation operations at selected towered and nontowered airports in Iowa, the predictive models consistently overestimated operations at the nontowered facilities and underestimated operations at the towered facilities.

GENERAL AVIATION FORECASTS FOR IOWA

In Iowa, more than 400 airports have been identified, of which 116 are publicly owned and 93 are privately owned but open to the public. Only 9 of the airports provide certificated air-carrier service, and even at those airports general aviation aircraft accounts for more than 80 percent of all operations. Thus, when state airport system planning studies were undertaken, one of the primary concerns was the adequacy of the forecasting techniques for general aviation operations. It was felt that the existing methodologies did not adequately represent variations in activity because (a) the data base did not represent the many smaller airports, (b) the community characteristics and growth potential were often not accounted for, or (c) the relations among variables had not been adequately determined.

This paper summarizes the procedures used in the development of forecasts for general aviation operations and passenger enplanements. Pertinent inventory and analysis techniques developed for the 1972 and 1976 system plans are discussed (1, 2). The models developed address the limitations as listed above, but only the final factors used are described. Many other factors that strongly related to general aviation total and itinerant operations were originally considered, but were not used in the final phase because they led to inconsistent relations or were insensitive to changes that occur during the planning period.

The models discussed relate primarily to 1975 base-year data, but frequent references are made to the 1972 operations so that traffic growth patterns can be discussed.

Forecasts of Registered Pilots

The variables explicitly used in the operation models were pilots registered in the county and aircraft based in the county. Historical and current data regarding the statewide total and the county distribution of pilots and aircraft were obtained from the Aeronautics Division, Iowa Department of Transportation (formerly Iowa Aeronautics Commission). Forecasts of future pilot registrations in the state were developed by using national forecasts and a step-down approach that accounts for variations between U.S. and Iowa population and economic growth.

The distribution of pilots among the counties was found to be closely related to population of the county. However, more populous counties tend to have less than a proportionate share of the pilots in the state. The forecasts of county distributions were made by accounting for the population growth of each county relative to the state growth and adjusting this value by the relative share of pilots in each county in 1975.

Forecasts of Based Aircraft

Statewide and county estimates of aircraft were developed in a similar manner. A further allocation of aircraft to the individual airports was required for the operation forecasting models. Available data indicate that the residence area of an owner is not necessarily associated with the site at which the aircraft will be based. Selection of a site for basing an aircraft may be affected by factors such as hangar space and rental rates, availability of navigational aids, and runway length and condition. An aircraft may be based several kilometers from the owner's place of residence in order to have access to the more attractive features. As a result, some airports may attract a larger number of aircraft than are registered in the county and other airports may not attract as many aircraft as are registered in the county. In forecasting future based aircraft, we assumed that a quality system throughout the state would remove much of the attractiveness differential among airports by the end of the long-range period. Thus, in the long run, the number of based aircraft in a county should be more nearly equal to the registered aircraft in that county.

A growth curve was used in which the ratio of based aircraft to registered aircraft would asymptotically approach 1.0. Based aircraft for the base year were taken from site surveys conducted at all principal public-use airports. In the 1975 update plan the ratio of 1975 based aircraft in the county to 1975 registered aircraft in the county was calculated for each county. Then 1995 county based aircraft were estimated according to the following equation:

$$\mathrm{BA}(95) = \mathrm{B}^{1/3} \times \text{(1995 registered aircraft in county)} \qquad (1)$$

1985 county based aircraft were estimated to be

$$\mathrm{BA}(85) = \mathrm{B}^{1/2} \times \text{(1985 registered aircraft in county)} \qquad (2)$$

1980 based aircraft were assumed to be the average of 1975 and 1985 values.

If there was more than one system airport in the county, the county based aircraft were proportioned among system airports by using the same relative ratio that existed in 1975.

This general procedure provided an overall assignment methodology. Second iteration adjustments, however, were incorporated as decisions were made as to which airports would be retained in the state system plan. Virtually all future growth in aircraft was assumed to occur at those airports. If an airport was not to be included in the system, adjustments were made in the allocation process, which considered factors such as surface travel time to alternative sites and registered pilots in the competing areas. After final adjustments, more than 95 percent of the general aviation fleet had been assigned to the system airports by the end of the long-range period.

Base Data for Forecast Models

Because accurate data regarding aircraft operations are available only for airports with traffic control towers, we selected 15 airports, representing the range of operations expected in Iowa, to be surveyed 16 h/d for 1 week during the summer of 1975. These 1-week counts are not representative of an average annual week, and additional data from the records maintained by the FAA traffic control towers were used to expand the 1-week counts. The monthly tower reports from the five Iowa control towers and the towers in Omaha, Nebraska, and Moline, Illinois, were obtained for 1972, 1973, and 1974. The monthly variations in general aviation itinerant, local, and total operations were used to develop monthly factors for converting 1-week counts to average weekly counts. The composite monthly factors are given in Table 1. Statistical tests generally indicated that the monthly factors remained constant throughout the years and that the factors were relatively constant from city to city. Assuming that the monthly variations in general aviation operations at the nontowered airports are comparable to the variations at the towered airports, we used these factors to expand the weekly counts to annual operations.

The data from 14 of the surveyed airports (one site was considered to be an outlier) were eventually combined with general aviation data from the 5 towered airports. Before these data were used in a combined model, however, the homogeneity of variances of the groups was established. We found that the groups could be combined only if a transformation was made. A logarithmic transformation was found to be statistically acceptable and was used. The final models were based on 19 observations.

General Aviation Total Operations

Several community and aviation system characteristics were evaluated for inclusion as explanatory variables in the operation models. Strong linear correlations existed between operations and other factors such as population, employment, gross sales, based aircraft, number of families with incomes of $15 000, and registered pilots in the county. All of these variables, however, are highly intercorrelated and do not independently explain variations in the operation data. Incorporation of all factors in a demand model would result in intuitively incorrect, if not statistically invalid, models. Instead, the interdependent nature of these factors was accounted for in the final model by forming multiplicative interaction variables. The best overall forecasting equation for total general aviation operations was

$$\log(\text{annual total operations}) = 2.614 + 0.501 \log(\text{based aircraft} \times \text{county pilots}) \qquad (3)$$

This model explained 88 percent of the variation in the data, and the errors were randomly distributed. Forecasts derived from this equation were generally found to be reasonable. However, in smaller communities within largely metropolitan counties, the large number of pilots caused unreasonably high forecasts. In this case a model considering the direct effect of community population and based aircraft was developed. This model was satisfactory for estimating the operations in the smaller communities.

General Aviation Itinerant Operations

Itinerant operations were also highly correlated with several other factors, particularly population. Larger communities that serve as regional centers increased the attractiveness of the area to individuals throughout Iowa and adjoining states, thus tending to increase the proportion of itinerant operations at the airports. Of course, the propensity for flights is directly related to the number of aircraft and pilots in the service area. The latter factors were dominant in the model formulation. The final model was

$$\log(\text{annual itinerant operations}) = 1.865 + 0.605 \log(\text{based aircraft} \times \text{county pilots}) \qquad (4)$$

This model explained more than 95 percent of the variation in itinerant operations, and the errors were randomly distributed. The impact of service area population appears to be adequately measured by variations in county pilots.

Adjustment Factors for Unique Community Characteristics

Previous experience indicates that, regardless of the statistical strength of a forecasting model, some communities possess unique economic or locational characteristics that are impossible to incorporate in a statewide model of aeronautical demand. To account for these unique characteristics, each professional staff member evaluated each community that was considered to experience some greater or lesser potential for travel that could conceivably not be accounted for in the statewide model. Multiplier factors for itinerant and total operations were calculated from these ratings. All ratings were completed before any operational data were obtained from field surveys. In this way the data could not interfere with or bias the staff ratings. The majority of the adjustment factors resulted in changes of 5 percent or less. The maximum community factor changes were approximately 20 percent.

EVALUATION OF FORECASTS AND FORECASTING MODELS

The activity counts taken at the 15 airports in 1975 repeated similar counts taken in 1971 at 8 airports and provided an opportunity to assess the changes in general aviation operations. The data supplement our knowledge about annual operations as measured at the air traffic control towers.

The number of operations per based aircraft is commonly used as a basis for comparing levels of operations at airports of differing size or at the same airport as the number of aircraft at the facility changes over time. This rate is expected to increase because increasing prices of aircraft and increasing navigational equipment requirements prompt aircraft owners to use their craft more intensively to justify the increased capital costs. The operations per based aircraft at all airports with air traffic control towers declined during the period (Table 2). At the smaller airports the trends were not as consistent, but overall a decrease was noted. The weighted average operations per based aircraft decreased 26 percent at all airports, from 840 in 1971 to 620 in 1975, and 15 percent at nontowered airports, from 776 in 1971 to 670 in 1975.

The Iowa Department of Transportation continued to monitor activity in 1976, and preliminary summaries show that the operations per based aircraft were fewer in 1976 than in 1971 at 5 nontowered airports and fewer in 1976 than in 1975 at 4 nontowered airports.

All factors that might have contributed to this reduction are not known, but the forecast models indicate that one of the principal factors is the reduced growth rate of registered pilots. Between 1972 and 1975 aircraft registrations increased by 9.4 percent, while the number of registered pilots declined by 2.8 percent.

Another factor is the percentage of itinerant operations. At the 8 nontowered airports, 26 percent of operations were itinerant in 1971 and 36 percent in 1975. Itinerant operations represent a larger portion of the total primarily because of the reduced growth rate of local operations, which is a reflection of the declining number of new pilots throughout the state.

These observations are based on short-term counts and are subject to the random variations occurring in those counts. Unfortunately, sufficient survey data are not now available to analyze this variation. A measure of the ability of the forecasting model to predict operations in spite of these variations is, however, afforded by portions of the 1976 data that are available. On the average, the models developed from the 1975 data underpredicted total and itinerant operations at 9 airports by about 6.5 percent. A t-test for paired differences indicated that these differences were not statistically significant at the 95 percent confidence level.

GENERAL AVIATION PASSENGER AND PEAK-HOUR FORECASTS

Peaking characteristics and general aviation passenger enplanements were developed primarily from the 7-d count data, hourly data from control towers, air taxi observed data, and estimates from airport managers and operators. Although the estimates are subject to high variability, they provide a sufficiently accurate estimate for statewide system evaluation. Master planning efforts would require more detailed analysis.

Table 1. Adjustment factors for seasonal variation in general aviation operations.

Month	Itinerant	Local	Total
January	1.22	1.29	1.25
February	1.21	1.18	1.20
March	1.02	1.02	1.02
April	1.00	0.98	0.99
May	0.90	0.89	0.89
June	0.82	0.86	0.84
July	0.83	0.76	0.80
August	0.83	0.82	0.83
September	0.94	0.90	0.93
October	0.95	1.00	0.97
November	1.21	1.27	1.24
December	1.42	1.51	1.46

Table 2. Annual general aviation operations per based aircraft.

Airport Type	City	1971	1975
Nontowered	Charles City	700	960
	Clinton	1030	620
	Fairfield	880	1200
	Fort Dodge	1140	1330
	Osceola	510	760
	Sac City	700	530
	Shenandoah	550	430
	Spencer	570	540
Towered	Des Moines	860	600
	Dubuque	680	610
	Sioux City	780	610
	Waterloo	1330	1060

Air Taxi Operations

General aviation itinerant operations include the number of air taxi operations. However, since the passenger volumes tend to be greater on air taxi flights than on regular flights, terminal area requirements would increase as air taxi operations increased. Air taxi operations tend to increase as community size increases, but data for determining the extent of these operations are extremely limited. Figure 1 shows the degree of variation evidenced in the surveys. Data from air carrier airports depict a reasonably consistent pattern, but these airports in Iowa are associated only with communities having more than 30 000 population. Estimates obtained from smaller cities tend to be proportionately higher because of the demand for additional air taxi service in smaller cities where scheduled service is not available, the optimism of local operators, or some combination of these and other factors. At any rate, estimates for a given city size show ranges that could vary by about an order of magnitude and can serve only as a guide. Data for specific airports would be most useful to estimate these operations.

In Iowa, the control tower data base was used in forecasts of air taxi operations for air carrier airports. For other airports, the estimate was obtained from a hand-fitted average line developed from the local operators' and managers' estimates, as shown in Figure 1.

General Aviation Passenger Enplanements

General aviation passengers include all passengers on private, air taxi, and air commuter aircraft. The number of passengers on nonscheduled certificated air carriers is significant in Des Moines, Cedar Rapids, and Waterloo but still less than 2 percent of all air carrier passengers at those airports. These passengers were simply included in the total enplaned passengers by commercial aviation.

General aviation passengers were calculated to be 1.5 times the general aviation itinerant operations, except at locations where air taxi potential seemed to be most significant, i.e., in communities of 10 000 or more population. At those locations, air taxi passengers were estimated separately. The range of air taxi loads was from 2.0 to 3.0 passengers per itinerant operation. General aviation passengers were then calculated as

$$\begin{aligned}\text{Total general aviation passengers} = {} & (\text{estimated passengers per air taxi operation}) \\ & \times (\text{air taxi operations}) \\ & + 1.5\,(\text{itinerant operations} \\ & - \text{air taxi operations})\end{aligned} \qquad (5)$$

General Aviation Peak-Hour Operations

The pattern of peak-hour operations was determined from field survey counts and various airport planning forecasts. The observed peak-day and peak-hour data are given in Table 3; Figure 2 shows the relation between annual operations and peak-hour operations. The line depicting a 20 percent peaking factor for the average survey data is also shown as a lower bound. A hand-fitted curve of the data points was used for estimating peak-hour operations.

Peak-hour passengers were calculated to be 1.5 times peak-hour itinerant operations except in communities with high air taxi operations. In those areas a weighted figure of 1.7 passengers per itinerant operation was used.

CONCLUSIONS

The forecasting procedures used to estimate general aviation activity have ranged from judgmental estimates to detailed econometric models. In nearly all instances, the information used to determine annual operations at nontowered airports is synthesized from national projections or is developed from incomplete data obtained at the local level. More complete activity data were collected in surveys in Iowa cities ranging in population from 3000 to 35 000 to supplement tower data available in cities ranging in population from 60 000 to 200 000. These data, combined with community and aviation-related factors, served as the base for developing forecasting models of air travel in Iowa.

The models used to estimate general aviation total and itinerant operations were able to explain quite well (coefficient of determination of 0.88 and 0.95 respectively) the variations in operations among different airports in 1975. Whether the models can predict growth at a specific airport over time cannot, of course, be completely judged at this time. Changes in operations must be sensitive to changes in the explanatory variables in the model. The two explanatory factors, registered pilots and based aircraft, are certainly not the only factors that affect growth, but the interaction of these variables is highly significant. Other factors such as employment or population can statistically explain variation between cities at a point in time, but general aviation changes over time will not respond quickly to a change in these parameters. Inclusion of these factors in the model would be intuitively correct, but would simply confound the forecasting tool.

A measure of the ability of the models to estimate changes in operations during a short time period was provided by the data collected in 1976. The models predicted the annual operations within 6.5 percent of the survey estimates. These estimates were not statistically different.

The peak-hour and passenger enplanement forecasts were based on data and factors from several sources, but a primary source was the short-term counts. As a base for making statewide estimates, these data are felt to be sufficiently reliable although subject to large but unknown variations. A subject of future research should be the acquisition of data covering an extended time period at selected general aviation airports. Peak-hour or monthly variations are often assumed to follow the same pattern at general aviation airports as at control-tower airports. The fact that an estimating equation using data from several towered airports where continuous counts were available and data from several tower-candidate and smaller airports where 1-week counts were available could not satisfactorily estimate operations in Iowa suggests that more information is needed.

Figure 1. Trends of air taxi operations.

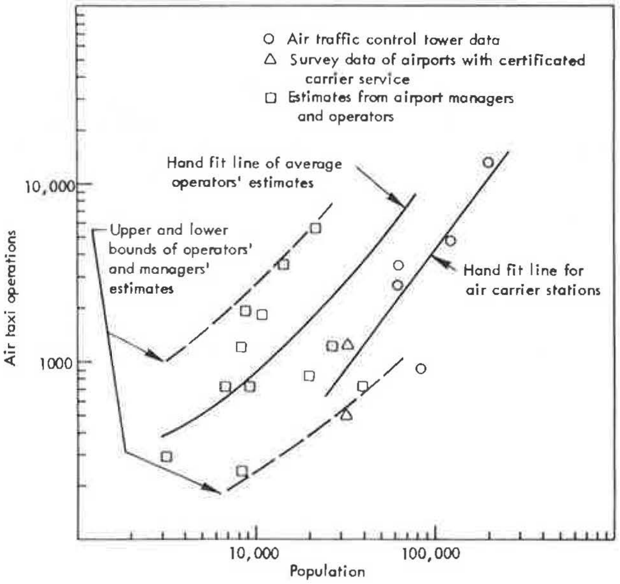

Figure 2. General aviation peak-hour operations.

