V/STOL Airline System Simulation

JOEL F. KAHN*
Lockheed-California Company, Burbank, Calif.

This paper describes an economic computerized simulation model of an airline carrier, where a mix of aircraft (CTOL, VTOL, STOL) competes for passenger markets by satisfying a given level of passenger demand and preference. Data inputs consist of aircraft characteristics of performance and cost; route characteristics of distance, yields, and various routings; port characteristics by type, size, and location; passenger preference for out-of-pocket costs, flight frequency speed, demand, and value of time; level of operation defined in terms of both an adequate service to the passenger and a satisfactory return on investment to the carrier. Simulation and dynamic programming techniques are employed. The five steps of the process are 1) initialization of input passenger demand, 2) development of route interaction, 3) flight evaluation by aircraft types, 4) flight assignments, 5) system summarization and analysis. A marginal concept is used such that flights are added to the system on the basis of incremental earnings to the system as a whole and not on the basis of individual routes. A major output of the model is the system summaries of revenues and expense. From these data, airline return on investment may be determined.

I. Introduction

LOCKHEED Airline System Simulation (LASS) is a computerized model in use since 1959.[1,2] LASS is an economic simulation of airline operations, formulated for conventional fixed-wing aircraft (CTOL)-type operations. It has been used extensively in evaluation of aircraft and, most recently, for the economic analysis of the U.S. supersonic transport.

Short-Haul System Simulation (SHSS) employs much of the logic and concepts developed for LASS. However, SHSS allows competition among various aircraft types including CTOL, vertical takeoff and landing (VTOL), and short takeoff and landing (STOL).

The fundamental premise is that the aircraft being studied compete with each other for markets by attempting to best satisfy a given level of passenger demand and preferences, using economic criteria. In addition, the effects that V/STOL aircraft may have on surface transportation (auto, bus, rail) are included. In this paper, vertical and short takeoff and landing aircraft will be referred to collectively as V/STOL aircraft.

Prior to describing this Short-Haul System Simulation, a concept known as "value of time" warrants special consideration. A passenger considers both dollar costs and time costs of travel. Total out-of-pocket costs for a trip, in addition to the ticket cost, includes the cost of getting to the terminal for departure and getting from the arrival terminal of actual destination. These additional costs are for use of the passenger's private auto, taxi, limousine, or public transportation. The simulation will use this out-of-pocket cost of the various modes of transportation as the basis for comparison of passenger costs on competitive modes.

The value-of-time method of allocating demand between existing and proposed modes of transportation has frequently been postulated in literature concerning the future of V/STOL transportation in the United States.[3–6] This method recognizes that the air traveler considers more than the out-of-pocket expense of a trip when choosing between modes of transportation. It is obvious that in addition to this out-of-pocket expense, the traveler considers the time spent in traveling. A monetary value attributed to this time is some function of the traveler income level and the purpose of the trip. In other words, the air traveler is willing to pay more for a mode of transportation that saves time. A full description of the value-of-time method of allocation is presented in Sec. III.

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* Project Leader, Transportation Systems Analysis Department.

II. Data Inputs

Various inputs to the simulation are summarized in Fig. 1 and described below.

Travel Market

The travel market is described by the forecast traffic flows and the purpose of travel for each city-pair. Separate inputs are employed for passenger traffic demands by air and surface mode of transportation. As air service improves between a city-pair, part of the traffic will transfer to air service, depending on the purpose of travel and passenger preference.

Aircraft Characteristics

Complete performance and operating expense data are given for each candidate aircraft. The program simultaneously considers a mix of up to five aircraft. These can be any combination of CTOL, VTOL, and STOL.

Route Characteristics

These consist of distances, revenue yields, and routes to serve the demand. This model can accept nonstop-, one-stop-, and two-stop-type routings, in any combination, for service of a city-pair demand.

Port Characteristics

These consist of the type, size, location, and cost of local transportation to city-center if the port is not located at the city-center.

