APPLICATIONS OF COMPUTER-DRAWN MOTION PICTURES TO VISUALIZATION AND VALIDATION OF AIRPORT SIMULATIONS

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Abstract

An airport simulation system has been developed for general use in evaluating and comparing design and operational alternatives of airport master plans.

A key feature of this system is the capability for producing computer-drawn motion pictures of simulated airport operations.

Experience to date has shown that these films are very effective for detecting flaws in the model, and of instilling user confidence in the model and the meaning of the statistical results.

INTRODUCTION

The recent increase in concern over the environmental effects of airports has had a serious impact on the plans of many of our major cities to construct new airports that are needed to satisfy the increasing demand for air travel.

These restrictions have caused a greater emphasis on increasing the capacity and efficiency of our present airports and assuring that master plans for airport expansions minimize detrimental environmental effects while using the available land resources most effectively.

Simulation of airport surface and airspace traffic appears to be an ideal tool for development and evaluation of these master plans. Simulations can be used to determine the capacity of the airport, to assess the operation costs to the air carriers and to discover potential problem areas in airport operation. Optimum operating techniques can be developed for the airport, and cost/benefit analyses can be performed to determine the need for air and ground control automation equipment.

A factor that appears to have limited the effectiveness of simulation for airport planning applications, however, is insufficient user confidence in the validity and meaning of the results. As the selection of airport design alternatives typically involves many millions of dollars, the airport planning team must justify their selections to each other and to higher authorities in terms that can be readily understood by all.

Figure 1 illustrates the communication process associated with the simulation of an airport. The initial problem statement and final decision are generally made by administrative, financial, and politically oriented individuals or groups representing airport and city management. The detailed airport planning is performed by professional airport planners who have an in-depth knowledge of airport operations but may not be familiar with computers and mathematical models. Likewise, the simulation analyst may not be an expert in airport operations.

A communication problem may therefore exist between the airport planners and management on one hand and simulation analysts on the other.

Airport planners and, in fact, most engineers are, in general, not sufficiently familiar with mathematical modelling techniques to make an assess-

FIGURE 1

AIRPORT SIMULATION COMMUNICATION PROCESS

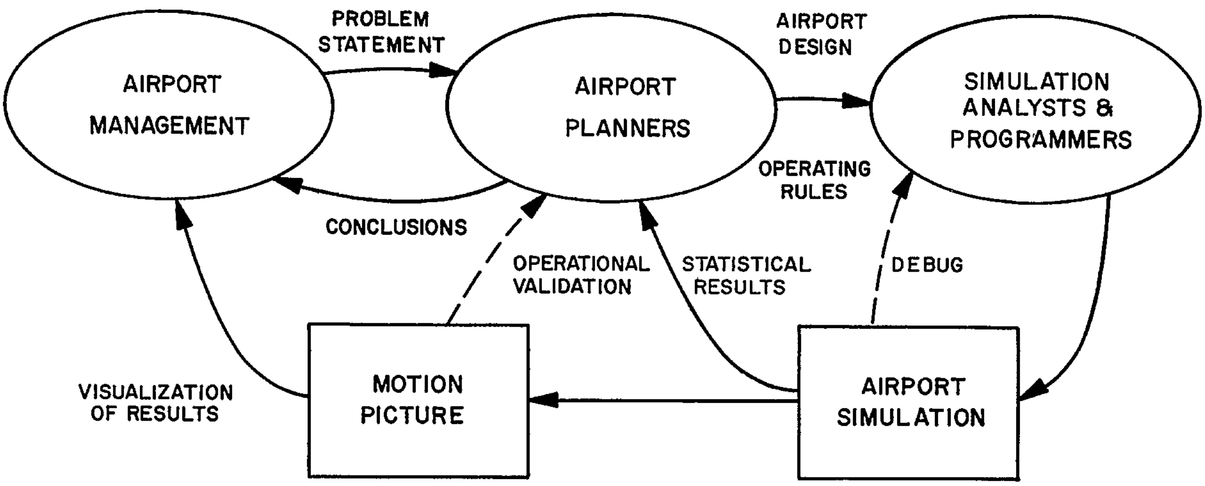
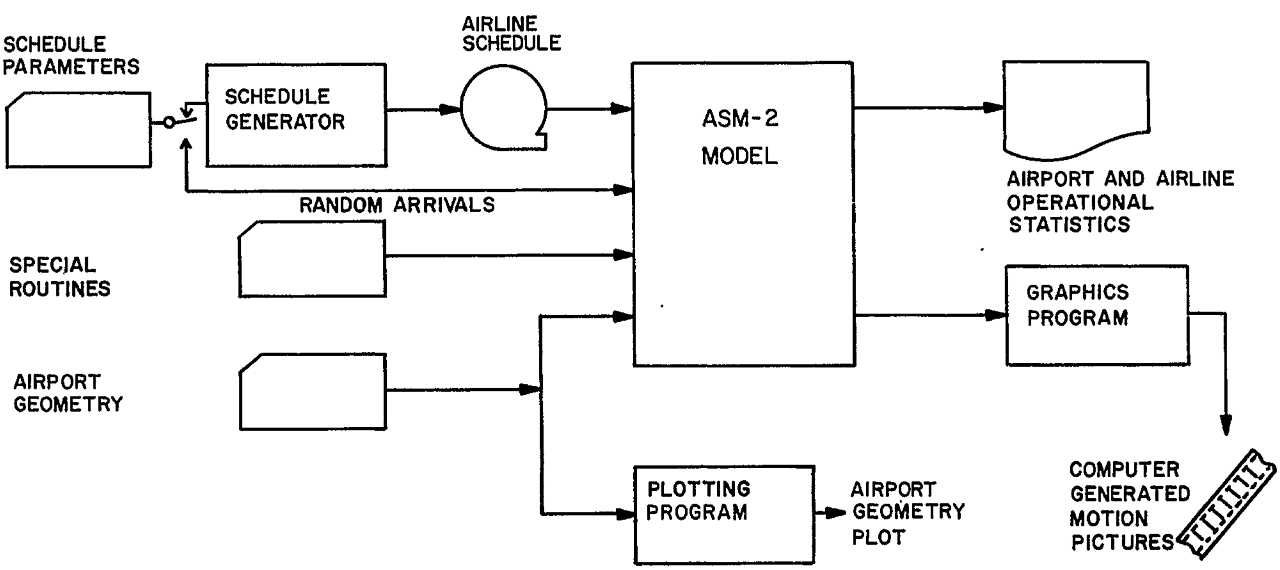