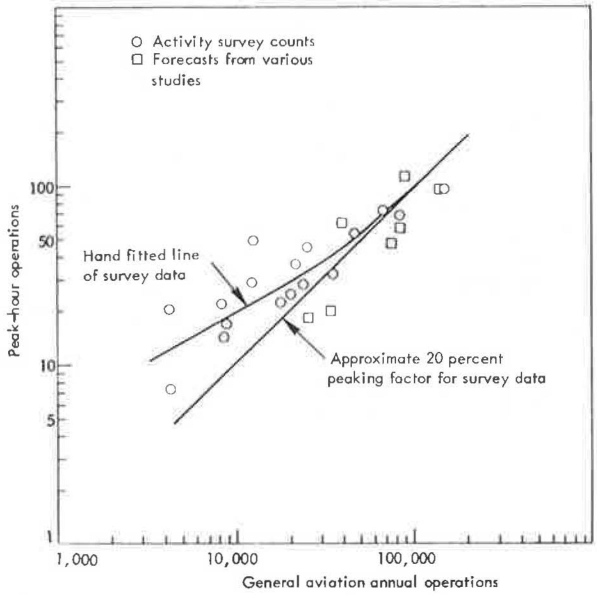

Table 3. Peak-hour and peak-day general aviation operations.

City	Peak-Hour Operations	Peak-Day Operations	Annual Operations	Peak-Hour/ Annual	Peak-Day/ Annual
Algona	16	46	8 700	0.001 84	0.005 29
Charles City	27	100	20 200	0.001 34	0.004 95
Clinton	24	96	19 900	0.001 21	0.004 82
Council Bluffs	36	123	21 400	0.016 80	0.005 75
Decorah	43	101	14 000	0.003 07	0.007 21
Fairfield	44	125	24 000	0.001 83	0.005 21
Fort Dodge	39	191	35 900	0.001 09	0.005 32
Keokuk	15	64	15 300	0.000 98	0.004 18
Manchester	20	26	4 220	0.004 74	0.006 16
Marshalltown	31	150	32 000	0.000 97	0.004 69
Orange City	28	60	12 000	0.002 33	0.005 00
Osceola	14	42	8 440	0.001 66	0.004 98
Sac City	7	19	4 340	0.001 61	0.004 38
Shenandoah	21	40	8 160	0.002 57	0.004 90
Spencer	21	94	17 700	0.001 19	0.005 31

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Abridgment

Survey of Ground Transportation at the Dallas-Fort Worth Regional Airport

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This paper describes a survey of ground transportation at the Dallas-Fort Worth Regional Airport (DFW) conducted on May 16 and 20, 1975. For purposes of the survey, trips were classified as follows: (a) trips made by air passengers and visitors in private automobiles, (b) trips made on public transportation, and (c) trips made by employees. Each of the three classes of trips was investigated separately. This paper describes the methodology and physical performance of the travel survey and some of its findings.

OVERVIEW OF DFW GROUND TRANSPORTATION SYSTEM

Highway Access

Automobile access to DFW is provided by several distinct roadway systems, the most important of which is the north-south spine highway, which passes through the center of the airport. The spine highway system is composed of a multilane public roadway flanked on both sides by a physically separated service road system.

Access via the public roadway is controlled by means of control plazas at the north and south entrances to the airport, each consisting of eight control booths. Control booths on inbound parkway lanes issue parking tickets; outbound booths collect parking fees.

The system of service roads is used mainly by employees and commercial, maintenance, and service vehicles. The service roads branch from the spine highway just outside the control plazas at each end of the airport.

Public Transportation Access

Public airport transportation is provided by bus, limousine, and taxi services. A quasi-public corporation created by the cities of Dallas and Fort Worth, Surtran, has an exclusive franchise to provide express airport bus service. In addition, shuttle bus service is provided by various companies using small minibuses or vans.

EMPLOYEE TRAVEL SURVEY

Over 13 000 employees make daily work trips to and from DFW, thereby contributing significantly to the total traffic volume. A general classification of employees by type of industry and the number in each classification is shown below.

Industry	Number of Employees
Airlines	8 364
Air cargo	1 139
General aviation	100
Food service	1 406
Maintenance (excluding airline employees)	379
Security and police	378
Rent-a-car firms	268
Miscellaneous	1 334
Total	13 368

The miscellaneous category includes employees of the U.S. air mail facility, the Federal Aviation Administration, the Dallas-Fort Worth Regional Airport Board (excluding security and maintenance employees), and the Airport Marina Hotel.

The employee survey form requested information on street address, mode of travel, time of arrival and departure, sex, age, occupation, income, and previous airport employment. Survey forms were distributed to employees by their supervisors. Most survey forms were mailed to the employer; some were delivered by hand. The completed questionnaires were collected in

Table 1. DFW ground transportation modal split.

	Vehicle Trips		Person Trips	
Mode	Number	Percent	Number	Percent
Automobile	43 133	93.0	64 992	89.8
Taxi	1 391	3.0	2 221	3.0
Surtran bus	393	0.8	3 035	4.2
Other buses, shuttle vans	813	1.8	1 301	1.8
Heavy trucks, other	650	1.4	845	1.2
Total	46 380	100.0	72 394	100.0

reverse order of the distribution. Of the 13 368 employee forms sent, 3157 were returned, a 23.6 percent rate of return.

PUBLIC TRANSPORTATION (SURTRAN) SURVEY

Surtran buses operate from five outlying passenger terminals—three in Dallas, one in Fort Worth, and one in Arlington. Surtran ticket clerks dispense tickets at Surtran terminals in the outlying stations as well as at kiosks within the DFW airline terminals. Sale of Surtran tickets in subcontracted to hotels served in downtown Dallas and Arlington. Daily over 3000 passengers ride Surtran to and from the airport.

Two separate forms were designed, one for buses bound for the airport and the other for buses leaving the airport. Ticket clerks handed out the forms to passengers and also provided pencils (not providing pencils might bias returns in favor of those who carry pencils). The rider then completed the form while in transit; the survey form was printed on heavy paper to facilitate onboard completion. Surtran drivers collected the forms as passengers left the bus.

ROADSIDE SURVEY OF AUTOMOBILE USERS

Most surveys of automobile travel by air passengers to and from major airports used questionnaires distributed and completed onboard the aircraft. Standard techniques for conducting such surveys are given in the Airport Travel Survey Manual (1), which also describes roadside interview techniques, the method selected for this research. We decided that much of the information sought (e.g., automobile occupancy, perceived time and distance, specific routes taken to and from the airport, and times of entering and leaving) could best be determined from a personal interview on the roadside.

Scope of Roadside Survey

Only drivers of vehicles in the outgoing lanes of the airport spine roads were stopped for interviews because we thought that persons leaving the airport would be less reluctant to stop for an interview than persons on their way to catch a flight. Feedback from the interviewers suggested that this hypothesis was correct.

The roadside interview stations were located just outside the control plazas, one on each side of the outgoing spine roads at each end of the airport, for a total of four interview stations. Interviews were conducted in turnouts located about 30 m (100 ft) beyond the control booths. Vehicle drivers were interviewed at both ends of the airport from 6:00 a.m. to 10:00 p.m. as they exited the control booths. Three interviewers, two flaggers, and two traffic counters were stationed at each end. A sign identifying the survey was placed at the entrance to each interview lane, and traffic cones were used to channel vehicles to the interview point.

Interview Rate and Sample Size

An average interview took approximately 3 to 4 min. Time was needed between interviews to record the time of day and vehicle occupancy figures and to recheck the form to see that all questions were completed and legible. Also, time was required between interviews to flag another vehicle into the interview lane. The average interviewer conducted 8.4 interviews/h. A total of 886 interviews were conducted, which corresponded to an approximately 5 percent sample size, based on traffic counts made during the same time periods.

Traffic counts were conducted to determine traffic volumes by direction and vehicle type on the various access roads to the airport. These data provide the basis for expanding the roadside interview sample to represent the entire population of vehicles entering and leaving the airport. Both machine and manual counts were conducted. Manual counts were necessary for determining the classification of vehicles and for converting axle counts (machine counts) to vehicle counts.

SUMMARY OF SURVEY RESULTS

A complete description and the full results of the DFW survey are presented in the project report (2). Some of the more salient findings are summarized below.

Table 1 gives the overall modal split determined from the data in terms of both person trips and vehicle trips. The automobile mode includes both personally owned and rented vehicles. Also included in that designation are pickup trucks, campers, and motorcycles. Other buses and shuttle vans refer to vehicles supplied by hotels and car rental agencies for the convenience of their customers. The other category refers to commercial vehicles.

Table 1 shows that Surtran accounted for 4.2 percent of person trips, but represented only 0.8 percent of the vehicular traffic because of the higher vehicle occupancy rates of Surtran buses compared to automobiles. The combination of Surtran, taxis, and the special-purpose transit services accounted for 9 percent of the total person trips to and from DFW.

The contribution of each of the three surveyed DFW ground transportation components (employees, Surtran riders, and air passenger and visitor automobile users) to the total is given below. Employees represent about one-fourth of the total person trips to and from DFW.

	Person Trips	
Trip Maker	Number	Percent
Employees and service personnel	18 623	25.7
Users of Surtran, taxis, and other buses (excludes employees)	6 107	8.4
Air passengers and visitors using automobiles	47 664	65.9
Total	72 394	100.0

Below is the ground transportation modal split of just air passengers. Clearly, Surtran's share of air passenger trips is significantly higher (10.9 percent) than its share of total person trips (4.2 percent). In fact, all public transportation modes taken together account for 25.7 percent of the air passenger ground travel to or from DFW.

Mode	Passenger Trips Number	 Percent
Automobile (includes personal light trucks and motorcycles)	16 626	74.3
Surtran bus	2 447	10.9
Taxi	2 088	9.3
Other buses, shuttles	1 223	5.5
Total	22 384	100.0

The modal split of employee ground travel to and from DFW for the sample date is given below. The automobile is the predominant mode, even though at the time of the survey employees paid a special fare of $1.00 on Surtran compared to $2.50 paid by others.

Mode	Person Trips Number	 Percent
Automobile (includes personal light trucks and motorcycles)	17 328	96.3
Taxi	18	0.1
Surtran bus	432	2.4
Other	216	1.2
Total	17 994	100.0

Modes of access to or from the outlying Surtran terminals are tabulated below. The largest proportion of passengers (over 58 percent) use personal vehicles (predominantly automobiles) in a park-and-ride (16.7 percent) or kiss-and-ride (41.9 percent) manner.

Mode	Percent
City bus	9.2
Limousine	3.9
Taxi	16.5
Private vehicle	
Driver	16.7
Passenger	41.9
Other (includes walking, riding bicycle)	11.8
Total	100.0

The third principal component of DFW ground traffic consists of air passengers and visitors driving their own vehicles. The ground trip purposes of interviewed vehicle drivers who used the public roadway is given below.

Purpose	Percent
Airline passenger	26.9
Pick up air passenger	22.9
Drop off air passenger	33.8
Pick up ticket	0.5
Business at airport	6.6
Visitor	1.6
Drive through	4.3
Other	3.4
Total	100.0

CONCLUSIONS

This survey has led to several conclusions that may help future travel surveys of this type.

1. All survey forms should be meticulously screened for possible confusing formulations. Review by outside parties is helpful; a test application of the proposed forms is recommended. Reference should be made to standard guides such as the one by Jacobs (3).
2. Adequate logistical preparation is essential. Special attention should be given to (a) recruiting survey staff at least 1 month in advance and conducting one or more training sessions; (b) planning and scheduling travel, work shifts, and meal breaks; (c) staffing to include adequate supervision, both to facilitate the administration of the survey and to continually monitor and possibly improve survey staff performance; and (d) where feasible, rotating staff among different functions, such as counting, interviewing, and flagging, to help alleviate monotony and enhance efficiency.

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**Mr. Dunlay was with the University of Texas when this research was performed.*

Abridgment

Cost-Effectiveness Models for Determining Priorities in State Aviation Systems

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Two major questions must be answered in developing a state aviation system plan: How should available funds be apportioned between new airports and improvement projects at existing airports? How can funds be utilized most efficiently within these two categories? To date, these questions have been answered on relatively subjective bases. The models we present provide a quantitative guide to the decision maker for the most effective use of funds within the two categories.

The two models discussed are the airport entry model and the improvement project model. The airport entry model analyzes candidate airports, both new and existing, that are considered for inclusion within a state aviation system. It provides a quantitative guide on which new airports should be constructed and which existing airports should be considered for inclusion in the airport system. The improvement project model performs a similar analysis of proposed improvement projects and provides a quantitative guide of the relative desirability of each improvement project. The two models are not designed to determine whether an airport or an improvement project is desirable or undesirable, but merely to quantitatively compare candidates with other airports or improvement projects.

EVALUATION FRAMEWORK

A consistent methodology should be used for determining whether an airport should be added to or deleted from a state aviation system plan or whether an improvement should be made on an existing system airport. Common evaluation criteria should be employed in specific decision models; the two sets of criteria (one for airports and one for improvement projects) should be derived consistently with one another, and the two models should have similar form. The criteria are developed with an emphasis on safety, economic justification, environmental impacts, and an equitable distribution of facilities to all segments of the state.

Although the two models manipulate similar criteria, the resulting index numbers they produce cannot be compared with one another. The entry model ranks airports with respect to their effects on the airport system and in relation to the community or communities they serve. In contrast, the improvement evaluation model measures the incremental benefit that an improvement project will have on a single airport.

EVALUATION CRITERIA

The evaluation criteria for both models are grouped by (a) safety, (b) efficiency, (c) environment, (d) economic development, and (e) cost. These specific criteria, although not necessarily the same for the two separate evaluations, utilize consistent logic and mathematical quantities for both evaluations.

Safety Criteria

Safety criteria are critical elements of the evaluation process because the aviation community emphasizes safety. Safety improvement criteria are divided into two categories: airport safety and aviation safety.

Airport safety criteria are included in both the entry and the improvement evaluations. The relative impact that each of 15 different types of improvement projects would have on an airport was assessed. Weightings quantify the safety impact of each project. The weightings were derived on the basis of combined judgments of airport planners and pilots and reflect the severity of an incident together with its probability of occurrence. Coupled with the safety weightings are safety ratings. The ratings emphasize projects that rectify serious safety defects or deemphasize projects for less serious safety defects.

In the improvement evaluation, the weighting of the project signifies its inherent desirability as a safety improvement. The greater the project's innate impact on a facility's safety is, the higher its weighting will be.

The safety rating emphasizes the magnitude of the benefits derived from a safety-related project. While the safety weighting indicates the inherent benefit of a certain type of project, the safety rating further defines the specific project and denotes the extent that project deviates from the norm.

An airport without safety problems has an airport safety factor of 1.0; otherwise, it receives a factor of 1.0 minus the effective safety factor of the improvement project that would correct the condition.

Establishing quantitative criteria for deciding whether an emergency landing strip is justified is difficult. Such decisions must be influenced by local pilots, who are familiar with weather conditions and topographical features in the state. When the need for an emergency landing strip is established, that should be sufficient to justify the construction and adequate maintenance of the strip. The emergency need should not compete with other airports on a quantitative rating basis. For this reason, decisions on establishing such airports should be made apart from the priority ranking of airport entry.

Efficiency Criteria

Efficiency criteria measure the extent to which a proposed change to a facility will increase or decrease its transportation efficiency. Three criteria are included in this set: (a) airport access savings, (b) operational efficiency, and (c) remote location.

The major quantifiable impact on efficiency to consider in adding an airport into a state aviation system is the effect of the addition on total user costs for airport ground access. A second factor, which actually measures system equity more than system efficiency, is included at this point in the model development as a matter of convenience. This is the remote location priority rating. This rating emphasizes airports serving remote communities to account for their greater reliance on air transportation to provide basic and emergency needs.

For airport improvement projects, two criteria relate to efficiency. The first is operational efficiency, indicating the extent that an improvement project will improve the capacity or capability of an airport. The second criterion, remote location priority rating, emphasizes improvements at remote locations to partially compensate for the low usage these locations generally exhibit.

