11. D. Davis and C. McCarthy. Introduction to Technological Economics. Wiley, New York, 1967.
12. R. A. D. Egerton. Investment Decisions Under Uncertainty. Liverpool Univ. Press, England, 1960.
13. G. P. Howard. Airport Economic Planning. MIT Press, Cambridge, MA, 1974.
14. E. V. K. Fitzgerald and G. B. Aneuryn-Evans. The Economics of Airport Development and Control. Journal of Transport Economics and Policy, Vol. 7, 1973, pp. 169-282.
15. A. P. Ellison. Air Transport Demand Estimates for United Kingdom Domestic and International Routes: Pt. 1—Demand Models. Aeronautical Journal, Vol. 76, 1972, pp. 261-267.
16. W. H. Long. Airline Service and the Demand for Intercity Air Travel. Journal of Transport Economics and Policy, Vol. 3, 1969, pp. 287-299.
17. J. V. Yance. A Flight Choice Model. Journal of Transport Economics and Policy, Vol. 4, 1970, pp. 144-161.
18. J. W. Forrester. Industrial Dynamics. MIT Press, Cambridge, MA, 1961.

Publication of this paper sponsored by Special Committee on Air Transport Activities of the Transportation Research Board.

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.

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.

Figure 1. Airfield simulation model.

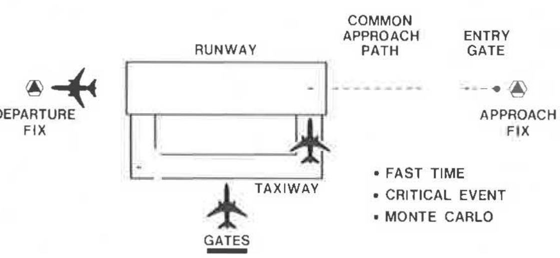
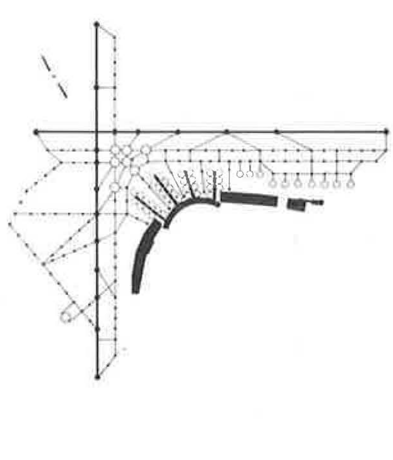


Figure 2. Airfield network.



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

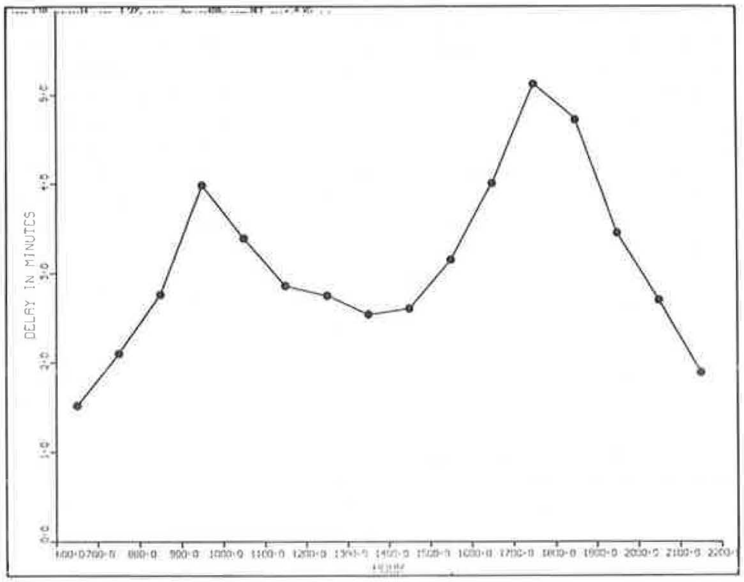


Figure 3. Graphical postprocessor output.

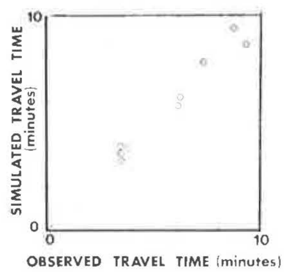


Figure 4. Simulation model validation results.

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.

Publication of this paper sponsored by Special Committee on Air Transport Activities of the Transportation Research Board.

Capacity of Terminal Airspace Sectors

George J. Couluris, Stanford Research Institute

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.