FIGURE 2

ASM-2 SIMULATION SYSTEM



ment of model validity from inspection of flow diagrams and mathematical equations. Better methods are therefore needed to validate airport simulations and to demonstrate the validity to those involved in making or approving the airport design and master plan.

This paper discusses the use of computer drawn motion pictures as a vehicle for facilitating communication in the airport planning processes. These films improve visibility of model operations so that the airport analyst is able to determine if the model does indeed reasonably approximate the way in which a real airport would operate. In addition, he can use the films to demonstrate to management the advantages of one airport configuration over another in a common language. We believe this motion picture plotting capability developed in conjunction with the ASM-2 airport simulation model represents a significant contribution to the solution of these validation and demonstration problems.

The ASM-2 model simulates the airport surface traffic from terminal gates to runway and the airspace in the vicinity of the airport. It is intended for use in investigation of runway, taxiway and terminal design and the operational aspects of the airspace and airport for both present and future years.

DESCRIPTION OF THE ASM-2 SIMULATION SYSTEM

A block diagram of the ASM-2 simulation system is shown in Figure 2. In addition to the airport model itself, the system comprises a schedule generator, a plotting program, and a graphics program for generating the motion picture films.

Inputs to the program are the schedule generation parameters, the airport geometry description, airline gate assignments and any special operating rules required for the particular airport. Aircraft can be generated at random intervals on a steady state basis directly from the schedule parameters or an airline schedule can be generated and saved for repeated use. The generated schedule is produced in accordance with the assigned market share and fleet mix, percent flight continuation (e.g. overnight, through, turnaround) of each airline, and the airport demand level for the particular year being simulated.

The airport geometry input includes the X and Y coordinates of each runway and taxiway intersection and each terminal gate. Each intersection and connecting taxiway segment is numbered for identification. For a particular simulation run it is also necessary to indicate any desired taxiway directional constraints. Apron and parking areas not bound by single file rules are also identified.

Experience has shown that occasional errors will occur in this type of input data and that it is quite difficult to detect these errors by proofreading because of the large quantity of data necessary when many different configurations are being simulated. A plotting program is used, therefore, to play back the data in graphical form for proofreading before simulation is attempted. A typical plot is shown in Figure 3.

In this plot squares indicate gate position, while circles indicate intersections or points at which aircraft leave the taxiway to enter the apron areas leading to a particular gate. Apron areas used for parking or passing in which single file rules do not apply are enclosed in dash lines labeled with the letter 'A'. Runways are denoted by the letter 'R'. Other taxiway segments have one direction or bidirectional arrows indicating any flow constraints that have been imposed for the particular direction of airport operation.