By assuming that aircraft access trips emanate from the address of aircraft registration and terminate at the nearest airport, we can estimate airport access trip distances. Using these distances, together with access costs per kilometer by automobile and estimates of aircraft usage, we can estimate the total access costs to an airport. When any proposed change is made to the system, revised access costs are calculated. The change in access costs can be determined by comparing the revised costs with the original costs. This method of evaluation provides only an approximation of access costs, but does reflect the relative effects of airport additions and deletions and is useful as a planning tool for airports in most parts of the state. Major discrepancies arise, however, if the method is applied in a large metropolitan area. In such a locale, where several airports are located rather close to one another, users do not necessarily base their aircraft at the nearest airport.

The operational efficiency factors, used in the improvement evaluation only, evaluate projects on their ability to increase an airport's capacity or capability through physical improvement of the facility. These factors are similar to the safety improvement factors and include an efficiency weighting and an efficiency rating.

We defined 12 types of projects that improve operational efficiency of an airport and associated specific weightings with each. As with the airport safety weightings, most projects that increase airport effectiveness can be characterized by one of the 12 project types.

The efficiency rating is utilized in a manner similar to that of the safety rating; it emphasizes projects that have a strong effect on the airport's efficiency and deemphasizes projects that have very little effect. The rating value should be 1.0, except in cases where a different value is clearly justified. The product of the efficiency rating and the efficiency weighting is the efficiency factor.

The remote location priority rating emphasizes locations that are distant from major and regional centers of commercial trade. At these locations, where the availability of many specialty items and services is low, the user may not merely desire adequate airport facilities, but may require them for reasonable access to trade centers. Since remote locations rely more heavily on air transportation on a per capita basis than do close-in urban areas and since the volume of traffic that a remote location is likely to generate may not be enough to justify economically an airport or an improvement project when compared to higher density areas, an additional factor in the entry and improvement project evaluations is necessary to provide the needed equity emphasis.

Environmental Criteria

The third criterion used in both evaluations is the environmental rating. This rating, in addition to the economic development rating, reflects airport impacts on the community as opposed to impacts on the user.

A rating of 1.0 is given to a proposed new airport if an opportunity area can be found in the region in which the airport is proposed. The opportunity area plotted on a map represents an area where no (or minimal) adverse environmental effects, no conflicts with current or projected future land use, and no potentially serious construction, clearance, or airport approach or departure problems are known.

When an existing airport is tested for entry into the system, an environmental rating of 1.0 is given when the airport is environmentally accepted in a community. Otherwise, a rating of less than 1.0, subjectively determined, should be assigned.

For airport improvement projects, known environmental considerations that would result in detrimental effects if the proposed project were completed should be described in as much detail as possible. However, no reduced environmental rating is given. The rationale for this procedure is that, when federal agencies or the courts make the final judgment, projects that have adverse environmental effects are either approved or disapproved.

Economic Development Criteria

The fourth criterion, economic development, is a tool for the planner to shape the growth of the state. If accelerated growth is desired in a specific area, providing complete and modern transportation facilities will tend to further the goal. Likewise, if a reduction in the rate of growth in another area is considered beneficial, reduced emphasis on transportation improvements would further this objective. The economic development rating allows the planner to increase or decrease the desirability of an airport or improvement project. Assigning a rating of greater than 1.0 boosts the project's desirability, while a rating of less than 1.0 would tend to suppress a project. As with environmental ratings, care must be taken in applying these ratings for they are prominent in the decision process and, therefore, must be used consistently on all projects.

Cost Criteria

Cost criteria provide the means for reflecting the magnitude of the project in the evaluation process. In the airport entry evaluation process, the cost is the annual capital cost, measured in one of two ways: For a new airport, it is the capital cost of building the airport; for an existing airport, it is the salvage value (taken as the resale price of the land) of the existing facility. In the improvement project evaluation process, the cost is the annual capital cost of the project.

THE MODELS

The entry and improvement models take the basic form of effectiveness cost models. They calculate, for each proposed airport entry or improvement project, an entry or improvement index for ranking the airports or projects within each evaluation process. The models combine the criteria previously set forth with all factors except the cost criteria in the numerator and cost criteria in the denominator of the model.

Space does not permit detailed discussion of the models, which are somewhat complex in their formulation. Separate formulas that use the variables described above are derived for airport entry and for airport improvement projects.

The entry model is used to test three cases:

1. Entry of existing airports,
2. Entry of new airports, and

3. Entry of a new airport to replace service provided by an existing airport.

Detailed procedures were formulated for developing the index numbers and for comparing the index numbers of the three cases above.

The resulting entry indexes range from large positive numbers to negative numbers. In general, the larger the positive index is, the more desirable the airport is. An airport with a negative index is undesirable. Exceptions to these rules exist, however. For proper interpretation of test results, these indexes should be fully understood.

The results of the improvement model are improvement indexes ranging from zero to large positive numbers. An absolute significance is not attached to these indexes, but rather a relative significance relates projects to each other. The decision maker makes the final decision of which projects are feasible and which are not.

MODEL RESULTS AND DECISION MAKING

The models result in rankings of airports and improvement projects that reflect the relative desirability to the user and the community of the airports or projects. These rankings, however, must be used in a subjective manner; the final decision of whether an airport should enter the system or a project should be undertaken rests with the decision maker. The rating indexes do not determine which projects are feasible or which airports should enter the system, but provide an indication to the decision maker of how the entities being analyzed relate to one another. These ratings must be viewed in conjunction with the budgets for improvement projects and new airports to arrive at a final plan.

These models represent an incremental, yet substantial, improvement over previous subjective methods of determining aviation system plans. In our models, many factors normally considered subjectively have been quantified and incorporated into theoretically sound and workable cost-effectiveness formulations.

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Dynamic Modeling of Airport Activity

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This paper discusses problems encountered in modeling airport activity and particularly emphasizes forward planning and policy making. It is concerned with the relations among airlines, airports, and users (passengers and freight). Three simple models of activity are indicated, dealing successively with capacity, investment, and pricing. A basic need is creating a workable typology of airports in which attributes other than size may be considered. A second requirement is considering the importance of fluctuations in airport output. We used multivariate analysis of data for the leading British airports in the period 1968 to 1972 to develop a successful typology, which is essentially applicable to other national airport systems. It stresses the differences between scheduled and nonscheduled activity. Correlations among definitive output variables are used as input to principal components and factor analysis to derive the typology. Output is then disaggregated by the use of a corrected moving mean to give seasonal and trend components. These are used for analyzing growth and growth variability and for studying the stability over time of seasonal variations. In addition, we note positive links between nonscheduled activity and output variability. The implications for planning are demonstrated, in particular the close association among nonscheduled activity, variability, and predictability. The variable associations also indicate possible investment scenarios for the airport manager and the airport modeler.

This paper considers a number of problems associated with building a fundamental dynamic system model of airport activity. At first sight, such activities as movements, passenger throughput, and financial turnover might appear to vary solely as a function of airport size. We examine this possibility, which would permit size variables to provide the basic structure of a simple system model, and also examine whether there is a valid alternative methodology for developing an activity-based system model. Moreover, we examine the amount of variability in the activity measures chosen for study, showing that the amounts are of significance for the forward planning of activity levels by airport management.

Although airports vary considerably in their size and scale of operation, they all fill the same operational function—providing a landing place for aircraft where users (both passenger and freight) can interchange to, from, and within the air mode. The basis of building an airport model is really one of synthesizing a typical airport, which is feasible only if airports are found to lie along some common operational continuum. An operational definition would constrain the analyst to consider airport output, making this appear as the continuum of greatest relevance. The question is, Are airports operationally similar, varying only in size? Were this so, other variations in the system might be expected to be of only minor importance. In fact, we discovered that the idea of the continuum is not strictly valid, that airports do appear to have structural differences in activity patterns based on function.

BASIC FORMS OF A DYNAMIC AIRPORT MODEL

In a dynamic model, output should be distinguished from demand. Demand is controlled not only by the internal variables of transport supply, but also by sociopolitical factors that act externally to the airport system. Output, however, can be considered to be determined internally at the interface between flight demand and flight provision. Forecasts of future demand activity are thus concerned with the prediction of internal and external variables, but the actual operation of the system can be considered to be determined by the balance of supply of flights and price.

We considered the development of an autonomous provision model in work not covered by this discussion (1), but the problems of modeling what is often ad hoc behavior have constrained considerations to an endogenous model (2), an approach previously used by Ellison and Stafford (3). The idea of considering the dynamic provision or supply model as a lagged demand model offers a number of procedural advantages. Clearly, parallels exist between the structure of such a model and the actual behavior of airline route managers (1, 4). In particular, emphasis is placed upon information feedback.

Management usually monitors activity by considering costs and revenues, which may be shown as functions of output (5). Therefore, basic models can be conceived that specifically exclude any consideration of external costs or benefits due to noise (6, 7) or to the economic impact of the airport on the surrounding community (8). In the absence of externally imposed constraints, only capacity limitations control output. Similarly, only an increase in capacity can increase the levels of costs and revenues if price changes prove ineffective at doing so. The relationships between pricing and investment can be shown to be crucially important.

Pricing, however, is often related to a particular financial target. A directive seeking to attain a misdirected financial aim may have the effect of precluding pricing at long-run marginal costs and may fail to direct investment into the most necessary areas (9). In other models (1, 5), although financial targets and the like are included, the pricing mechanism is used simply to relate revenue and output in a log-log or even linear manner. The treatment of investment policy was restricted to the specification of alternative investment scenarios (1, 2). This approach differs somewhat from that of other researchers (10, 11, 12, 13) who, in attempting to produce elegant solutions (14), proposed normative solutions. These solutions considered the relations between output and capacity and the balance between costs and revenues. The latter consideration is particularly pertinent; recent research demonstrates that, for United Kingdom airports at least, investment and development programs increase costs considerably (on the average by as much as 70 percent) without necessarily increasing revenues. Many airports operating at a loss have found that their attempts to invest their way out of financial difficulties resulted only in compounding problems.

Figure 1. Fixed-capacity model.

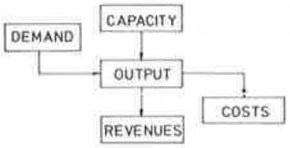


Figure 2. Investment feedback model.

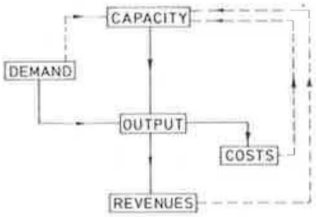
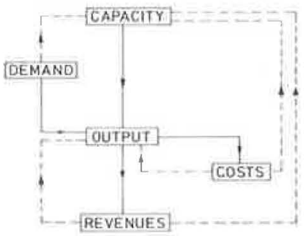


Figure 3. Investment-pricing feedback model.



Figures 1 through 3 show the structure of models in an increasing order of complexity. These are (a) a fixed-capacity model (Figure 1); (b) an investment model in which costs, revenues, and demand give feedback in the form of investment that modifies capacity (Figure 2); and (c) a pricing model, which is similar in structure to the investment model except that costs and revenues give additional feedback and consequent modification to output (Figure 3).

The details of the dynamic model are reported elsewhere (1, 2); the main thrust of this paper is an examination of the output measures of a number of airports to determine whether, in fact, all airports are of a similar nature and can be fitted into a simple dynamic model in which output is considered as a simple variable, easily measured in terms of passengers or movements.

DETERMINING AIRPORT TYPES

Airport demand is not totally exogenous to the airport, but is partially dependent upon the airport system in terms of such parameters as destinations and frequencies (3, 4, 15, 16, 17). A basic question the modeler should ask is whether there are stable relations among these functions and the size of the airport, as measured in terms of its level of output. Significant qualitative differences between the types of airport outputs if related to size would imply discontinuities in the scale of operations. Note that we do not discuss whether a particular airport serves a significantly larger number of destinations or a greater number of passengers than its rival airport. Rather, we attempt to determine the implication for the airport of differing output emphasis.

Output can be classified broadly into two categories: movements and passengers. A further possible breakdown of these categories is shown below.

Airport Movements	Airport Passengers
Total	Total
Air transport	Domestic
Scheduled	International
Nonscheduled	Scheduled
General aviation	Nonscheduled

This form of subcategorization was used in the multivariate analysis to examine the structure of operational output. An additional output variable used was the work load unit, which equates passengers and freight on a weight basis. One work load unit is equivalent to one passenger or 90 kg (200 lb) of freight. Previous research (5) and intuition indicate the following juxtapositions:

1. Passengers and movements;
2. International and domestic activity; and
3. Air transport and nonair transport movement.

In general, the data used in the multivariate analysis were for 18 British airports for the 4 operational years 1968 to 1969 and 1971 to 1972, inclusive. The selected airports include all those with major scheduled air transport activity within Great Britain and Northern

Table 1. Correlations between output measures.

Measure	Air Transport Movement	Scheduled Air Transport Movement	Nonscheduled Air Transport Movement	General Aviation Movement	Total Passengers	Domestic Passengers	International Passengers	Scheduled Passengers	Nonscheduled Passengers	Work Load Units
Total movements	0.977	0.961	0.179	0.058	0.977	0.976	0.977	0.960	0.186	0.978
Air transport movement		0.988	0.157	-0.154	0.996	0.993	0.997	0.983	0.168	0.998
Scheduled air transport movement			0.001	-0.171	0.975	0.968	0.983	0.998	0.012	0.982
Nonscheduled air transport movement				0.093	0.207	0.204	0.167	-0.013	0.996	0.176
General aviation movement					-0.134	-0.128	-0.143	-0.156	0.078	-0.139
Total passengers						0.999	0.999	0.975	0.223	0.999
Domestic passengers							0.997	0.967	0.225	0.997
International passengers								0.983	0.183	0.999
Scheduled passengers									0.001	0.982
Nonscheduled passengers										0.190

Table 2. Principal components and factor analysis of output measures.

	Components			Rotated Factors		
Measure	C1	C2	C3	F_1^1	F_2^1	F_3^1
Movements						
Total	0.980	-0.015	0.192	0.985	0.101	0.134
Air transport	0.998	0.032	-0.014	0.992	0.087	-0.078
Scheduled air transport	0.982	0.187	0.002	0.993	-0.070	-0.086
Nonscheduled air transport	0.186	-0.976	-0.103	0.073	0.995	0.041
General aviation	0.133	-0.223	0.966	-0.082	0.058	0.995
Passengers						
Total	0.999	-0.022	-0.007	0.988	0.140	-0.062
Domestic	0.998	-0.056	-0.008	0.983	0.173	-0.058
International	0.999	0.018	-0.005	0.992	0.099	-0.067
Scheduled	0.980	0.198	0.019	0.994	0.083	-0.070
Nonscheduled	0.133	-0.223	0.966	-0.082	0.058	0.995
Work load units	0.999	-0.010	-0.004	0.992	0.108	-0.064

Note: Eigenvalues and percentage of variance explained are F_1^1 = 7.96 (72.4 percent); F_2^1 = 2.03 (18.4 percent); and F_3^1 = 0.99 (9.0 percent).

Table 3. Airport average growth rates and variability at selected airports from 1968 to 1972.

	Airport Movements		Airport Passengers	
Airport	Growth Rate	Rate Variability	Growth Rate	Rate Variability
Belfast	1.812	3.156	4.894	3.243
Birmingham	6.374	10.071	13.924	4.634
Blackpool	-5.705	9.507	-0.307	7.257
Bristol	0.198	16.163	21.146	19.830
Edinburgh	4.318	10.251	5.399	5.151
East Midlands	7.759	23.165	22.942	16.857
Gatwick (London)	18.304	7.803	26.634	12.105
Glasgow	4.445	1.187	8.235	5.530
Heathrow (London)	2.940	1.118	8.633	3.585
Isle of Man	-0.806	3.901	3.826	6.006
Leeds-Bradford	-4.953	9.545	2.311	4.333
Liverpool	-3.687	6.579	5.191	10.492
Luton	37.242	30.216	49.711	38.409
Manchester	6.0776	4.779	12.647	4.078
Prestwick	-5.519	7.891	7.516	20.240
Southend	-6.478	18.916	-8.646	17.253
Stansted	14.185	39.359	34.427	60.343
Teeside	9.368	37.116	21.084	13.483

Ireland. To examine the relations between variables, a correlation analysis was run on output data for the operational year 1970 to 1971. This year was chosen to permit comparison with other research work (5). Table 1 gives the correlations found between the output variables. When subjected to principal component analysis, the correlation matrix produced three principal components, C_1, C_2, and C_3, as indicated in Table 2. The total of these components accounted for 99.8 percent of the variance of the correlation matrix when subjected to the varimax procedure of factor analysis. The variance associated with each component is maximized by component vector rotation, allowing the components to be arranged in terms of the importance they play in contributing to the total variation. Three measures appear to account for virtually all the variation in the original data: total activity for factor 1 (this measure is synonymous with scheduled activity and does not differentiate among movements, passengers, and work load units), nonscheduled (charter) activity for factor 2, and general aviation activity for factor 3.