Passenger Preference

Passenger preference is based on the interrelationships of out-of-pocket costs (air fare and ground transportation fares if applicable), flight frequency, difference of trip times between modes of transportation, passenger demand, and the value of the passenger's time. Therefore, inputs include air and surface fares and trip times, city-center to airport fares and trip times, and value-of-time relationships for the various modes of transportation.

Level of Operations

The level of operations is defined in terms of adequate service to the passenger and a satisfactory return on investment to the carrier. Government or other subsidies, if necessary, are a part of the return to the carrier.

III. Method of Analysis

For the simulation to provide realistic answers, it is necessary to include consideration of the many pertinent variables, described previously, and their mutual interaction. Taken individually, the handling of these variables is simple and straightforward. However, when interaction effects are introduced, the number of calculations becomes so great that use of a high-speed, high-capacity computer is essential.

The computerized method employs simulation and dynamic programming techniques that are widely accepted operations research analytical tools. This method may be described as a five-step process:

Step 1—initialization of input passenger demands: determination of the potential transfer of auto, rail, and bus passengers to V/STOL service, assuming "infinite" V/STOL frequency.

Step 2—development of route interaction: determination of the interaction patterns of system traffic flows for each city-pair. A city-pair demand can be served by nonstop, one-stop, and two-stop routings. As many as 91 different routings could serve one city-pair demand.

Step 3—flight evaluation by aircraft types: evaluation of system economics that would result from assignment of one flight with each candidate aircraft on each candidate route. That one flight which possesses the best system economics is assigned.

Step 4—flight assignment: successive selection and assignment of route/aircraft combinations that produce the most favorable system economics, with suitable restraints for passenger preference.

Step 5—system analysis and summarization: continuation of steps 1–4 until a scale of operation is reached which will produce an acceptable degree of service to the passenger and profitability to the operator. Subsidy to the carrier, if necessary, will be included.

Revenues and expenses (and therefore earnings) associated with flight assignment are totaled on a system basis, and traffic flows on other routes affected by a flight assignment are continually updated. This results in consideration of total incremental system effects with each potential flight assignment.

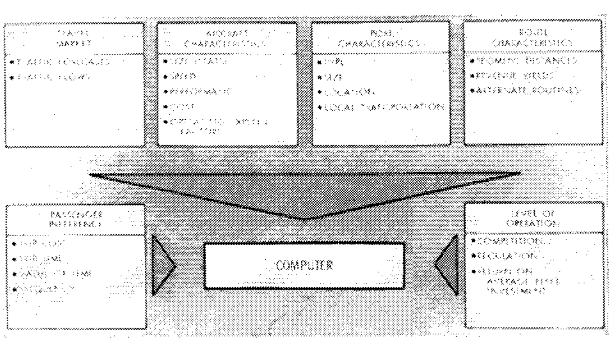

Fig. 1 Short-haul system simulation inputs.

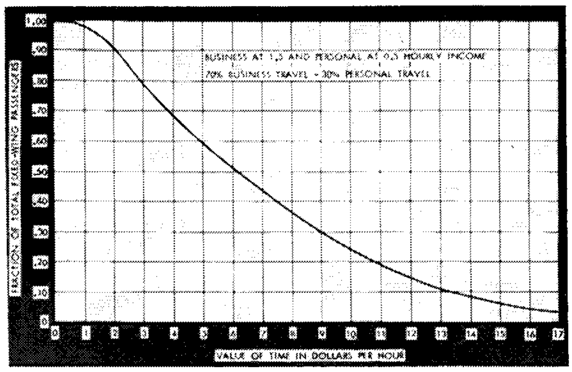

Fig. 2 Composite value-of-time distribution—1964 air passengers.

An expanded discussion of the five steps of the analysis method is provided to convey a more complete understanding of the simulation program and the method in which the input data are actually used.

Initialization of Input Passenger Demands—Step 1

The value-of-time concept is used to evaluate potential transfer of passengers to V/STOL service from alternate modes of transportation. To apply the value-of-time method, trip times and costs associated with each alternate mode of transportation and value-of-time to travelers must be known.