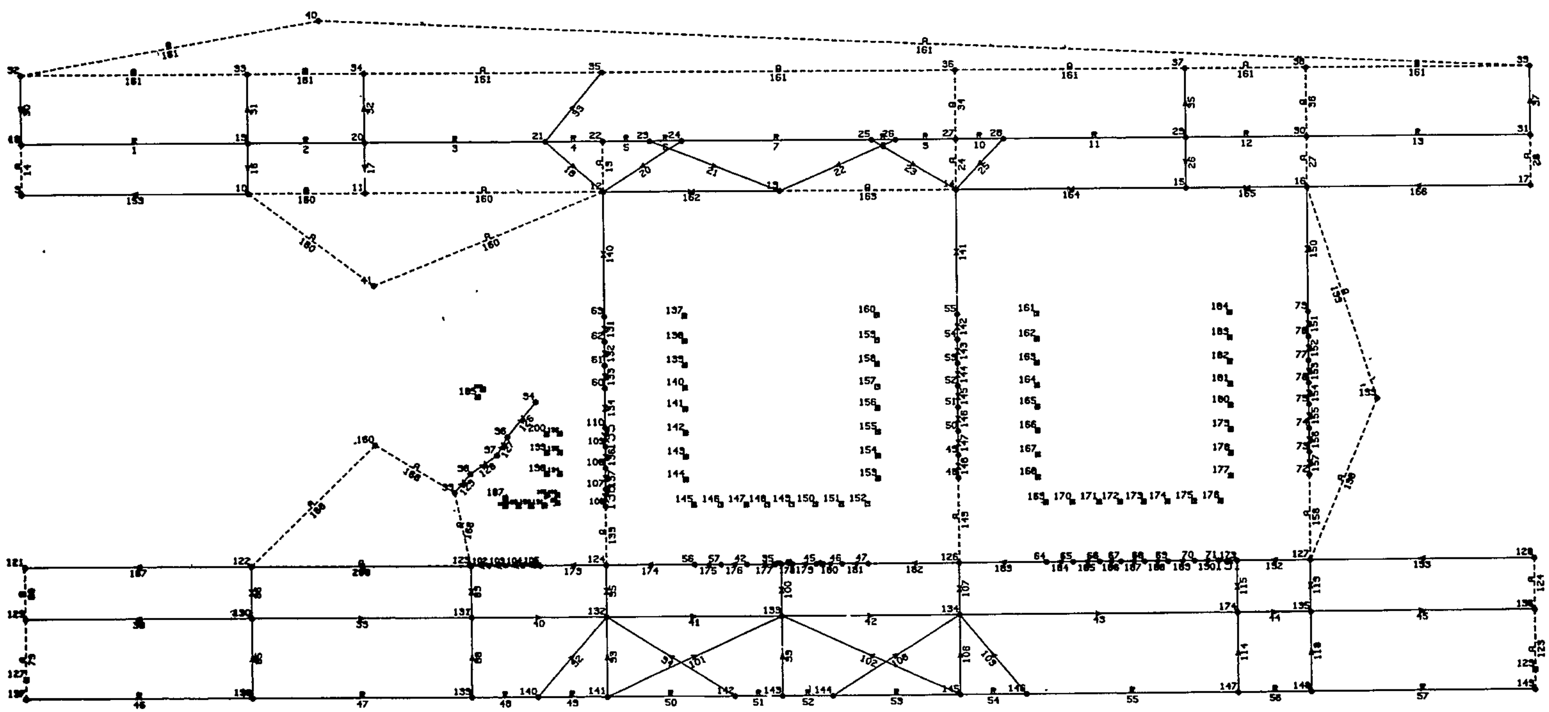
SELECTION OF REAL WORLD FEATURES AND LEVEL OF DETAIL

The determination of which airport features and parameters must be explicitly represented and validated in the simulation depends on the use to be made of the simulation. A simulation that is to be used to investigate gate use, for instance, might be quite insensitive to accuracy of approach sequencing and spacing features. Since the ASM-2 model was designed for general multi-use applications it includes all important aspects of the airport involving aircraft operations (gates, taxiways, runways and terminal airspace) and is sensitive to all airport design and operation features and parameters that can cause aircraft delays if improperly designed or overloaded.

Use of the model for investigation of airport operations is perhaps more important for future years than for current years since current year operations can often be observed directly. It is important therefore that the model be sensitive to those parameters that may change substantially in future years and the validation procedures be conducted on submodels to assure that conditions not observable at current airports are adequately represented.

FIG. 3

CODED AIRPORT GEOMETRY INPUT



The ultimate master plan configuration for an airport may evolve over a period of 30 years. During this time the aircraft mix may change appreciably with higher percentages of wide body jets and the introduction of STOL or VTOL for short haul travel. The model therefore must be shown to be sensitive to the effects of this mix variation. As current airports cannot usually be observed operating with these future mixes, validation of approach separations, for instance, must be performed on pairs of aircraft types in an arrival stream rather than an average taken over the total population of arriving aircraft.

For purposes of discussing the features that must be included, the ASM-2 model can be subdivided into 6 submodels:

.. The approach sequencing and spacing model accepts aircraft an hour before landing and simulates progress via the feeder fix and approach path to the landing threshold.

.. The landing model picks up the aircraft at the threshold and simulates the deceleration, exit selection, and turn-off processes.

.. The taxi flow and management model includes route selection algorithms, intersection priority rules, taxi speed regulation, segment capacity constraints, and special routines for management of flow over bidirectional taxiway segments.

.. The runway management model provides for the assignment of arriving and departing aircraft to the appropriate runways, the designation of runway operational mode (e.g., landing only, takeoff only or mixed) and the sequencing of operations on dependent (e.g., crossing or close parallel) runways.

.. The takeoff and departure model simulates advancement of the aircraft to the runway, and takeoff and departure from the airport including consideration of airspace constraints along the departure route.

.. The gate and parking management model includes assignment of aircraft to gates and provisions for holding of aircraft when gates of a particular airline are full.

In order to determine features to be included in the model and requirements for validation, a rough sensitivity analysis was made for each of the 6 submodels with respect to the following 5 potential applications areas:

- comparison of terminal configurations
- comparison of taxiway configurations
- comparison of runway configurations
- comparison of ground control alternatives
- comparison of approach control alternatives

A rough estimate was also made of the greatest effect each model feature or parameter could have on the overall estimate of airport capacity.