Several significant conclusions may be made. First, for some purposes of system analysis, there may be little reason to differentiate between land activity measures (passengers) and air measures (movements). Second, scheduled and charter activities are clearly differentiated in the factor analysis. Third, general aviation activity provides a third factor, orthogonal to the first two factors. The second conclusion is important from the viewpoint of the planner, who is aware that scheduled output can differ significantly from nonscheduled output in the incidence of demand on airport time. Cross-sectional analysis of either demand or output fails to identify the level of temporal variation and, therefore, results in a lack of proper design emphasis on such temporal variations.

OUTPUT VARIATIONS

Airports experience short- and long-term variations in output. The level of analysis we use does not consider the daily fluctutations, but rather focuses on those fluctuations to which the airport can adjust in an investment sense. Using the data for the period 1968 to 1972, we made an analysis of the growth fluctuations for the major British airports. The statistics derived were

1. Annual growth rates for passengers and movements, both scheduled and nonscheduled;
2. An average growth rate for the 5-year period (r);
3. The standard deviation of the average growth

rate ($\sigma_{\bar{r}}$), which is a measure of the variability of the growth rate from year to year (if we assume that forward planning is a question of estimating future trends, then this variability measure may also be used to connote predictability).

Table 3 gives growth rates and their variability for the selected airports. Using nonparametric statistical tests, we found no statistical evidence of a relation between variability and growth rate. However, there is evidence of a relation between variability in growth and operation type. As nonscheduled activity increases, variation in growth rate increases and predictability is consequently weakened. This phenomenon adds weight to the concept of a functional airport typology based on traffic type. The data would tend to support the assertion that airports with a high level of nonscheduled activity have less predictable growth rates than those where scheduled activity predominates.

We also examined short-term seasonal variations during the year. Traffic varies seasonally at all airports. High seasonal peaks may lead to congestion and, conversely, very low troughs may mean underutilization of equipment and buildings for a considerable portion of the year. The levels of seasonal variations differ greatly, depending on the nature of the airport. To make a comparative analysis of seasonal variation across the selected airports, a seasonality activity index (S_i) was computed:

$$S_i = 100/\sigma_{\overline{OD}} \times (OD_i - \overline{OD}_i) \qquad (1)$$

and

$$\overline{OD}_i = {}^1\!/_{12} \sum_{i-5}^{i+5} OD_i + {}^1\!/_2(OD_{i-6} + OD_{i+6}) \qquad (2)$$

where

OD_i = original output data, month i,
$\overline{OD}_i$ = moving mean, centered on i, the trend value, and
$\sigma_{\overline{OD}}$ = standard deviation of the mean $\overline{OD}_i$.

Seasonal profiles were constructed for the 4 years for which data were available. Although seasonal charter traffic is subject to wide variation, charter traffic for most passenger airports is only a small proportion of the total traffic. Consequently, a measure of overall seasonality can be calculated for passengers and for movements without any further differentiation. The annual measure is constructed by averaging the 12 monthly seasonal indexes. Thus, for the jth airport the annual average seasonality (Y_j) is given as

$$Y_j = \sum_{i=\text{July}}^{i=\text{June}} S_{ij} \qquad (3)$$

Examples of the form of the season profiles, by type of output measure, are shown for Manchester Airport in Figures 4 through 7. Table 4 presents the summary seasonal data for all airports. Also computed was an average of the values of Y_j over the 4-year period for which data were available. This was designated as the total seasonality index (TSI_j):

$$TSI_j = \sum_{1968}^{1972} Y_j/4 \qquad (4)$$

In view of the smallness of the denominator in this equation, we computed an index of variability of seasonality (IVS) without using the standard deviation. This was defined in the following manner:

$$IVS_j = \sum_{\text{July}}^{\text{June}} MD_{ij}/12 \qquad (5)$$

$$MD_{ij} = S_{ij}\text{max} - S_{ij}\text{min} \quad \text{for i = July, . . . , June.} \qquad (6)$$

Table 5 indicates the values of the computed indexes for the selected airports.

After computing a number of indexes that express the seasonality of airport operation and the variability of these operations, we subjected these indexes and the data on operational output to multivariate analysis to determine the principal factors underlying the operational performance. The results are displayed in Table 6 and Table 7, which show the results of correlation and factor analyses. The variables in the two tables are as follows:

Variable	Notation
Seasonal index	
Movements	V_1
Passengers	V_2
Growth variability	
Movements	V_3
Passengers	V_4
1970	
Movements	V_5
Passengers	V_6
Seasonal variability	
Movements	V_7
Passengers	V_8
Nonscheduled activity	
Movements	V_9
Passengers	V_{10}
1970 surplus	V_{11}
1968-1972 capital expenditure	V_{12}

The factor analysis indicates that there is little correspondence between seasonality and the usual output variables. Rather, there is a stronger correlation between seasonality and airport activity type, as indicated in Table 6. This would tend to strengthen the argument for a scheduled versus nonscheduled activity typology.

The eigenvalues of the factors given in Table 7 are as follows:

		Variance Explained	
Factor	Eigenvalue	Percent	Cumulative Percent
F_1^1	6.93	57.7	57.7
F_2^1	3.23	26.9	84.6
F_3^1	0.73	6.1	90.7
F_4^1	0.42	3.5	94.2
F_5^1	0.38	3.2	97.4

Variability is analyzed in terms of its peaks in any one month and the stability of the peak from year to year. Figure 4 and Tables 3 and 4 permit the reader to comprehend the relation between graphical form and summary statistics. With respect to the analysis of variability the study found that

1. Nonscheduled passenger activity has higher seasonality indexes than any other activity, and scheduled movements have the lowest seasonality indexes;
2. Movements are slightly less seasonally affected than passenger activity, probably a reflection of the variation in load factors common to most routes;

3. Nonscheduled output is more seasonally affected than scheduled output; and
4. Based on limited evidence, activity, in general, shows fewer seasonal variations over time as it grows.

As noted, output variability is an important, but a complicating, factor in airport management and in forward planning. Therefore, establishing relations among output, variability, predictability, and financial performance is worthwhile. The factor structure given in Table 7 shows five orthogonal factors associated with the data. These are output, variability in output, seasonality, variability in seasonality, and variability in growth.

The first factor accounts for just under 60 percent of the total variance in the correlation matrix of Table 6. The factor of size of operation is further exemplified by

Figure 4. Seasonal variation of scheduled passengers at Manchester Airport.

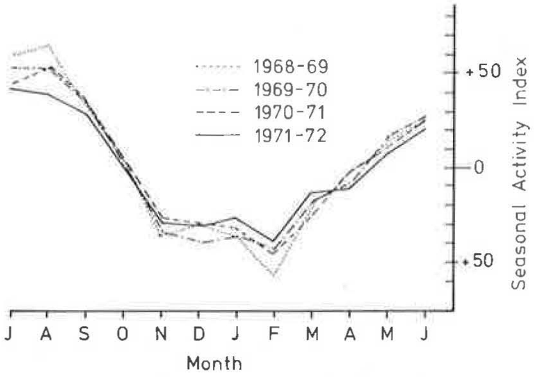


Figure 5. Seasonal variation of scheduled air transport movements at Manchester Airport.

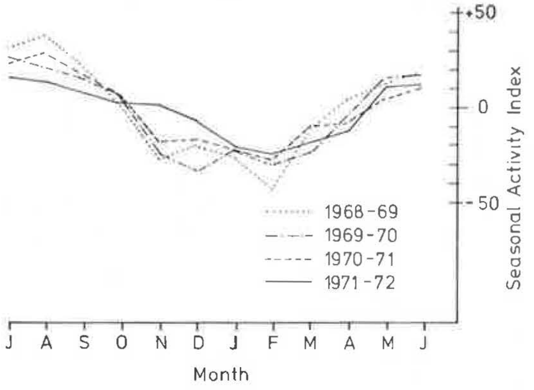


Figure 6. Seasonal variation of nonscheduled passengers at Manchester Airport.

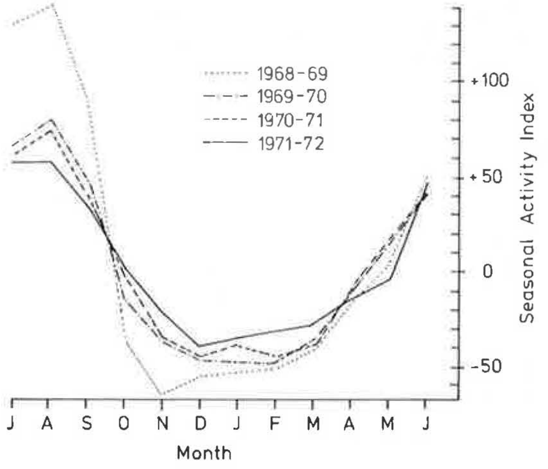


Figure 7. Seasonal variation of nonscheduled movements at Manchester Airport.

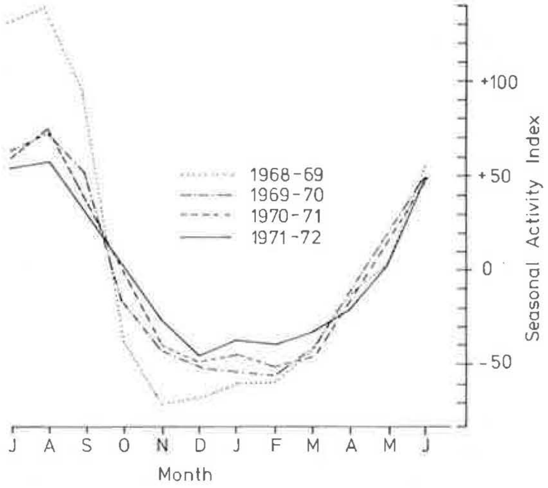


Table 4. Seasonality measures for scheduled and nonscheduled operations.

	Scheduled		Nonscheduled	
Airport	Movements	Passengers	Movements	Passengers
Belfast	13.01	24.64	88.02	126.95
Birmingham	21.36	32.32	60.87	66.07
Blackpool	65.75	79.47	63.72	129.10
Bristol	44.33	61.08	67.35	68.76
Edinburgh	20.08	27.49	80.02	86.54
East Midlands	31.55	56.46	62.59	67.97
Gatwick (London)	18.27	30.89	54.00	61.98
Glasgow	15.07	19.46	54.05	98.35
Heathrow (London)	14.94	25.48	46.69	54.57
Isle of Man	56.45	74.89	109.12	112.15
Leeds-Bradford	32.87	46.08	24.58	57.17
Liverpool	12.04	30.01	35.68	81.63
Luton	70.63	82.11	52.76	57.96
Manchester	13.91	23.75	61.32	72.05
Prestwick	23.42	58.90	76.45	102.51
Southend	36.70	60.37	30.31	61.77
Stansted	130.16	143.46	57.92	75.05
Teeside	33.41	48.46	77.33	85.00

Table 5. Total seasonality and variability indexes.

	Seasonality		Variability	
Airport	Movements	Passengers	Movements	Passengers
Belfast	14.94	27.09	7.28	7.92
Birmingham	26.56	40.28	11.07	17.82
Blackpool	61.87	73.48	16.31	15.73
Bristol	44.97	54.25	24.45	39.47
Edinburgh	20.77	28.36	14.02	13.41
East Midlands	34.98	57.76	15.87	15.15
Gatwick (London)	39.24	55.01	19.94	24.91
Glasgow	18.22	26.68	12.99	14.84
Heathrow (London)	15.64	26.44	6.24	6.09
Isle of Man	56.37	74.66	11.17	13.24
Leeds-Bradford	30.41	45.68	20.40	17.44
Liverpool	14.35	35.31	8.07	9.62
Luton	51.92	57.91	25.93	29.76
Manchester	22.50	39.61	10.12	13.22
Prestwick	28.73	71.55	21.73	42.37
Southend	34.00	59.66	19.68	26.02
Stansted	60.42	76.36	41.83	45.13
Teeside	38.52	56.72	25.79	27.19

Table 6. Correlations among variables of output, seasonality, and growth.

Variable	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}
V_1	1.00											
V_2	0.86	1.00										
V_3	0.68	0.62	1.00									
V_4	0.67	0.66	0.78	1.00								
V_5	-0.34	-0.41	-0.37	-0.23	1.00							
V_6	-0.29	-0.38	-0.33	-0.19	1.00	1.00						
V_7	0.78	0.76	0.83	0.87	-0.38	-0.34	1.00					
V_8	0.62	0.79	0.64	0.80	-0.36	-0.33	0.89	1.00				
V_9	0.66	0.51	0.68	0.86	-0.17	-0.11	0.79	0.68	1.00			
V_{10}	0.62	0.55	0.64	0.79	0.17	-0.11	0.75	0.74	0.95	1.00		
V_{11}	-0.34	-0.40	-0.33	-0.22	0.99	0.98	-0.38	-0.38	-0.20	-0.22	1.00	
V_{12}	-0.20	-0.26	-0.22	-0.13	0.96	0.96	-0.26	-0.27	-0.15	-0.16	0.97	1.00

Table 7. Factor analysis of output, seasonality, and growth.

	Principal Components		Rotated Factors				
Variable	C_1	C_2	F_1^1	F_2^1	F_3^1	F_4^1	F_5^1
V_1	0.807	-0.220	-0.160	0.434	0.846	0.032	0.207
V_2	0.817	-0.125	-0.223	0.280	0.811	0.396	0.153
V_3	0.813	-0.215	-0.187	0.480	0.327	0.151	0.776
V_4	0.835	-0.404	-0.064	0.719	0.309	0.299	0.322
V_5	-0.636	-0.769	0.973	-0.055	-0.154	-0.082	-0.181
V_6	-0.591	-0.803	0.979	0.002	-0.126	-0.099	-0.112
V_7	0.918	-0.261	-0.199	0.590	0.429	0.436	0.382
V_8	0.857	-0.219	-0.203	0.539	0.352	0.719	0.157
V_9	0.785	-0.434	-0.052	0.947	0.228	0.075	0.168
V_{10}	0.777	-0.420	-0.056	0.935	0.227	0.188	0.109
V_{11}	-0.640	-0.759	0.974	-0.110	-0.145	-0.087	-0.048
V_{12}	-0.538	-0.812	0.987	-0.106	-0.010	-0.013	0.020

the close correlations between (a) capital expenditure and fixed assets at the end of the study period, (b) surplus and passengers (r = 0.984), (c) surplus and movements (r = 0.991), (d) investment and movements (r = 0.963), and (e) investment and passengers (r = 0.965).

The second factor firmly links nonscheduled activity with variability in growth. The period of 1968 to 1972 saw considerable growth in charter activity for British airports. Exceptions to the rule that nonscheduled activity is unpredictable are airports that specialize in charter traffic. The main traffic at these airports showed less growth variability, even though it was charter. The third, fourth, and fifth factors are of limited explanatory value. None of these factors contributed more than 6 percent to the variation of the correlation matrix.

CONCLUSIONS

The paper emphasizes the importance of an appropriate scale for measuring output for airport system modeling. Only after airport type has been considered is a discussion of the problems of estimating parameters of the model appropriate. Any good model structure must parallel reality in its important facets; therefore, a model must be dynamic in nature (18). Feedback, therefore, has been considered and included. Feedback assumes crucial importance in the area of policy formulation.

Investment must be considered the most important decision affecting airport systems. This is due not only to the degree to which it can affect the supply of physical plant, but also to the scale of investment itself, which for airports is substantial. Moreover, new construction in runway additions, terminal extensions, or even new airports, all increase the supply potential of a national airport system and cannot, therefore, be considered peripheral and marginal to it. Mistimed and ill-directed investment may be worse than no investment at all.