Value-of-time to air, auto, rail, and bus travelers is derived using as a base the income distribution of these travelers. One source for these data is the Michigan University National Travel Surveys. Average earnings per hour are calculated according to incremental income groups by dividing the average annual income by the average hours worked during the year. Business and nonbusiness travelers value their time on different standards. One assumption is that business travelers value their time at $1\frac{1}{2}$ their hourly earnings and nonbusiness travelers at $\frac{1}{2}$ their hourly earnings. Using this assumption, along with a 70-30% split of business and nonbusiness travelers, a value-of-time distribution for air travelers is shown in Fig. 2. Rail and bus travelers have similar, but different, distributions.

For each input city-pair, the cost per hour saved is computed for V/STOL aircraft against each alternate mode of transportation. Using air travelers as an illustration, the cost per hour saved is derived by dividing the additional trip cost of the V/STOL as compared to the CTOL by time saved between the city-pair. To illustrate, assume the CTOL trip cost (air fare plus ground transportation costs to and from the airport to city-center) is \$20.00 and total trip time is 2 hr. For V/STOL the trip cost is \$24.00 and trip time is $1\frac{1}{2}$ hr. Thus the cost per hour saved is

$$\frac{\$24 - \$20}{(2 - 1.5)\ \text{hr}} = \$8.00/\text{hr}$$

Entering this value into the distribution of Fig. 2, it is found that 36% of the air travelers value their time at least at this amount and would be in potential demand for V/STOL service, if adequate frequency were available. Potential V/STOL demand from air travelers is found by taking this percentage of the city-pair input air passenger demand.

In this first step the computer evaluates potential V/STOL demands from air, auto, rail, and bus in the manner described. Actual demand generated and allocated to V/STOL flights depends upon the frequency of V/STOL flights. This will be explained in Step 3.

Development of Route Interaction—Step 2

Route interaction is the combined effect of a single flight addition on other nonstop, one-stop, and two-stop routings

Fig. 3 Primary route interaction.

within the system. These effects are far-reaching and must be evaluated to determine incremental system-wide effect of each potential aircraft/routing combination. As an example, addition of a nonstop flight between A and D will affect traffic on other routings that serve A to D passengers, Fig. 3. All one-stop routings, such as A-E-D, and two-stop routings, such as A-B-C-D, are re-evaluated when the A-D flight is considered. Flights that provide nonstop service to A-D passengers but continue on to another city are also affected. A-D-F is an example of this route type.

Route interaction affects routes other than the primary one-stop and two-stop routes described (A-E-B, A-B-C-D). As passenger loads on the individual legs of these primary interacting routes are changed, effects are felt on other routes that provide passenger service on these legs. For example, the change in traffic on the A-B-C-D route will in turn cause changes in loads on the A-C and A-G-B flights, Fig. 4.

When considering the addition of a single flight on A-B, one also considers the effects of such secondary interaction as well as the primary interaction. Further, as each aircraft/routing combination is in turn evaluated for potential assignment, routes formerly under consideration for assignment become interacting routes. For example, when route A-C is evaluated for potential assignment, route A-B-C-D will be one of the interacting routes.

Flight Evaluation by Aircraft Types—Step 3

Flight assignments are made on the basis of obtaining the most favorable system economics. This requires knowledge of the operating income, which is derived from operating expenses and operating revenues.

Operating expenses

The decision to assign an aircraft on a route is made on the basis of revenues and expenses. Expenses considered in this decision are marginal expenses, which are the total incremental system expenses resulting from each potential flight assignment.

Direct operating expenses are included in marginal expenses, and are computed on the basis of input factors for each aircraft type (fuel consumption, price of airframe, engines, and spares, depreciation schedules, crew costs, maintenance costs, insurance). Appropriate input factors such as flight hours, block hours, utilization hours, labor dollar hours, and fuel costs are used to compute direct operating expenses.

To these direct expenses are added the indirect operating expenses, which are allocated on a flight-by-flight basis (the marginal indirect operating expenses). These include landing fees, stewardess expenses, ticketing expenses, and so forth. The remaining indirect operating expenses are not considered during the flight-assignment phase, but are included in the total system expenses in the summary. These are expense items that remain essentially fixed for a single flight assignment but change gradually as the total scale of operations is varied. It is pertinent that all expenses, as well as revenues, are continuously updated as flight frequency is varied.