Table 1 shows some of the more important parameters for each of the 6 submodels.

A basic validation parameter as shown in the table has been selected for each submodel as the variable that seems to be most meaningful in relating submodel performance to the model as a whole. In some cases the sensitive parameters can be related to the basic validation parameter in a quantitative way (designated by Q) while other cases of a discrete or logical nature, perhaps involving human decisions or historical practice, are more ideally validated by having experienced controllers and pilots view the operation to see if it conforms to reasonable (though generally unwritten) operating procedures. This type of validation procedure is designated by 'V' for 'visual'. As over half of the sensitive model features are capable of visual validation, the application of computer-drawn films to display model operation for this purpose is apparent.

DEPTH OF SIMULATION

In representing the real world the depth of simulation and use of empirical versus physical models is an important tradeoff. The design of the approach spacing and runway turnoff selection models illustrate the considerations involved.

The spacing between successive arrivals at the runway threshold or the selection of runway turnoff, for instance, could be modeled quite simply by collecting empirical data at one or more airports, developing a statistical distribution function, and basing the spacing or exit selection on a random variable having the prescribed distribution function. This technique, however, is not sensitive to:

. Aircraft Mix
. Approach geometry variations

TABLE 1

SUBMODEL	BASIC VALIDATION PARAMETER	SENSITIVE MODEL LOGIC & PARAMETERS	VALIDATION MEANS	DECISION SENSITIVITY TO MODEL ACCURACY AND COMPLETENESS					CAPACITY SENSITIVITY %
				TERMINAL CON-FIGURATION	TAXIWAY CON-FIGURATION	RUNWAY CON-FIGURATION	GROUND CONTROL ALTERNATIVES	APPROACH CONTROL ALTERNATIVES	
APPROACH SEQUENCING and SPACING MODEL	THRESHOLD INTERARRIVAL TIMES (by pairs of aircraft types)	A.T.C. Separation Rules(incl.Wake Turb)	Q						30
		Controller/Pilot Spacing Performance	Q						30
		Aircraft Mix Effects	Q						20
		Assignment of Runways	V						30
		Runway Priority Mode	V						15
LANDING MODEL	RUNWAY OCCUPANCY (by aircraft type)	Threshold Speed	Q						20
		Deceleration	Q						30
		Exit Selection	V						20
TAXI AND FLOW MANAGEMENT MODEL	TAXI TIME	Taxi Speeds	Q						10
		Routing	V						20
		Priority Logic(e.g. bidirection segments	V						30
RUNWAY MANAGEMENT MODEL	SEQUENCE OF RUNWAY OPERATIONS	Assignment of Runway	V						30
		Dependent Runway Sequencing	V						15
		Selection of Operating Mode	V						15
		Departure Clearances	V						10
TAKEOFF AND DEPARTURE MODEL	TAKEOFF INTER-EVENT TIMES	Controller/Pilot Lags	Q						10
		Airspace Constraints	Q						30
GATE & PARKING MANAGEMENT MODEL	GATE WAITING TIMES (by airline)	Gate Maneuver Constraints	V						5
		Penalty Box Assignments	V						10
		Aircraft Type/Use	Q						100
		Flight Continuation	Q						50
		Airline	Q						100

- Physical aircraft characteristics
- ATC regulations and practice

When only near-future investigations are to be conducted and when it is possible to calibrate the simulation against the present operation of the subject airport, this approach might seem reasonable. Even in these circumstances, however, important relationships affecting airside efficiency, such as the correlation of aircraft type and runway turnoff, may be missing.

The other extreme in the modelling of these operations is to use a purely deterministic model based strictly on aircraft physical parameters such as the manufacturers' recommended approach speeds and maximum runway decelerations, and on ATC regulations such as minimum spacing on final approach. This approach would be sensitive to the parameters described above but would not recognize the differences that exist between regulations and actual practice which result from the randomness in human motivation and behavior. Also, in certain cases regulations are not sufficiently specific, and the model must rely heavily on empirical data describing current operational practice.

The ASM-2 model employs a combination of these statistical and deterministic submodels so that the important parameters are explicitly represented, with empirical data used to establish the random variations with respect to the deterministically derived norm.

DATA GATHERING

Radar photography has been used extensively to gather data for calibration of the ASM-2 model. Airport Surveillance Radar (ASR) and Airport Surface Detection Radar (ASDE) are photographed using a motion picture camera synchronized to expose one frame per radar sweep. These films can be played back at faster-than-real-time speeds to obtain speed and spacing information for aircraft in the terminal airspace and on the surface of the airport. Aircraft type identification is added from manual observation, and the data are processed using various sorting and statistical routines to develop data such as the following for use in model calibration:

- Distribution of approach spacing over outer marker and runway threshold by pairs of aircraft type.
- Distribution of average speed on final approach by aircraft type.
- Distribution of over-threshold speed by aircraft type.
- Distribution of average runway deceleration by aircraft type.

When new regulations are introduced by the FAA such as the recent wake turbulence regulations on the spacing of lighter aircraft with respect to heavy jets, it is necessary to obtain new data to determine the revisions required in the model. Because of the importance of the heavy jet regulations with respect to future airport capacity, additional ASR radar data were obtained recently at Chicago's O'Hare Airport. This airport was selected because of its high activity level, extensive heavy jet traffic, and availability of ASDE radar.