Clearly, new investment should be considered only against a background of growing demand and future revenue increases. Demand and revenue, in turn, require an appreciation of the differences between airports and the likely inherent variations in growth rates. The study pointed out where growth variability is likely and where seasonal influences can be expected to be of maximum importance and presented problems of congestion or underutilization.

In summary, the paper indicates that airports differ greatly in function. Planners must recognize a typology or taxonomy of airport types according to function.

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Development and Application of an Airfield Simulation Model

S. L. M. Hockaday and D. Maddison, Peat, Marwick, Mitchell and Company

Many major airports experience aircraft delays caused by increasing aviation activity and decreasing airfield capacity. But the traditional solution to the problem—building new airports or expanding existing ones—is often infeasible because of environmental, financial, or institutional constraints. Instead, managing demand or improving operational efficiency seems to offer the best opportunities for relieving airport congestion. We discuss the quantitative techniques available for evaluating the merits of managing demand or improving operational efficiency and then describe our preferred technique—an airfield simulation model. An airfield simulation model requires a large data base, but its output can be selected and tailored to individual situations. It can be used to investigate different elements of the airfield and to provide the finest level of detail for short-term planning and summary outputs for analyzing longer term problems.

The air transportation industry experienced rapid growth during the 1960s, partly because jet aircraft (with increased speed and seating capacity) replaced propeller aircraft in the airline fleet. By the summer of 1968, the air transportation system was severely congested; very large delays became an everyday occurrence at some major hub airports.

Aircraft delays dropped considerably in the early 1970s because an economic downturn reduced traffic growth to less than half of previous predictions, the introduction of wide-bodied aircraft increased passenger capacity, and the Federal Aviation Administration (FAA) introduced an hourly aircraft movement quota at five of the nation's busiest airports (Chicago O'Hare, John F. Kennedy, LaGuardia, Newark, and Washington National). In late 1973, a severe fuel shortage further reduced aircraft traffic.

Aviation activity has increased since then. At some airports, traffic is now at record high levels and delays are once again on the upswing. Increased delay stems from increased aviation activity and reduced airfield capacity. New air traffic control rules, implemented to ensure safety for aircraft flying behind or below heavy jets that produce significant wake turbulence, have reduced airfield capacity.

Past response to increasing congestion was construction of new airports and major expansion of existing ones. But current environmental, financial, and institutional constraints reduce the feasibility of this approach at most major airports. The current situation indicates that severe airport congestion may occur in the near future. Managing aviation demand and implementing operational, procedural, or minor physical improvements offer some of the best opportunities for relieving airport congestion.

Quantitative techniques are needed for measuring aircraft performance on the airfield under different situations. These measures of performance can be used to analyze the operational feasibility of various improvement options and can also be used as inputs to economic analysis. Analytical and simulation models for estimating airfield capacity, delay, and travel times have been developed to assist in these analyses. These models are being utilized increasingly at major airports to help in decision making on airfield improvements. This paper discusses the different types of models available and describes an airfield simulation model developed by Peat, Marwick, Mitchell and Company and its application at several major airports.

MODELS OF AIRCRAFT PERFORMANCE ON THE AIRFIELD

A number of different models of aircraft performance, which are oriented to different objectives, are available. For example, Peat, Marwick, Mitchell and Company has a series of models that estimate airfield and airspace capacity, aircraft delays and travel times, controller workload, collision risk, noise exposure, and air pollution. Our discussion is restricted to models that measure aircraft delays and travel times.

Aircraft delay is the difference between the actual time it takes an aircraft to operate on an airfield and the time it would take to operate without interference from other aircraft on the airfield. Thus, delay is defined in terms of a difference in travel times or by an amount of waiting time. Two principal types of models may be used to compute airfield delays—analytical models and simulation models.

An analytical model is a set of mathematical equations that provide a specific output based on assumed relations of system parameters. These equations are often so complex that computers are used to perform the calculations. An advantage of analytical models is that they usually require considerably fewer person-hours to design and program and considerably less computer time than do simulation models. On the other hand, there are significant limitations in applying analytical models to the entire airfield system; mathematically describing the complex interactions of airfield components (runways, taxiways, and gates) is difficult.

An airfield simulation model is a series of logical statements that describe the movement of individual aircraft or groups of aircraft through the components of the airfield. The logical statements allow simulated aircraft movements to occur for a defined time period. Appropriate output parameters are measured in a fashion similar to the way that they would be measured in the real world.

Simulation permits detailed analysis of individual components or of the total airfield and related airspace. The validity of an airfield simulation model depends on properly identifying and selecting parameters that are significant in the operation of the airfield. The accuracy with which the relations of significant parameters are incorporated in the model also influences its validity. As the number of parameters selected for consideration and the accuracy of their representation increase, so does the validity of the model. However, complexity, development time, and computer cost usually increase concurrently. Theoretically, an unlimited complexity of situations can be simulated, or accuracy achieved, but cost considerations usually dictate the degree of sophistication reached. Therefore, in developing a model, we must examine the trade-off in terms of the required accuracy of the model output as well as the accuracy and availability of input data. An experienced model maker can produce sufficiently accurate results at minimum costs.

The flexibility of simulation techniques allows us to produce a wide variety of delay-related information for any particular application of an airfield simulation model. For example, in addition to the normally required flow rate and average aircraft delay information, data can be obtained on the distributions of aircraft delays, queue lengths, and travel times and the location of congested areas. This information can be stratified even further by airline, aircraft type, air or ground, and arrival or departure delays.

SIMULATION MODEL OVERVIEW

Over the past 7 years, Peat, Marwick, Mitchell and Company has developed, refined, and applied an airfield simulation model, which is illustrated in Figure 1. Our model is a critical events model that employs Monte Carlo sampling techniques. The model contains a set of logical statements that encompass the significant movements performed by aircraft on the airfield and adjacent airspace. The modular structure of the model permits analysis of the total airfield or its individual components by simply manipulating model inputs. This approach is more flexible and efficient than one having separate submodels for the individual components and a composite model for the total airfield. Using submodels precludes analysis of the total airfield when events at one location on the airfield affect operations at another location. For example, if demand is such that excessive departure queues build up, certain airports will instigate gate hold procedures. Under such conditions, a model must consider the total airfield.

The model operates by tracing the path of each aircraft through space and time on the airfield and adjacent airspace. The airfield and airspace are represented by a series of links and nodes depicting the paths that an aircraft could follow. The traces of the paths of all aircraft are made by continually advancing clock time and recording the new location of the aircraft. The model then processes the records of aircraft movement to produce desired outputs, including delays and flow rates.

Certain model parameters are stochastic (time variant and random) in nature. Use of Monte Carlo sampling techniques allows the model to simulate the daily variations encountered in real life. For example, arrival aircraft approach speeds will vary from day to day for any given aircraft, depending on such factors as payload, wind, and temperature. Analysis shows that the normal distribution approximates the distribution of these variations. Hence, the model assigns arrival aircraft approach speeds by sampling values from a normal distribution with mean and standard deviation specified by the user. Below are other stochastic model parameters:

1. Arrival to arrival separations,
2. Departure to arrival separations,
3. Arrival to departure separations,
4. Departure to departure separations,
5. Arrival runway occupancy time,
6. Touch-and-go runway occupancy time,
7. Departure runway occupancy time,
8. Exit taxiway choice,
9. Gate service time, and
10. Arrival aircraft deviation from schedule.

Variable time increments are used as the time flow mechanism (i.e., clock time is advanced by the amount necessary to cause the next event to take place). Therefore, running time for the model depends on the levels of aircraft demand and the size of the airfield for any particular application. As an example, a 3-h simulation of 70 aircraft operations/h at an airport similar in complexity and size to LaGuardia Airport, using 10 random number seeds, took some 18 s on a CDC CYBER 70/model 76 computer. The cost of the run is approximately $18.

The model's source code is written in FORTRAN IV and contains approximately 4700 lines of FORTRAN-coded statements. The model program consists of a main program and 31 subroutines and requires the equivalent of the following core storage on a CDC CYBER 70/Model 76 computer: (a) small core memory= 73 000_8 words and (b) large core memory=375 000_8 words. The large core memory is for data storage. The program can be exercised on most commercially available large core computers in batch or time-sharing modes.

The airfield simulation model was developed to be applicable to the existing range of airfield configurations and to those configurations that are likely to evolve. Consequently, the model does not contain any specific airport or aircraft data; all data are input. Thus, the model may be applied directly to airfields ranging from a nontower general aviation field to a complex international airport.

A short form of the model can be applied when only analysis of a component of the airfield is required. For example, the model may be used to evaluate the impact of increased demand on runway and terminal airspace delays. In this case, a set of runway delay values corresponding to various demand levels must be developed. These delays may be obtained from the model by minor adjustments to the input data that, in effect, suppress aircraft movements on the taxiways and gates, such as locating dummy gates at each exit from the runways. This very simple modification to model inputs has the effect of producing only the desired delay information and significantly reducing model running time.

Manipulating input data in this manner contributes to the efficient use of the model. Similar efficiencies are attained by using preprocessor models to develop demand and routing data and postprocessor models to reduce detailed output to a form suitable for review by management and nontechnical personnel.

By manipulating the input data we can also simulate the occurrence of unusual events. For example, the impact of a disabled aircraft on the runway can be simulated by specifying that the runway use be changed in the middle of the model run. A simulation of the effect of a change in weather conditions is another example. The effects may be simulated by changing aircraft separations, runway uses, and aircraft operating characteristics in the middle of the simulation model run.

MODEL INPUTS AND OUTPUTS

Inputs to the model relate primarily to the physical characteristics of the airfield, such as the airfield network shown in Figure 2, and operational characteristics of the aircraft, such as runway occupancy times. Full details of model inputs and format requirements, together with guides for preparing inputs (including the use of preprocessor models), are contained in a model user manual.

The primary outputs from the model are aircraft delays, travel times, and flow rates. Additional available data include the location of aircraft delays and departure queuing statistics. Recognizing that different model applications have varying requirements in terms of output detail, we have designed the model so that outputs are obtained in either summary or detailed format. Because of the voluminous nature of the detailed output, postprocessor models are available to produce a statistical analysis of the data. For example, delays may be classified by airline, aircraft type, and location on the airfield. In addition, distributions of delays and queuing information may be obtained for varying time periods. An example of postprocessor model output is illustrated in Figure 3.

Figure 1. Airfield simulation model.

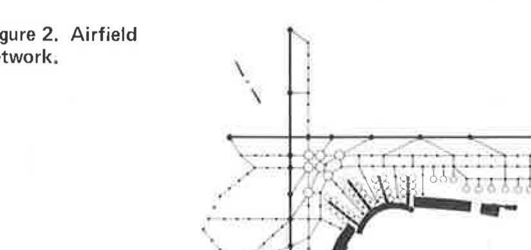


Figure 2. Airfield network.

Presenting model outputs in this format helps management and nontechnical personnel understand the full capabilities of the model and interpret the results of model runs.

MODEL VALIDATION

Validation compares the values of model outputs with values of the same information observed in the real world. Model inputs used in the validation process should reflect the operating conditions observed in the real world at the time output parameters are measured. Under these circumstances, validation occurs when model outputs and observed values agree within the required accuracy limits.

The Peat, Marwick, Mitchell and Company airfield simulation model was validated at various stages of its development to establish that the model is correct in code and logic and able to reliably represent the real-world system modeled. A rigorous validation was performed under an FAA contract requiring the validation of a generalized model to satisfy the following criteria.

1. Validation must be conducted at airports other than those used for simulation model development.
2. A cross section of airports and airport operating conditions must be included in the validation.
3. Model outputs must compare with observed data within specified tolerances.

To validate the model, field data were collected at three high-density airports over a period of several weeks. The three airports were Chicago O'Hare International Airport, Dallas Love Field, and Orange County (California) Airport. At the time of validation, Dallas Love Field was the principal air carrier airport in the region. Since then, the majority of air carrier operations has been transferred to the new Dallas-Fort Worth Airport.

These airports differ from the airport used in developing the simulation model (San Francisco International Airport) and were selected primarily because we wanted to validate the model at high levels of operations and for a representative range of conditions, including

1. Runway use,
2. Weather,
3. Aircraft mix,
4. Types of navigation aids,
5. Exit taxiway configurations,
6. Runway length, and
7. Airspace usage.

The three airports represent a cross section of the above conditions at some of the nation's busiest airports. We collected extensive data on actual aircraft operations and travel times at each of the airports. The data were used as measures of observed values for comparison with the outputs of simulation runs. Results of the validation, shown in Figure 4, indicate that simulation model outputs were within 10 percent of actual field observations 90 percent of the time. Further details of the validation are available and documented.

No published or regularly collected delay data exist that precisely match the definition of model outputs for use in validating a simulation model in any rigorous

Figure 3. Graphical postprocessor output.

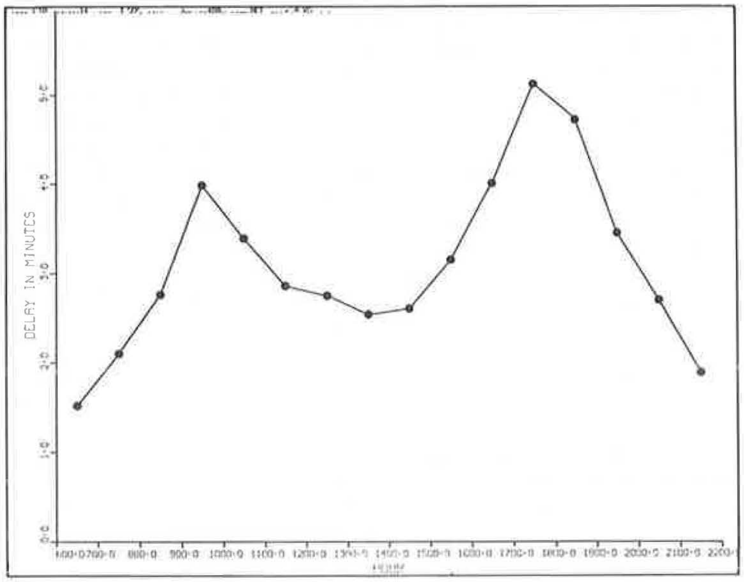


Figure 4. Simulation model validation results.

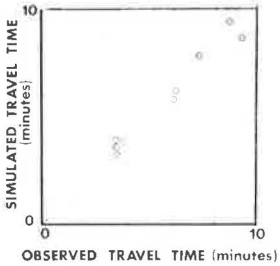
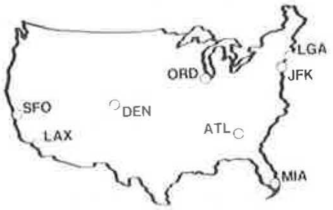


Figure 5. Task force airports.



sense. For this reason, FAA invested considerable resources in collecting needed data for simulation model validation.

Observed field data are the most reliable, meaningful data to use in a rigorous validation exercise. Other sources of delay data contain inconsistencies and biases that limit their use to general comparisons. For example, the use of airline-reported delay data would be insufficient for a rigorous validation because of the absence of uniform airline delay reporting procedures and controls.

MODEL APPLICATION

The model was applied successfully at several large hub airports to study a variety of problems. At San Francisco International Airport the model was applied as part of an evaluation of two alternative terminal building configurations. The first configuration had 90 gates located around banjo-head pier fingers; the second configuration had a similar number of gates located on straight pier fingers. The simulation model output showed that aircraft experienced more delays when operating from the banjo-head configuration, as opposed to the straight configuration, because of push backs into a busy peripheral apron taxiway. The results played an important role in the incorporation of the straight pier finger configuration in the airport master plan.

At Los Angeles International Airport the model was applied to the existing airfield configuration to validate the model and establish a set of baseline delays and travel times for the department of airports. Further applications evaluated (a) changes in operational procedures (e.g., runway use patterns for noise abatement) and (b) near-term terminal building expansions (e.g., above-ground concourses to connect satellites with ticketing buildings).

The short form of the model was applied at Chicago O'Hare International Airport to provide aircraft delay information as part of a Wake Vortex Avoidance System (WVAS) cost/benefit analysis. Model runs were made with inputs that reflected a variety of assumptions about aircraft separations due to wake turbulence. We used delay values from each of the runs in a cost/benefit analysis of WVAS.

The model is currently being applied in support of the FAA Airport Improvement Task Force at the eight major U.S. airports identified in Figure 5. Specifically, the model is being applied to (a) determine current airfield delays, (b) identify site-specific causes of aircraft delays as they exist today in the terminal airspace and on the airfield, and (c) quantify delay reduction benefits of alternate improvements options (e.g., changes in air traffic control procedures) for immediate, short-term, and long-term implementation.