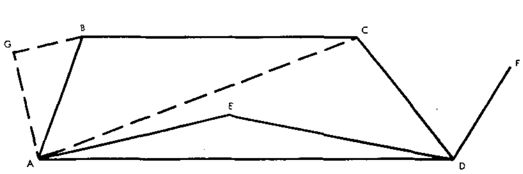

Fig. 4 Secondary route interaction.

Operating revenues

Operating revenues are determined on the basis of 1) the number of passengers served and 2) revenue yields. Determination of the number of passengers served is most significant and requires the bulk of the discussion. Revenue yields are obtained by weighting the classes of fares offered to arrive at the average yield per passenger.

When calculating the number of passengers served, one evaluates competitive differences in passenger preference. Experience has shown that passengers have a strong preference for fast service. It is well known that passengers prefer low fares, even at some sacrifice in seat spacing or other convenience factors. For short-haul systems, these concepts are extended so as to be defined as total trip fare and total trip time and not just the fare and time of the principal mode of transport. Passengers seeking service are allocated sequentially to each aircraft on the basis of 1) frequency of service, 2) fare preference, and 3) speed preference.

Frequency allocation

The frequency-allocation function is used to generate passenger demand at any specific flight frequency from the potential demand. Potential demand is defined as the limiting demand obtainable when flight frequency is at infinity. Therefore, the actual demand obtained depends upon the number of flights assigned. This function is based on the normal probability function and takes into account variations in competitive transportation trip times. The input parameters for the function are based on current trip times, and are adjusted within the simulation to the trip times of the actual aircraft assigned.

The frequency allocation function is used to 1) generate the total air demand from the input air potential demand. 2) generate the V/STOL air demand from the generated air demand and value-of-time computations of step 1. CTOL air demand is obtained from the difference between the total air demand and V/STOL air demand. 3) Generate V/STOL demand transferred from the input rail and bus demands using the value-of-time computations of step 1. As flights are increased, one by one, these demands are regenerated using the total frequency of the various aircraft being evaluated at that time. Generation of total air demand will be used to illustrate the frequency allocation function.

Figure 5 illustrates the effect of flight frequency on passenger demand for service, taking into account variations in

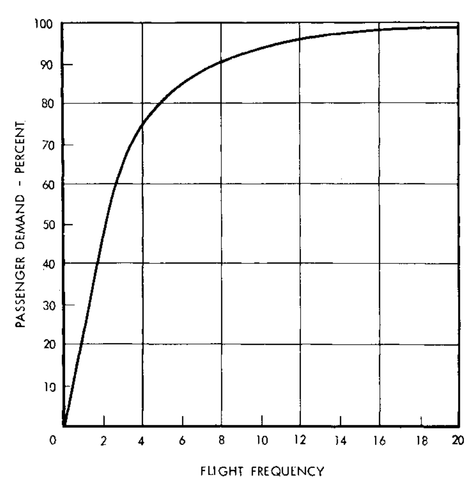

Fig. 5 Demand vs frequency.

competitive ground transportation travel time. On the basis of this figure, one can compute the percent of the total number of potential air passengers who will seek air service for any flight frequency per day, given the ground travel time. Here, the total number of potential air passengers consists of those who would fly if there were a continuous "conveyor" of seats between the origin and destination. Since continuous (conveyor) air service is not provided, some potential passengers will use the surface mode because it is more convenient.

For a given surface travel time, the percent of potential airline passengers who will seek service can be computed for any given frequency. An example of a high-demand, short-distance market of Fig. 5 shows that one flight per day will find about 20% of the total passengers seeking the service. With two flights this grows to about 39%, and when 20 flights per day are offered, the demand increases to 98%.

With demand generated for CTOL and V/STOL aircraft, allocation to each aircraft type is accomplished by allocating the CTOL demand to various CTOL aircraft and then allocating V/STOL demand to the various V/STOL aircraft. The following allocation procedures may be applicable to either type of aircraft.