The ASDE data obtained at O'Hare were of great value in modelling the deceleration and runway turnoff process. ASDE radar provides aircraft position each second during runway deceleration. These data can be used to derive the velocity and acceleration profiles of aircraft and the distribution of turn-off speeds used with angled and right-angle runway exits.

For modelling of flow in the taxiway system it was considered desirable not to require entry of explicit aircraft routing as an input to the model as it is a rather burdensome task to work out the best routes from each runway exit to each terminal gate. Furthermore, this approach does not lend itself to extension to adaptive routing when required. A shortest route algorithm was included in the model to allow an aircraft to find its way from any intersection to any other intersection or gate position via the shortest route consistent with directional constraints placed on taxiway use.

To allow for specification of various directional constraints, the taxiway segments connecting the intersections (nodes) are assigned one of the following designations:

+ Single file positive direction

- Single file negative direction

B Single file either direction

D Dual lane, one positive and one negative direction

A Apron or wide segment allowing passing.

Each of the above except the 'A' type connects two nodes while the 'A' type connects two or more nodes. Directional constraints are normally assigned as a function of the airport operational configuration which in turn varies with wind direction and demand level. In the computation of the shortest route only legal directions are employed. Sequences (or trees) or bi-directional segments present special problems in logic design to assure efficient use of these segments without allowing blocking conditions to develop for the taxiing aircraft.

TYPICAL APPLICATION OF MODEL

The importance of some of the model's design features can be illustrated by considering an application.

A typical application of the simulation was a master plan study for the expansion of Sky Harbor International Airport in Phoenix, Arizona.

In the preliminary airport master planning stages the city's planning group developed three alternative terminal configurations and a three-phased plan for expansion from the present to the final master plan level. The ASM-2 simulation was then used to develop a time-table for the phased improvements to provide the runway and terminal capacity required to meet the anticipated demand growth and to evaluate, with respect to airside operations, the relative efficiency of the three proposed concepts.

The first stage of development for the three terminal concepts is shown in Figure 4. Airport design and operational features that differ among the concepts and were evaluated by simulation included:

- Need for single or dual taxiway adjacent to the north runway
- Number of north/south cross taxiways required
- Bi-direction or dedicated direction of cross taxiway use
- Split of north and south facing gates, or south, east, and west facing gates.

The runway assignment logic was determined to be a sensitive parameter in determining delays as it influences taxi distance, use of cross taxiways and relative allocation of delay between the north and south runways. Since the north runway was not designed to accommodate heavy jets, all heavy jet operations were constrained to the south runway. Because of this, airlines operating large aircraft were assigned to southerly gates with air taxis, local airlines and general aviation located near the north runway. When arriving and departing, an aircraft was assigned to the runway most convenient to its gate position unless the queue length differential was greater than three, in which case it would use the runway with the shorter queue.

Simulation runs were conducted for a matrix of 12 configurations in all; each of the three basic terminal configurations sized for four future time periods (1983, 1990, 2000, and 2015).

A schedule of arrivals and departures was prepared for each of the above design years by means of a schedule generation program. The schedule duplicated the forecasted total demand and hourly profile while preserving the forecasted market share, the characteristic fleet mix, and ratio of overnight, through, and turnaround flights for each airline. The statistics developed for each configuration included utilization and delays at nodes, segments, terminal gates, runways, and runway turnoffs by hour of the day and by airline. Numbers of taxi miles, taxi stops, and total cost of delays were also computed.

Figure 4 shows typical figures for taxiway utilizations and delays for the first phase of development. Delays (indicated by numbers in circles) are shown to develop on the westerly cross taxiway where aircraft from two terminals enter the taxiway in the same area.

A profile of runway delays for the north runway (8L) and south runways (8R) is shown in Figure 5 while Table 2 summarizes the total taxi and gate delays for the three concepts.

The computer-drawn motion picture produced in conjunction with the simulation proved to be very useful in confirming the validity of the simulation and allowing the city officials to visualize the operational alternatives being considered. A film was produced for the peak hour from 8 to 9 a.m. for five of the most important simulation runs. A few frames are shown in Figure 6.