CONCLUSIONS

The airfield simulation model is useful for investigating the details of airfield operations and for measuring aircraft performance on the airfield. Airfield simulation is most useful at large airports where airfield congestion is a significant problem. Airfield simulation can be used to investigate different elements of the airfield, including runways, taxiways, and apron-gate areas and can reflect the influence of environmental or airspace constraints on airfield operation. The model can provide the greatest levels of details, which are useful in short-term planning for operational improvements or demand management, and can provide summary outputs, which are more appropriate in looking at longer term considerations such as implementation of FAA engineering and development program products.

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Capacity of Terminal Airspace Sectors

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Current air traffic control facilities in terminals that operate with automated radar terminal system III equipment require controllers to (a) monitor displays of radar-derived situation data; (b) make decisions; (c) voice communicate with pilots to transmit clearances, maneuver instructions, proximate traffic, and navigational advisories; (d) communicate with other controllers to coordinate their control actions; and (e) maintain computerized and hard-copy data records describing aircraft flights. The time spent performing these activities depends on local traffic routing characteristics and related procedural control requirements, including visual versus instrument airport approach operations. The work-load models differentiate the work activity characteristics of various airspace sectors and quantify traffic capacity (aircraft per hour) according to the number of persons assigned to a sector control team. The modeling approach demonstrated uses field data collected at the Oakland Bay Terminal radar approach control facility. Traffic capacities are calculated for various sector operational alternatives that represent current and proposed automated control systems.

Various Federal Aviation Administration-sponsored studies examined the potential impact of automation on air traffic control operations (1, 2, 3, 4). Techniques were developed that relate the traffic-handling capabilities of air traffic controllers to their operational work requirements. This paper describes the methodology used to model terminal airspace capacity corresponding to controller work-load constraints. Specifically, I examine the airspace under the jurisdiction of high-density terminal radar approach control (TRACON) facilities that currently are operating with automated radar terminal system (ARTS) III equipment.

The methodology uses field observations to define operational requirements of TRACON facilities and identify the control work activities associated with the current ARTS III equipment. The field data are used to structure and apply mathematical descriptions of control work requirements, which are adjusted to represent postulated future air traffic control automations.

OPERATING CHARACTERISTICS OF TRACON FACILITIES

This paper addresses the traffic capacity aspects of TRACON operations, as distinguished from airport traffic control tower and air route traffic control center operations. The TRACON-controlled terminal airspace is a transition zone between airports and en route airspace, which is divided into volumes of airspace, called sectors. Each sector is under the jurisdiction of a controller or team of controllers, who maintain radio contact with and radar surveillance of aircraft in the sector's airspace. Sectors are configured according to a system of airport arrival and departure routes; the control operations for each sector are procedurally structured and integrated to facilitate traffic flow and separation assurance.

The terminal area route structure is designed to segregate the major arrival traffic flows from departure traffic flows. This minimizes conflicts between descending and climbing aircraft, which could become frequent and difficult to control in dense traffic situations. Route segregation is achieved procedurally by means of formal altitude separation (tunneling one route under another) and geographic separation (defining arrival and departure corridors). In some terminal areas, especially those serving numerous airports, the complexity of the required route network and airspace constraints preclude the complete segregation of arrival and departure traffic. The degree of procedural segregation achievable, however, is normally sufficient to arrange sectors along predominant inbound and outbound routings.

Arrival Operations

Arrival traffic flows from diverse directions are integrated by means of a series of merges. The merging operations require arrival sector controllers to determine the sequence for processing aircraft through the merge points while maintaining proper spacing. The controller is guided by a system of procedural specifications. The center conducts initial route mergings in order to organize the traffic according to control specifications required for entry to the terminal airspace. By this means, aircraft are brought into TRACON arrival sectors along defined routes according to prespecified or negotiated in-trail separations and often according to specified altitude and speed restrictions. Arrival sector controllers process the aircraft through a succession of fewer and fewer merge points until the traffic is funneled to airport final approaches. Control jurisdiction is then transferred to the tower, in accordance with the appropriate in-trail separation, speed, and altitude specifications. Radio communications are necessary for issuing speed, altitude, and vectoring commands to slow all descending aircraft to approach speed, clear them along their planned routes, sequence them through the merges, and space them to maintain separation.

At some TRACON facilities, such as at Oakland Bay, which controls traffic into San Francisco International Airport (Figure 1), arrival operations are based on the feeder and final sector concept. Under this concept, a feeder sector's controller accepts aircraft entering from a center, processes the aircraft through its airspace, and transfers control jurisdiction to a final sector's controllers. The latter continue controlling the aircraft until the aircraft approach airport runways, when control jurisdiction is transferred to a tower. In this operation, a feeder sector's controllers establish the arrival traffic organization plan, since they determine the sequence in which aircraft are cleared for landing.

At other TRACON facilities, such as at Los Angeles, operations in a designated arrival sector are not delineated according to feeder and final sector pairs. However, either design concept may be used to handle traffic in separate or parallel routing corridors. For example, one feeder and final pair or one arrival sector may control aircraft destined for a specific runway or runway complex of an airport, while an identical sector operation may control aircraft destined for other runways. At some TRACON facilities, such as both Oakland Bay and Los Angeles, two traffic corridors converge to final approaches to parallel runways. Here, a feeder and final pair or an arrival sector may operate relatively independently of its complementary sectors, especially during visual approach conditions. However, if the runway configuration design is such that aircraft on the parallel approach courses are in lateral proximity, special precautions must be taken to ensure adequate aircraft separation during instrument approaches (where poor visibility precludes the pilot's separation assistance). Each final feeder or arrival sector's controllers must coordinate their sequencing and spacing operations with those of the parallel sector to integrate their traffic for airport approach.

In summary, arrival sector operations depend on the traffic requirements of each TRACON site. Controllers handle local merging operations for aircraft directly under their control and also influence merging situations in downstream sectors. During instrument landing operations, controllers coordinate approach mergings with other controllers. Such coordination may be unnecessary during visual approach operations. Additionally, controllers must maintain separation assurance for aircraft that are potentially in conflicting situations while at the same time facilitating the flight of aircraft in accordance with pilot plans and procedural requirements.

Departure Operations

Departure sector operations differ from those of arrival sectors only in that (a) aircraft are usually diverging rather than merging and (b) control requirements do not depend on visual versus instrument approaches. Departure sector controllers accept climbing aircraft from an airport tower, process the aircraft through their airspaces, and transfer control jurisdiction to a center when the aircraft enter en route airspace. Some local merging may occur in order to integrate takeoffs from other runways or airports. Although parallel departure sectors may be designated (as at the Oakland Bay TRACON site), departure routings are usually sufficiently separated so that extensive coordination between controllers of different departure sectors is unnecessary.

ARTS III OPERATIONS

ARTS III is a semiautomated terminal air traffic control support system composed of a computerized data acquisition subsystem, data processing subsystem, and data entry and display subsystem. ARTS III equipment design affects the control actions performed and the allocation of work duties among a controller team.

ARTS III supports control operations through (a) the presentation of alphanumeric data on sector controllers' radar displays, (b) the semiautomatic transfer of data between sectors, and (c) the automatic transfer of flight data between the terminal and center computers. Each sector teams's operating console contains the ARTS III automation devices.

An ARTS III console includes a plan view display (PVD) and keyboard and track-ball units that jointly provide a data entry and display interface between the controllers and the computer system. The PVD is the sector team's primary display device and presents radar-derived aircraft situation and computer-processed alphanumeric and symbolic data. The presentation includes

1. Primary radar targets,
2. Beacon targets,
3. Control position symbols,
4. Aircraft data blocks (from beacon targets only),
5. Video maps,
6. Tabular lists (arrival-departure and coast-suspend lists),

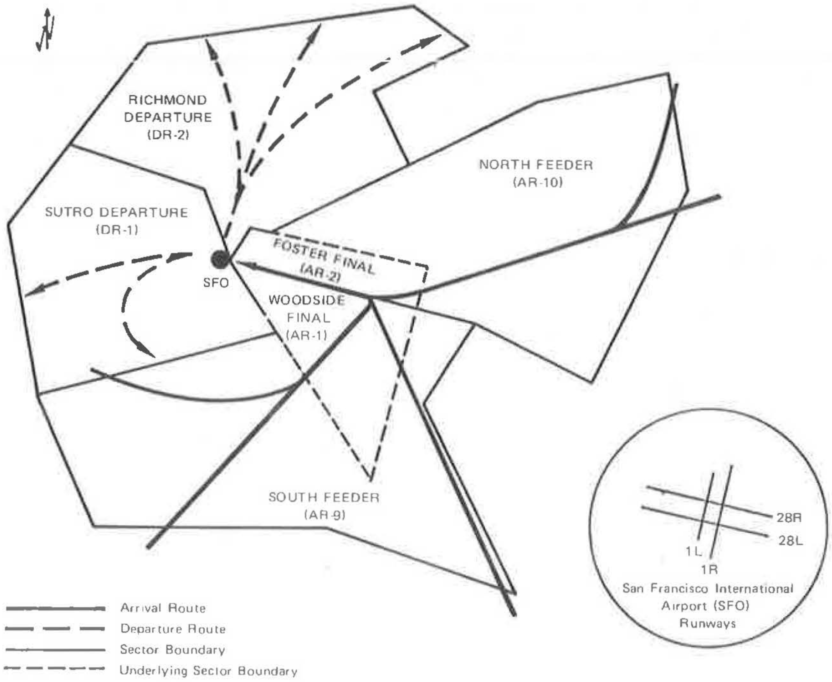

Figure 1. Primary arrival and departure routes for Oakland Bay TRACON.

7. Time,
8. Altimeter setting,
9. Selected beacon codes, and
10. General system information (e.g., weather).

A track-ball and keyboard unit operates in conjunction with the PVD to provide the controller-computer interface mechanisms for data entry and display control. The unit includes a track-ball panel, alphanumeric keys, and quick action, special function keys. The track ball is used manually to slue and capture PVD targets; manual keypunching is used to access the computerized operation. These capabilities enable controllers to select and revise data presented on the PVD, enter flight data, and carry out special control operations (e.g., transfer control jurisdiction and manually initiate or drop beacon tracking).

In addition to the ARTS III automation, the sector console includes air to ground (A/G) radio and interphone communication apparatus and work space needed to maintain flight strip or paper scratch pad data records. A/G communications enable two-way voice conversation between pilot and controller; interphone communications enable two-way voice conversation between controllers of different sectors or facilities. Hard copy records provide flight data to supplement PVD-displayed data and are updated by hand.

Sector Control Responsibilities

The lead member of an ARTS III sector team is the radar controller, who is responsible for separation assurance, minute-to-minute decision making, and A/G voice communications. The radar controller may be supported by a coordinator, a hand-off controller, or both. During periods of light traffic, the radar controller may be the only controller in the sector and performs all necessary communications and related data processing activities. As traffic increases, the radar controller's work-load requirements become restrictive, necessitating the allocation of some operational activities to one or both of the other team members.

A single hand-off controller may be assigned to assist a radar controller, but a coordinator is assigned to a pair of sectors and simultaneously supports both radar controllers. As a result of the shared nature of coordinators' services, there are four sector team regimes:

1. A 1-person team (radar controller);
2. A 1.5-person team (radar controller and 0.5 coordinator);
3. A 2-person team (radar and hand-off controllers); or
4. A 2.5-person team (radar and hand-off controllers and 0.5 coordinator).

The ARTS III console is organized so that each controller and coordinator is equipped with keyboard and interphone apparatus and the radar controller has direct access to a single PVD and track-ball panel. Each radar controller is equipped with A/G apparatus and all sector team members may handle flight strips or paper scratch pads, depending on local operating procedures. The equipment arrangements enable the effective division of control responsibility among sector team members.

Roles of Sector Control Members

In a one-person team the radar controller performs all of the sector control operations necessary to ensure separation and facilitate traffic flow. These operations include PVD surveillance, A/G communications, data entry and display, flight strip or paper scratch pad data processing, intersector interphone and face-to-face coordination, and related decision making.

In a 1.5-person team the radar controller maintains responsibility for ensuring separation and minute-to-minute decision making, but shares traffic planning decision making with the coordinator. The coordinator performs intersector coordination and some data entry operations, while the radar controller performs separation assurance, surveillance, and related data processing operations. Based on observed control activities, the coordinator is usually able to perform the interphone communications for both sectors he or she is supporting and half of the computerized hand offs for each sector. However, these activities induce some additional face-to-face communications with the radar controller because he or she must advise the radar controller about the completed intersector negotiations. A coordinator supports a pair of arrival sectors, determines the sequence for merging aircraft, and advises each radar controller of his or her plan. Each radar controller sets up traffic in accordance with the coordinator's plan. A coordinator supporting a pair of departure sectors integrates tower departure operations with those of each sector. Such interfacility coordination is also performed for arrival sectors and is also conducted with adjacent centers. The coordinator may assist in distributing flight strips to the appropriate radar controller.

In a two-person team the radar controller maintains responsibility for ensuring separation and facilitating traffic flow and shares some of the mechanical aspects of control operations with the hand-off controller. The hand-off controller supports only one radar controller and should have time, therefore, to perform the routine interphone communications and computer hand-off operations. The radar controller must coordinate sequencing and spacings for merges with other sector teams while performing surveillance and the remaining communications and data processing activities. Again, direct intrasector communications are needed to maintain operational cognizance of each team member's activities. The hand-off controller may also assist the radar controller by arranging and correcting flight strips.

In a 2.5-person team the radar controller maintains responsibility for ensuring separation and minute-to-minute decision making, but shares traffic planning decision making with the coordinator and delegates some of the mechanical control tasks to the hand-off controller. The coordinator is primarily concerned with integrating intersector and interfacility operations and is active, therefore, in interphone and face-to-face communications. Where appropriate, he or she also assists in flight strip distribution. The hand-off controller performs interphone communications not handled by the coordinator, carries out computer data entry and display operations, and may assist the radar controller with flight strip preparation.

WORK-LOAD MODELING

The work-load modeling approach estimates the traffic-handling capabilities of an individual sector by encoding the controller work associated with the sector's operational requirements. This approach develops work-load models for each of the four team regimes during instrument and visual approach operations. The models are based on the frequency of occurrence of specific control events and the minimum time required to perform each event. These data are obtained by observation at a TRACON study site.

A major work-load modeling assumption is that the controller's work load, determined by his or her operational requirements, is the factor limiting the number of aircraft that can be handled by the controller during any given period of time and, thus, determining the traffic capacity of the sector. Past observations (1) of air traffic control activities indicate that within a given period of time there is a maximum total time that a controller can spend performing control tasks. For instance, a radar controller's work-load threshold has been found to be typically 48 person-min/h, and the number of aircraft per hour that generates this amount of work represents his or her traffic capacity. In effect, over a long period of time, such as 1 h, radar controllers can be expected to spend, at most, 80 percent of the 60 min available doing control work. This work-load limit enables them to handle the very intense traffic and work-load surges that typically occur over a short period of time (5 to 10 min) but that could not be handled if they worked more than the 48 person-min/h limit.

The objective of a work-load model is to correlate work time requirements with traffic flow rates to identify the traffic flow rate (capacity) corresponding to the work-load threshold. The 1-h period is used as a base for capacity estimation because this is the time a controller normally spends at a sector position.

In modeling terminal sector operations, the radar controller's work load (with a 48 person-min/h threshold) is considered the critical determinant of the traffic capacity of a sector team. That is, the radar controller, rather than the coordinator or the hand-off controller, is the team member whose work-load requirements will limit traffic-handling capabilities. These conclusions are based on the observation that a significant proportion of terminal air traffic control work is centered on surveillance, quick decision making, and A/G communications that are not delegated to other positions under any of the alternate sector team regimes. Therefore, the radar controller work-load model incorporates each of the four regimes. The regimes will be differentiated by remodeling the radar controller's operational requirements each time an additional controller or coordinator is added to the team. In each case, the radar controller's work-load threshold will be used to define the sector team's traffic capacity.

Model Structure

Operational activities are mutually integrated and interactive and are very difficult to model as independent entities. Therefore, the various control work requirements are aggregated into activity categories that represent operational relations. For modeling purposes, control requirements are organized according to routine work, surveillance work, and conflict processing work.

Routine work includes A/G, interphone, and face-to-face communications; data entry and display operations; and flight strip or paper scratch pad data processing tasks needed to facilitate traffic flow. Surveillance work is the visual observation of the PVD data to facilitate following flights. Conflict processing work includes the decision making and communications needed to detect and assess potential conflicts, resolve the conflicts by means of A/G communications, and coordinate these actions with other controllers. The potential conflicts are categorized further according to crossing, local merging, overtaking, and coordinated approach merging. Radar controller work-load time (W_R) measured in person-minutes per hour and corresponding to a specified hourly traffic rate, is calculated by using the following additive formulation:

$$W_R = [k_1 N + ct_s N + (k_2 + k_3 + k_4 + k_5)N^2]/60 \qquad (1)$$

where

N = number of aircraft per hour through the sector,
t_s = average sector flight time (min),
c = surveillance work-load constant (person-s/aircraft-min),
k_1 = routine work-load weighting (person-s/aircraft),
k_2 = crossing conflict work-load weighting [(person-s/h)/(aircraft/h)^2],
k_3 = local merging conflict work-load weighting [(person-s/h)/(aircraft/h)^2],
k_4 = overtaking conflict work-load weighting [(person-s/h)/(aircraft/h)^2], and
k_5 = coordinated approach merging conflict work-load weighting [(person-s/h)/(aircraft/h)^2].

A set of four radar controller work-load times (W_R), corresponding to the four regimes, is calculated for each sector. The regimes are distinguished by adjusting the work-load weighting parameters (k).

The importance of the work-load component structure of the radar controller model is its capability to distinguish the control work requirements of different sectors in a manner that is sensitive to each sector's operational characteristics. Sector routine work-load time (k_1N) increases in direct proportion to the traffic flow rate, but varies from one sector to another depending on the pattern of traffic flow through each sector as well as each sector's procedural rules. For example, the routine work-load weighting (k_1) for an arrival sector, where speed control instructions are frequent, would differ from that of a departure sector, where speed control is less frequent.

The surveillance work-load time (ct_sN) increases in direct proportion to sector flight time; therefore, surveillance work is sensitive to the geographic size of a sector as well as to traffic flow rate. The flight time parameter (t_s) distinguishes the surveillance work requirements of different sectors, since the same surveillance work-load constant (c) applies to each sector. The product (ct_s) is the surveillance work-load weighting measured in person-seconds per aircraft.

In the processing of potential crossing, local merging, overtaking, and coordinated approach merging conflicts, work-load times (k_2N^2, k_3N^2, k_4N^2, and k_5N^2) increase with the square of the traffic flow rate. The conflict work-load weightings (k_2, k_3, k_4, and k_5) calculated for one sector differ from those of another, depending on the complexity of each sector's route structure and its procedural rules. In particular, the derivations of the conflict work-load weightings can model a variety of aircraft crossing and merging situations (e.g., level to level, level to climb, climb to climb, level to descent).

The routine work-load time (k_1N) represents the time required by normal control events to clear aircraft through the sector. Field data collected for each sector are used to identify the routine control events, specify the set of tasks required for each event, determine task performance times (minimum times), and measure the frequency of occurrence of each event by sector.

Each routine event is included in one of the following functional categories:

1. Control jurisdiction transfer,

2. Traffic structuring,
3. Pilot request,
4. General intersector coordination, and
5. General system operation.

Control jurisdiction transfer is the collection of control events required to hand off an aircraft from one sector to another. Traffic structuring refers to the procedurally based, decision-making process of guiding aircraft through a sector. Pilot requests result in real-time flight modifications, thus increasing work. General intersector coordination includes those intersector informational transfers that are performed to keep cognizant of multisector traffic movement, but are not part of hand-off, traffic-structuring, or pilot-request activities. General system operation refers to activities, such as PVD maintenance, not included in the above categories.

Each routine event consists of a single task or a sequence of tasks that must be performed to complete the event. The tasks are

1. Air-to-ground communications,
2. Computer data entry and display operations,
3. Flight strip or paper scratch pad data processing,
4. Interphone communications, and
5. Face-to-face direct voice communications.

For example, one control event routinely required for control jurisdiction transfer is hand-off acceptance. This event requires that the controller perform manual data entry and display operations and flight strip data processing tasks. On the other hand, an altitude instruction event issued by the controller as part of the traffic-structuring function might involve only the A/G communication task.

Results of field experiments enable the specification of individual task times and the frequency of occurrence of each event by sector for any given team regime. These data are used to calculate the routine work-load weighting (k_1).

$$k_1 = \sum_i \sum_j r_i t_{ij} \qquad (2)$$

where

r_i = frequency of occurrence of type i routine events (events/aircraft), and
t_{ij} = minimum performance time required for each type j task included in routine event i (person-s/event).

Surveillance work-load time (ct_sN) is the time spent scanning the PVD. Past field data collection efforts were unable to measure the number of times a controller looks at the PVD or the duration of each look. The following assumptions were developed from interviews with controllers and reflect their perceptions.

To maintain a mental picture of traffic movement, the radar controller is likely to look at an aircraft's data display once every minute; 1 to 1.5 s/look is sufficient time to identify aircraft and recognize or recall situations. The assumptions (1.25 person-s/look and 1 look/aircraft-min) set the surveillance work-load constant (c) equal to 1.25 person-s/aircraft-min. The corresponding surveillance work-load weighting is 1.25 t_s person-s/aircraft.

The work-load times for crossing, merging, overtaking, and coordinated processing of approach merging conflicts (k_2N^2, k_3N^2, k_4N^2, and k_5N^2) represent the time spent to maintain separation assurance, including time for communications and decision making. Aircraft conflict situations arise when there is a prospective violation of the minimum separation allowable between aircraft. Corrective action is required in advance to prevent such situations. Conflict avoidance by the controller necessitates a rather well-developed capability to perceive potential conflict, to mentally project flight trajectories. The radar controller activities are detection and assessment, coordination, and resolution of potential conflicts.

To estimate work-load weightings of conflict processing, we use the duration of each conflict processing event and its frequency of occurrence:

$$k_2 = t_c e_c \qquad k_3 = t_m e_m \qquad k_4 = t_o e_o \qquad k_5 = t_a e_a \qquad (3)$$

where

t_c, t_m, t_o, t_a = minimum performance times required for crossing, local merging, overtaking, and coordinated processing of approach merging conflicts (person-s/conflict), and
e_c, e_m, e_o, e_a = conflict event frequency factors that measure the rates of occurrence of crossing, local merging, overtaking, and coordinated processing of approach merging conflicts [(conflicts/h)/(aircraft/h)^2].

Conflict processing times (t_c, t_m, t_o, and t_a) are determined by estimating and summing the minimum times needed for the detection and assessment, resolution, and coordination tasks. These task times are based on field observation of control activity and subsequent interviews of controllers; videotape playback of the observed situation is used to review controller actions.

The hourly conflict frequency factors (e_c, e_m, e_o, and e_a) determine the number of conflicts per hour (e_cN^2, e_mN^2, e_oN^2, and e_aN^2) for any hourly traffic flow rate (N) and represent the total number of conflicts that may occur at one or more conflict points in the sector. These factors are calibrated for each sector through the use of mathematical models that determine the expected frequency of occurrence of each conflict type at each selected location or along each selected route. The models define conflict frequencies as functions of aircraft speeds, route intersection angle, route lengths, and minimum separation requirements as perceived by controllers. These relations are formulated as the summation of the probability of pairwise conflicts between aircraft and are described by Siddiqee (5, 6).

OAKLAND BAY TRACON CASE STUDY

A field experiment conducted at the Oakland Bay TRACON site during March 1976 examined the operational activities of the six sectors handling arrival and departure traffic to and from San Francisco International Airport. Data sources included (a) videotape recordings of PVD data; (b) audiotape recordings of A/G and interphone communications; (c) manual observations and stopwatch measurements of controller actions; (d) flight strips and paper scratch pads; and (e) structured interviews with controller and supervisory personnel.

Control event frequencies of occurrence and minimum performance time data needed to calculate the routine, surveillance, and potential conflict work-load weightings for ARTS III operations were determined (4). The work-load weightings were used to calculate radar controller

Table 1. Estimates of sector capacity by team regimes for Oakland Bay TRACON ARTS III.

Sector	Visual Approach Operations (aircraft/h) 1.0-Person	1.5-Persons	2.0-Persons	2.5-Persons	Instrument Approach Operations (aircraft/h) 1.0-Person	1.5-Persons	2.0-Persons	2.5-Persons
AR-1, Woodside final	41	44	45	47	37	40	41	42
AR-2, Foster final	41	43	44	45	36	38	38	39
AR-9, South feeder	46	51	53	57	42	47	48	52
AR-10, North feeder	45	49	51	56	40	44	44	49
DR-1, Sutro departure	39	45	48	48	39	45	48	48
DR-2, Richmond departure	37	41	44	46	37	41	44	46

work load for successive 5 aircraft/h increments in traffic flow and to interpolate the sector traffic capacity corresponding to 48 person-min/h of radar controller work. The resulting capacity estimates, by visual and instrument approach operations, are presented in Table 1 for each of the six sectors.

These sector capacities reflect the characteristics of the radar controller activity defined by the work-load weightings. We see that feeder and final sector capacities for instrument approach operations are less than those for visual operations because of the additional approach merging work, but departure sector capacities are not affected by approach conditions. The sector capacities generally increase for each successive increment in the sector team members because the radar controller usually delegates some portion of routine or conflict work to the added team member.

In the modeling of possible future operations, the work-load event frequencies and performance times were judgmentally revised to represent various automation concepts (4). The corresponding work-load weightings and traffic capacities for each sector were determined. Results for sector AR-9 are given below for instrument approach operations under a one-person team.

Air Traffic Control System	Sector Capacity (aircraft/h)
Current ARTS III	42
Plus basic metering and spacing	47
Plus data link	65
Total	154

Under the above conditions, the radar controller's traffic capacity is estimated to increase by 12 percent relative to ARTS III operations when basic metering and spacing is implemented. This automation generates and displays control instructions, which are relayed to arrival aircraft by the radar controller; automatic flight data displays are included. The data link system, which automatically transmits digital messages to aircraft, is estimated to increase capacity by an additional 38 percent.

A similar analysis of automation effects on the capacities of other Oakland Bay TRACON arrival and departure sectors enabled a study of the number of controllers required for each air traffic control system (4). This study estimated that, with metering and spacing, the same number of controllers required to operate the six ARTS III sectors could handle 50 percent more traffic than they handled in 1975 during a day of heavy traffic. With data link automation, the same number of controllers could handle twice as much traffic. These results depend heavily on the judgments made in constructing the work-load models and should be considered as first order estimates of automation impact.

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Abridgment

Relief of Congestion Delays at Major Airports

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An airport system is congested whenever the actual demand is greater than the volume that the system can handle without delays or when one flight must wait for another flight. Airlines have developed reporting systems to measure the actual congestion delays by flight by comparing the actual times against standard times for each airport when there is no interference from other traffic. At least 85 to 90 percent of departure delays are due to holding for congestion in the terminal airspace or airfield at the destination.

The direct costs incurred by United Airlines for such congestion delays range from $36 to $38 million/year. The total industry costs are probably four to five times those for United Airlines alone, exceeding $150 million/year. Directly chargeable costs range from $5 to $25/min of delay for the various equipment types. This only includes crew time in excess of schedule, maintenance, and jet fuel (which is about 50 percent of all costs). The real costs of delay provide solid cost/benefit justification for improving procedures, instrumentation, equipment, and concrete. The total added jet fuel consumption for the industry, at 28 to 189 L/min (6 to 50 gal/min) for the various equipment types, probably exceeds 0.8 million m^3 (5 million bbl/year). This is a fruitful area for energy conservation.

The direct costs incurred by United Airlines at O'Hare International Airport are five times as great as those for the next most critical airports; therefore, United Airlines actively participated in the joint study by the O'Hare Delay Task Force composed of representatives of Federal Aviation Administration (FAA), airlines, and operators. This study provided the bases for several of the following examples and conclusions.

Figure 1 illustrates the underlying relations of average congestion delays during peak periods as a function of the ratio of demand to capacity. This curve is typical of many queuing situations; delay gradually increases as demand increases, up to an apparent knee in the curve. Beyond the knee, a small increase in demand results in a substantial increase in delay. Similarly, a reduction in capacity of only 5 to 10 percent can increase substantially the delay level for a constant demand. Congestion delays can be reduced by (a) limiting or controlling the demand during the peak period or (b) increasing the capacity of the system.

The actual traffic demand at O'Hare is approximately 17 movements/h until 6:00 a.m., 120 movements/h between 8:00 a.m. and 1:00 p.m., and 137 movements/h until 8:00 p.m., when the demand drops off.

The cumulative method of charting, shown in Figure 2, highlights the spread between the actual demand and the processed demand; the shaded area represents congestion delays. A major irregularity illustrated is the effect of a 40-movement/h reduction in capacity from 1:00 p.m. until 4:45 p.m. The horizontal lines show the delays incurred by individual flights, and the vertical line shows the backlog of 150 airplanes at 4:45 p.m.

The airlines have been accused of contributing to congestion delays by scheduling arrivals and departures on the hour or at 5-min intervals for the convenience of the traveling public. For example, up to eight flights have been scheduled to arrive at O'Hare at 3:59 p.m., considerably above the average capacity of 1.5 arrivals/min. Similar peaks occurred at 4:10 p.m. and 4:30 p.m. However, because of such factors as departure delays at the up-line stations and variations in en route winds, the actual arrival times in the O'Hare area vary considerably from scheduled times. As a result, the expected actual arrivals by minute vary from 1 arrival/min to a maximum of 1.8 arrivals/min. Because of the variations in actual arrival times, detailed analyses and simulations show that the nominal peaking of schedules contributes less than 1 min of delay per flight.

To determine the potential increase in delays at O'Hare that would be incurred under increased demand, the O'Hare Delay Task Force conducted a series of validated simulation runs. They established that an increase in demand of 10 movements/h, from 137 to 147, would increase the average delay by more than 45 percent under visual flight rules (VFR) conditions. In fact, the addition of only 1 operation at the 137 level raises the total system costs by at least $300 in delay to that flight and added delay to all subsequently affected flights. This imputed cost per added operation ranges from $100 to $600.

The best way to reduce congestion delays is to increase the effective airfield capacity or maximum throughput over a period of time. The capacity of an airfield varies directly with the number of independent runways in use and the average speed and varies inversely with the average in-trail separation, as shown in Figure 3. For example, an average separation between airplanes of 105 s [equivalent to 6.5 km (3.5 nautical miles) at an average speed of 62 m/s (120 knots)] would result in an effective capacity of 34 movements/h for one runway, 69 movements/h for two independent runways, and 103 movements/h for three independent runways. At most airports the runways are not independent of one another because of actual intersections or intersecting paths. The capacity of various runway pairs is dependent on the intersection distances, ranging from 12 to 55 departures/h, as the intersection changes from a far distance to a near distance.

The O'Hare Delay Task Force determined by a series of detailed simulation analyses (subsequently verified by actual operations) that the effective capacity of O'Hare ranges from fewer than 130 to more than 170 movements/h, depending on the runway configurations used. The average delay can be reduced from more than 10 min to 2 min or less with the increased capacity available from the better runway configurations. One of the best runway configurations utilizes parallel runways 27L and 27R for landing and parallel runways 32L and 32R and runway 22L for takeoffs. This is one of several triple departure configurations.

Because the capacity of a runway or an airfield varies inversely with the average in-trail separation, during recent years the dominant cause of reduced capacity and increased congestion delays has been the increase in separations required to avoid the turbulence of wake vortexes. According to FAA estimates, the average separation at O'Hare could be reduced by 12 s on approach and 8 s on departure when no wake vortex is detected in the approach and departure paths, for an overall increase in

Table 1. Congestion delays at airports.

Critical Factors	Potential Improvements
Demand during peak period	
Limit	Instituting quota period during day, 1-h or 30-min periods, and arrival and departure limits
Control	Reporting of movements and delays, enforcing quota rules, and controlling flow during major disruptions
Effective capacity	
Runways, configuration, and usage	Selecting best (low delay) configuration for wind and weather conditions
Average in-trail separation	Installing wake vortex system and making other improvements (e.g., metering and spacing)

Figure 1. Average congestion delays versus ratio of demand to capacity.