IMPLEMENTATION OF THE MODEL

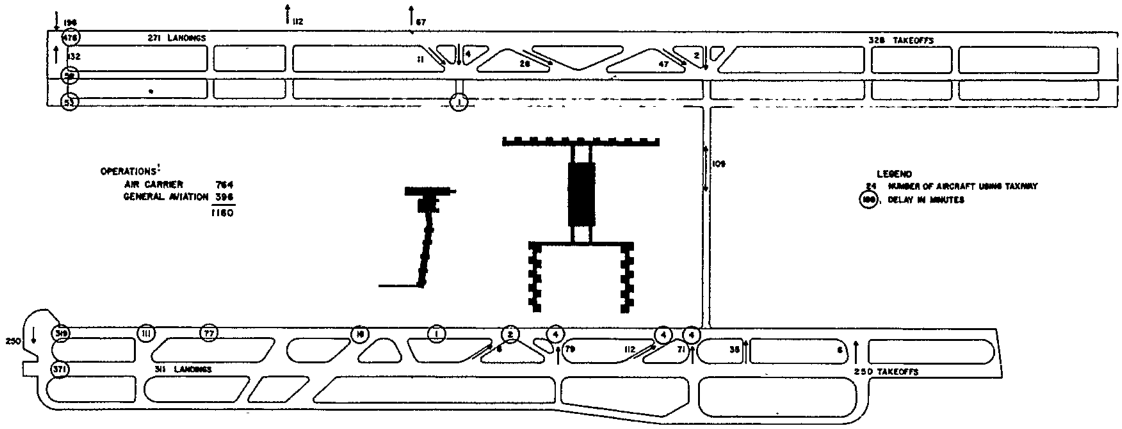
The ASM-2 simulation system has been implemented on the IBM 360 series computers. Runs have been made on 360-85, 360-75, and 360-65/67 to date. Core requirements vary from 300k to 450k bytes depending on the size and activity of the airport. Running time is less than 1 minute per day of simulation on the 360-85 for the simulation itself.