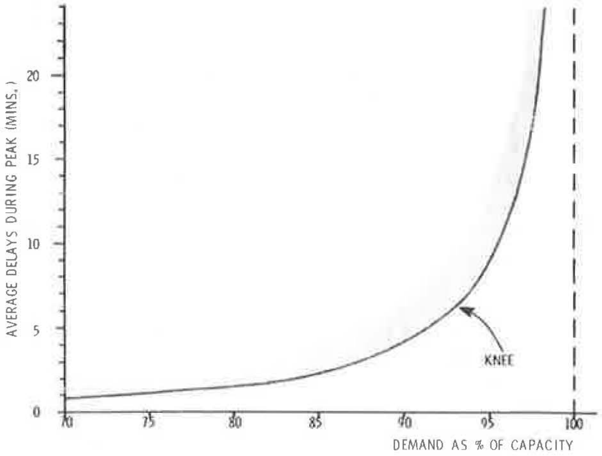


Figure 2. Cumulative traffic movement demand at O'Hare Airport.

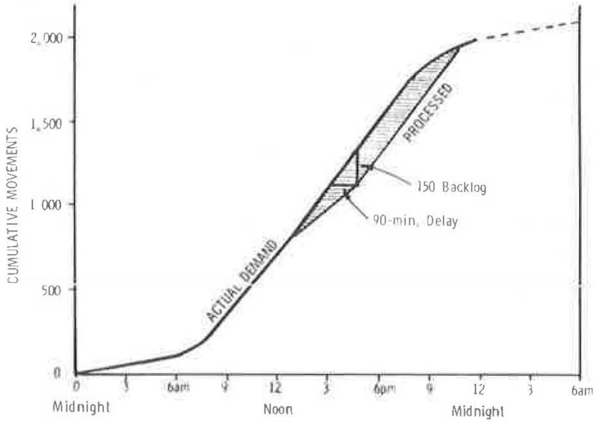
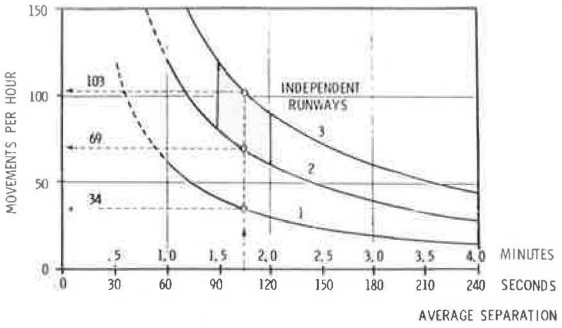


Figure 3. Capacity dependent upon separation and runways.



capacity of approximately 15 percent. Because of the extreme sensitivity of delays to relatively small changes in capacity under peak demand conditions, the 15 percent increase in capacity could reduce the average delay at O'Hare by over 50 percent under instrument flight rules (IFR) conditions. For this reason, the airlines are hopeful that the wake vortex detection system installed at O'Hare in 1976 on a test basis will be proved, expanded, and made operational during 1977.

Table 1 summarizes the findings of the O'Hare Delay Task Force—the critical factors affecting congestion delays and the areas for potential improvements. The greatest near-term payoffs can be realized by

1. Selecting the best (lowest delay) runway configurations for the existing wind and weather conditions;
2. Installing wake vortex detection systems similar to those installed at O'Hare for use with a manual system for reducing in-trail separations when wake vortexes are not a problem; and
3. Improving the systems for controlling traffic demand during the peak periods of the day by (a) more complete and detailed real-time reporting systems covering movements by runway and delays by hour, (b) enforcing the quota rules and not accommodating additional traffic when incremental delay costs would exceed a certain dollar value (e.g., $100), and (c) an effective and equitable system of flow control when disruptions are anticipated, including improved predictions of capacity for the coming period.

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Air Traffic Control Performance Measurement in the Federal Aviation Administration

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The Federal Aviation Administration uses two manual systems to measure air traffic control system performance and is now in the process of developing a third, which uses its recently installed computer equipment to collect performance data. Our objective is to obtain insight and understanding about the utilization of capacity, the causes of air traffic delays, the magnitude of delays, and the the locations at which they occur so that air traffic control can be performed more efficiently. The first system, started in 1968, identifies aircraft delays of 30 min and where, when, and why they occur. The second system, implemented in late 1975 at major airports where delays occur, utilizes hourly airport runway capacity standards to assess performance when demand reaches or exceeds capacity. Performance is indicated by an index comparing actual aircraft services to a standard. The system also provides data on delays of 15 min or more, causes for delays, and substandard performance as measured by the performance index, runway utilization, and weather data. The third system, now in early stages of development and testing, will collect accurate delay data on aircraft flying into major airports. This delay data base will be the most comprehensive and accurate of the three systems and will provide total information on aircraft delay. Coupled with the data provided by the second system, it will give a sophisticated and accurate performance data base that will indicate system performance and areas for improving the air traffic control system.

The Federal Aviation Administration (FAA) uses two manual systems to measure air traffic control system performance. It is now in the process of developing a third system. The earliest measurement, the national airspace system communication (NASCOM), was started in 1968. It identifies all aircraft delayed over 30 min. In 1975 a second system, the performance measurement system (PMS), was implemented. It uses comparisons of deviations from runway capacity standards to measure performance. A third technique, automated delay measurement system (ADMS), using computers, is now being developed and tested.

NATIONAL AIRSPACE SYSTEM COMMUNICATION

NASCOM was established to provide timely performance data on several aspects of the air navigation system. One aspect studied was the amount of delay incurred at airports, in the surrounding airport areas, and in the en route airspace. Specifically, NASCOM

1. Measures the number of aircraft delays of 30 min or more,
2. Identifies the airport at which the delays occur,
3. Indicates whether the delays are experienced by departing or arriving aircraft,
4. Records the time period in which the delays occur, and
5. Pinpoints the cause of the delays.

Air traffic controllers collect the data manually as delays occur and transmit their findings daily to the FAA for review. The results over the years indicate that approximately 70 percent of delays occur at four major airports: Chicago O'Hare, John F. Kennedy, Atlanta International, and LaGuardia. The major cause of delays and fluctuation in the number of delays is adverse weather. Based on annual statistics, weather causes approximately 73 percent of delays. Other causes identified are such things as equipment failures, airport disruptions, and airport emergencies. NASCOM also shows that the majority of delays occur to arriving aircraft in the airspace surrounding busy airports. The NASCOM system serves as a good indicator of trends in delays and causes of delays.

PERFORMANCE MEASUREMENT SYSTEM

The PMS is based on standards for the hourly traffic throughput capacity of the airport defined for various runway configurations, weather conditions, and traffic mixes. Performance is measured by comparing the actual amount of traffic serviced to the engineered performance standards (EPSs). Many factors were considered in the development of EPS. First, a throughput capacity standard was defined as the number of aircraft that can be serviced in 1 h under specified conditions, assuming a continuous supply of aircraft without regard to the delay encountered. It does not indicate a specific amount of delay because delays are influenced highly by factors that are only partially controlled by the FAA, such as scheduling. This standard combines observed aircraft operating characteristics and air traffic control procedures over which the FAA has control.

The next step in developing EPSs was an identification of all of the major runway configurations used, the relevant physical characteristics of the runway layouts, and runway taxiway locations. Then, runway operating strategies were identified. These include such considerations as (a) Are the runways used for both arrivals and departures, or are they segregated by arrivals and departures? (b) Are there any restrictions on runway use dictated by type of aircraft or noise abatement? and (c) Does the weather influence runway usage? EPS development also reflects air traffic control operating procedures that influence arrival and departure separation aircraft under visual flight rules and instrument flight rules.

Since standards can be developed for a wide range of arrival and departure mixes, we selected a representative mix. An analysis of arrival and departure mixes during busy hours at the major airports included in the PMS showed that a 50:50 mix is representative. This, therefore, was used to develop the standard for all airports. We also needed to categorize aircraft by type and figure the percentage of each type of aircraft using the airport. We were interested in the size and performance characteristics of aircraft. The aircraft size (gross weight) indicates runway-use capabilities and dictates required aircraft arrival and departure radar separation distances, which must be maintained by an air traffic controller. Aircraft performance refers to landing and takeoff speed, which translates into times and corresponding longitudinal distances. Initial EPS focused on four categories of aircraft. Field investigation later indicated some generalizations could be made about aircraft size and performance characteristics; however, an individual mix by aircraft category was developed for each airport. An aircraft weighing over 136 054 kg (300 000 lb) has the most significant influence on capacity. These aircraft are called heavies and normally require extended separation distances for following aircraft because of wake vortex hazards.

Once the major factors that influence capacity were identified, we began development of the standards. First we quantified the probabilities of event occurrences and event restraint times for the various arrival and departure phases of flight. A probability of occurrence matrix of all possible arrival and departure sequences for the various categories of aircraft was developed for each configuration. Then for each possible combination an event restraint time, measured in seconds, was developed based on actual field measurement under peak traffic conditions. Restraint times are the times required for aircraft to perform an event that restrains the next aircraft from performing an event. For example, if a nonheavy aircraft is to depart after another nonheavy aircraft, the restraint time would be the time it takes the first aircraft to start its departure roll, lift off the runway, and fly a distance of 3.2 km (2 miles). The trailing aircraft is restrained from beginning its departure roll until the leading aircraft attains this distance.

A summation of the related probabilities multiplied by the appropriate restraint times divided into 1 h (3600 s) yields the capacity for a particular runway. If more than one runway is used, which generally is the case, and there are interdependent conditions (i.e., the operations on the one runway are influenced by the operations on the other, as in crossing runways), we follow the same process of using probabilities and restraint times to arrive at a standard.

The aircraft separation criteria used for developing EPSs were those required during radar conditions of 4.8, 6.4, or 8 km (3, 4, or 5 miles), depending on the size and sequence of the arriving and departing aircraft. However, on-site measurements indicate that 5.6 km (3.5 miles) is more realistic than the 4.8-km (3-mile) separation standard. The increased separation required behind heavy aircraft has made modification of the standard necessary. Capacity determination is based on the assumption that the demand is always ready to be served when there is time available to service the aircraft.

At the present time, capacity standards have been developed for 24 of the largest domestic airports. Approximately 160 sets of capacity standards have been developed for the various airport configurations. These sets include variations for four different weather conditions and reflect variations in runway use based on these conditions.

Although airports are unique with respect to airspace, runway, and taxiway design, most airports are developed from a basic set of components. Examples of these are single runways, parallel runways, intersecting runways, and high-speed turnoffs. Several patterns obviously emerged, and many of the standards at the various airports are similar for similar runway configurations when the type of traffic serviced is also similar.

The concept used to develop the standards is quite simple. Analysis showed that many of the factors analyzed and initially thought to have significant impact on capacity were later found to have little impact when the type of performance system being developed was considered. The major advantage of the approach is that it can accommodate changes in operating procedures quite readily without extensive data collection. The approach also reflects the practical aspects of measurement—only those factors that could be ultimately identified on an hourly basis during performance measurement were considered. A comparison of these PMS standards with those developed by more sophisticated techniques shows only minor differences.

Once we developed the EPS values, we could evaluate actual performance at the 24 selected airports. The airports were divided into three groups based on the level of traffic and NASCOM delays experienced.

Group 1 airports include Chicago O'Hare, LaGuardia, John F. Kennedy, Washington National, and Atlanta International. These airports have the most detailed performance reporting requirements. Each reports detailed operational, traffic, and weather information covering approximately 10 h/d. This time period includes the busiest hours of the day.

Group 2 airports include Boston Logan International, Cleveland Hopkins, Dallas-Ft. Worth Regional, Newark International, Los Angeles International, Miami International, Philadelphia International, Greater Pittsburgh, San Francisco International, and Lambert-St. Louis International. These airports report only delay data on a daily basis. On a quarterly basis they report detailed operational, traffic, and weather data for a 7-d period. The quarterly data yield traffic pattern, runway usage, and capacity data. These data are used for general analysis and to determine whether a group 2 airport should be moved into group 1.

Group 3 airports include Baltimore-Washington International, Port Columbus International, Detroit Metropolitan-Wayne County, Houston Intercontinental, Minneapolis-St. Paul International, Phoenix Sky Harbor International, San Antonio International, and Tampa International. These airports are not required to report any data. The standards are used for local operational evaluations and for planning. The airports are potential candidates for group 2 airport classification.

The group 1 airports experience most of the delays and have traffic demands that consistently reach or exceed capacity on an hourly basis. At group 2 airports demand only occasionally reaches or exceeds capacity, and at group 3 airports demand comes close to but rarely reaches or exceeds capacity. Below the specific types of data collected hourly.

1. The actual amount of traffic serviced (subcategorized by air taxi, air carrier and military, and general aviation),
2. Scheduled demand,
3. Runway configuration,
4. Weather conditions,
5. EPS,
6. Performance index (PI) when applicable,
7. Number of aircraft delayed 15 min or more, and
8. Causes of delays.

Our primary interest is in assessing the air traffic control system when demand challenges capacity; hence, the PI is calculated for an hour when scheduled demand is near or exceeds the EPS. The PI is the ratio of actual traffic services to the EPS. PIs are not calculated when demand is substantially lower than EPS, since this would not aid in measuring efficiency. When the hourly PI is 95 or less, a cause for the substandard performance index must be identified. This five-point buffer from 100 takes into account the minor deviations for which no perceptible cause can be identified and the approximations made in the EPS calculations. The detailed hourly data also facilitate analysis of the hourly operation. For example, knowing the actual number of arrivals and departures allows assessment of actual performance regarding the 50 percent arrivals: 50 percent departures assumption used to calculate EPSs. Knowing the traffic mix by type of aircraft also aids in this assessment. In addition to being used for performance measurement, the EPS and hourly performance information is used on a select basis for national air traffic flow control management on a real time basis.

Of major importance is that this system not only indicates when the system is experiencing delays, but also indicates how well the air traffic control system is operating on a continuous basis when demand is near capacity. Indications to date are that the overall system is very efficient. When airport traffic is near or exceeding capacity, the air traffic control system generally operates close to 100 percent of capacity.

AUTOMATED DELAY MEASUREMENT SYSTEM

The third performance measurement technique uses the computer systems (NAS Stage A) recently implemented in the 20 en route air traffic control centers across the United States and the automated radar terminal system (ARTS) III, which was implemented several years ago at major high traffic density terminals. The ADMS measures the actual airborne delay of aircraft flying into the major airports from the time an aircraft departs one airport to the time it arrives at its destination. In the other systems, the data were collected manually; in this system, the majority of the data will be collected by computer; only a small amount of data will be recorded manually. Off-line computer programs will produce data reduction and report summaries. Since arriving aircraft incur the major amount of delay, present plans are to record delay data only for aircraft arriving at the major airports. The basic initial computer programs for data extraction and reduction have been developed, and Chicago O'Hare has been selected as the first site for implementation, testing, and refinement.

Since initial testing, the system has been sent to several other major high-density airports where implementation is in process. At the present time at Chicago O'Hare, delays are measured for the majority of arrival aircraft from approximately 240 km (150 miles) out to landing. Delay measurement is accumulated in several phases of flight: (a) the en route airspace and (b) the airspace near the airport in a radius of approximately 32 km (20 miles).

In this system delays are calculated by identifying all the possible flight paths of aircraft to the various airport runways along with normal flight speeds for the various phases of flight. Using these data, a matrix of standard flight times is developed for each path. As an aircraft is tracked through the airspace, its actual flying time is accumulated and flight path identified. To indicate delay, the actual time is compared with the appropriate standard time.

Three output reports are now being tested. The most detailed includes data on every aircraft and identifies each aircraft by flight, flight path, landing runway, delay data, and relevant check point crossing times. The second report consists of hourly distributions of delay; it shows the number of aircraft delayed for various 15-min increments of delay through more than 60 min. It also indicates various delay averages and the number of aircraft serviced. The third report gives daily delay summaries.

This system will be refined, improved, and implemented at additional airports over the next year. The data produced will be used to measure delays and serve as a data base for analyzing delay-demand relationships and evaluating runway configuration efficiency, weather impact, and operating efficiency.

SUMMARY

As data collection technology has advanced, the FAA has progressed in its efforts to measure air traffic control system performance. The PMS gave new insight into airport capacity and system performance with regard to this capacity. After the development and refinement of the ADMS is complete, we will be able to obtain detailed and accurate data on delays. This has been made possible through the automated environment of the air traffic control system. Eventually, PMS and ADMS will be merged into one comprehensive data base. The joint ADMS-PMS data base will allow new in-depth analyses that will give additional insight into the air traffic control system and yield a better understanding of the magnitude of delays and their causes. This will allow improvements to the system to reduce delays and improve efficiency.

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