The simulation and schedule generator are

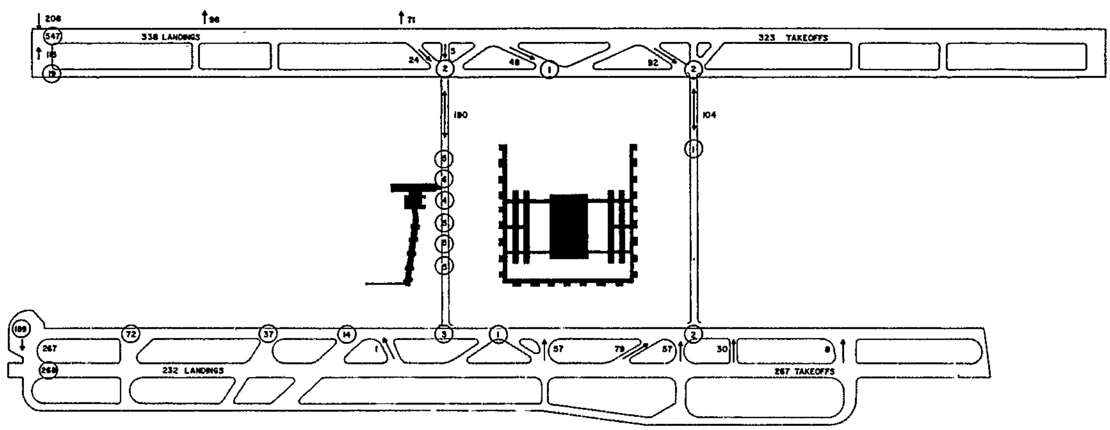
FIG. 4

RECORD OF TRAFFIC FLOW AND DELAY

CONCEPT B



CONCEPT C



CONCEPT B-C

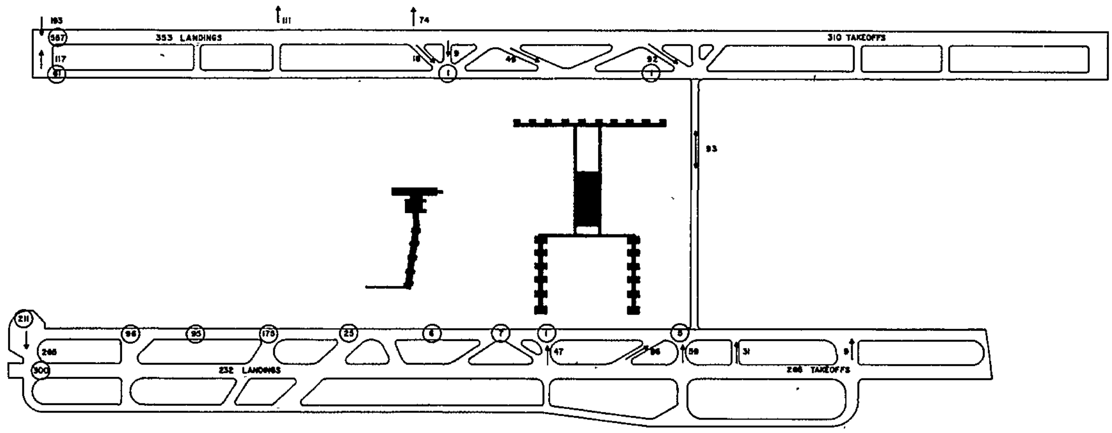
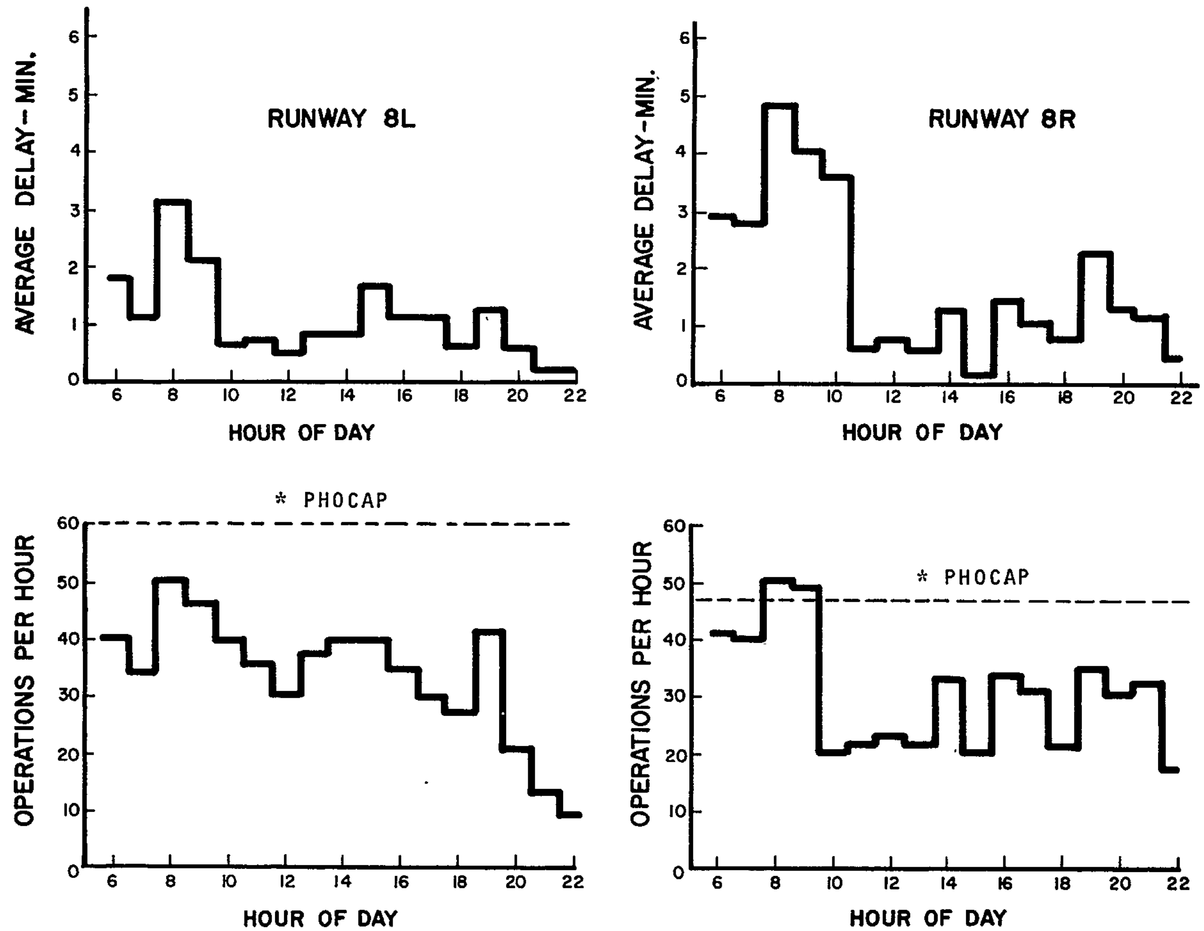


FIG. 5

AVERAGE DELAY BY HOUR ON A PEAK DAY – CONCEPT B



*Steady State Demand Producing 4 minute average delay per the analytical model.

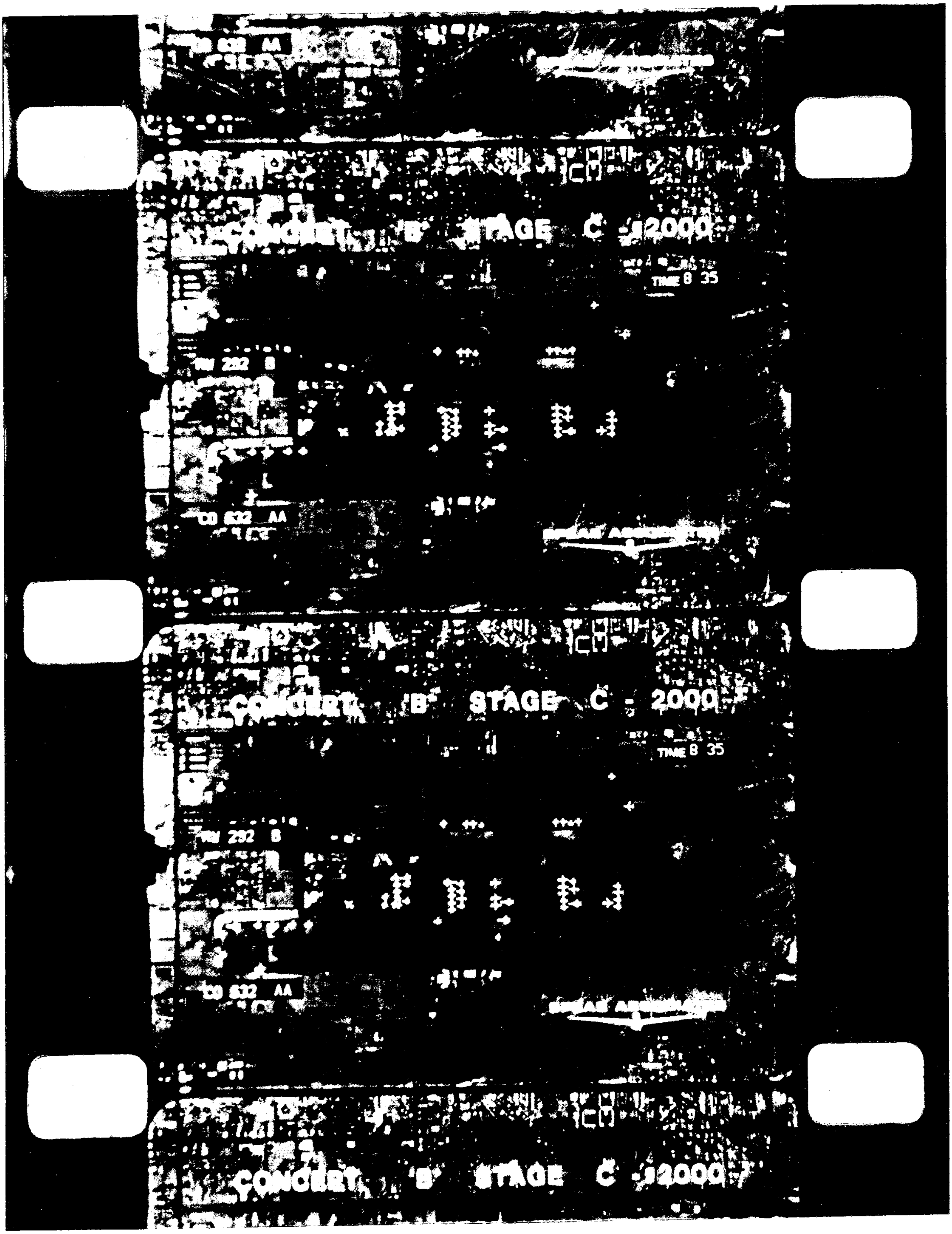

CONCERT 'B' STAGE C - 2000
TIME 8 35
CO 632 AA
CONCERT 'B' STAGE C - 2000
TIME 8 35
CO 632 AA
CONCERT 'B' STAGE C - 2000

FIG. 6

TABLE 2

RESULTS FROM SIMULATING
PEAK DAY OPERATION
WITH FIRST STAGE TERMINAL DEVELOPMENT

	MINUTES OF DELAY					
Concept	Taxi	Gate	Delay Cost($)	Taxi Stops	Miles Taxied	No. Aircraft Using Crossover Taxiways
B	73	984	21,242	930	952	109
C	71	1087	17,087	860	900	294
BC	96	927	20,233	933	910	93

written in SIMSCRIPT II Plus while the plotting and motion picture graphics routines are written in FORTRAN IV.

Choice of simulation language was guided by the desire to allow modelling to be performed directly in a high level language by analysts with a minimum of support from the programming staff in order to minimize the associated communication problems. SIMSCRIPT with its special simulation implementation and debug features was therefore chosen over FORTRAN.

Also, the general purpose format of SIMSCRIPT appeared to be preferable to the more structured form of GPSS since the model contains many special purpose routines for report generation, data input, routing of aircraft and generation of graphics output in addition to the queuing model type routines.

With SIMSCRIPT, additional capabilities can be added to the model as it is used and improved over the years without redesign or even recompilation of the basic program.

The motion picture plotting routines compute the position of each aircraft once each second and plot the corresponding aircraft figures on the face of a cathode ray tube. The cathode ray tube is photographed and the resultant high density black and white negative is optically combined with a color negative of the airport plan view to produce the final film. When projected at 16 frames per second, an hour of airport operation can be shown in about four minutes.

COMPARISON WITH ANALYTICAL MODELS

A considerable amount of work has been done on the formulation of analytical models for computing runway capacity and delay. The steady state formulation of the process for relatively simple queue disciplines employs closed form results based on queuing theory (1)(2) while the analytical models that accommodate time varying demand are generally formulated as Markov processes requiring solution of sets of differential state transition equations(3). While these analytical techniques are considerably more efficient than simulation with respect to computer time for idealized configurations of runways, they do not treat the taxiway system and terminal gates that, along with the runways, comprise the total airport. Also it may be quite difficult to incorporate seemingly minor operational changes in airport operation without completely revising the model. The direct correspondence between the simulation model and the real world, on the other hand, facilitates changes and modifications in the model without the need for major surgery.

It would appear therefore that both techniques will continue to be used: analytical techniques for capacity estimates of runway configuration, and simulation for detailed design of the total airport layout and operation.

A check of the simulation results obtained for the year 1983 simulation of the Phoenix Sky Harbor International Airport using the steady state model of reference 1 resulted in a practical hourly capacity (PHOCAP) of 60 operations per hour for the north runway and 48 operations per hour for the south runway, under the assumption that the north runway handles both general aviation and the smaller air carrier,while the south runway handles only air carrier including all heavy jets. Although it is somewhat difficult to compare steady state with time varying results these capacity ratings which are based on a four minute average delay appear quite reasonable when compared with the simulation results in Figure 5.

CONCLUSION

The use of computer-drawn motion pictures has proven to be a useful tool for visualization and validation of airport simulations. It would appear that this technique would also be of value for simulations in other areas such as studies of other types of transportation systems, production lines, and other processes where it is necessary to work closely with experts in the subject technology and to communicate with them in a common language.

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