Fare allocation

The two terms that relate travel habits to fares are external-fare elasticity and cross-fare elasticity, as defined by

$$\text{External-Fare Elasticity} = \frac{\text{Percent Change in Amount of Travel}}{\text{Percent Fare Differential}} \quad (1)$$

$$\text{Cross Elasticity} = \frac{\text{Percent Passengers Diverted to Low Fare Aircraft}}{\text{Percent Fare Differential}} \quad (2)$$

Basic forecasts of air passenger traffic do not take into account any additional traffic generated by airplanes operating at fares significantly lower than the forecast fare. The concept of external-fare elasticity is used to estimate the effect of lower fares on the demand for air travel. This elasticity depends largely on the purpose of travel and has a value of 0.1 for business travel, as compared with 1.4 for nonbusiness travel. This is based on estimates resulting from discussion with airline planning and marketing personnel. Basic traffic forecasts implicitly assume that there will be some response to any fare differential between faster, higher-fare aircraft and slower, lower-fare aircraft. This is measured by cross elasticity, and the value depends largely on the purpose of travel. A constant value of 0.1 is assumed for business travel as compared with a value of 2.0 for nonbusiness travel. It was assumed that the business travel market is inelastic.

Absolute trip time allocation

A faster aircraft may depart later than its competitor and arrive at the same time, or it may depart at the same time and arrive earlier. Even though it is unlikely that a carrier with slower aircraft would attempt to compete in this manner, the concept forms a reasonable basis for allocating to the faster airplane all of the demand that exists in the time interval between departures. If this situation exists in a market that can support many flights per day, the faster aircraft can be scheduled to blanket the flying day. Under these conditions, the major part of the demand, if not all, will be allocated to the faster aircraft.

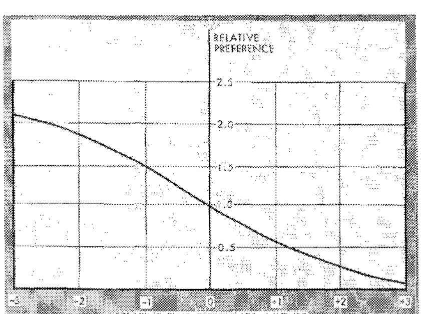

Fig. 6 Relative allocation.

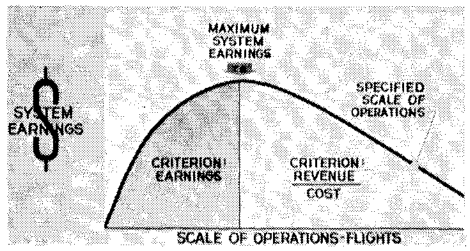

Fig. 7 Systems earnings vs scale of operations.

Absolute trip time allocation ratio is expressed mathematically by the equation

$$\frac{\text{Absolute Allocated Traffic}}{\text{Total Traffic}} = \frac{\text{Block Time Difference}}{\text{Hours in Operating Day}} \times \text{Flight Frequency} \quad (3)$$

Relative allocation

Relative allocation is based on passenger preference, frequency, and capacity of the service offered. Since it is relative, it is calculated from a reference or standard service, in this instance a standard fixed-wing aircraft in service today. Frequency and capacity are self-explanatory. Determination of passenger preference is based on a combination of total trip time and out-of-pocket costs. To combine these mathematically, they must be expressed in similar units. The unit used is hours. Therefore, the trip time value is found as the difference between selected aircraft and reference aircraft. Out-of-pocket costs are divided by the value-of-time, which is expressed in dollars per hour. Now, this cost-of-time value is found by a similar subtraction between the two aircraft. The curve of Fig. 6 shows the form of this preference function. In deriving this figure, the reference aircraft has a relative preference of 1.0. An aircraft with a smaller value of reference time, thus saving time for the passenger, will have a value of greater than 1.0. Conversely, an aircraft with a greater value of reference time is less preferred and will have a value less than 1.0. Relative allocation is also used to allocate to the various V/STOL aircraft the V/STOL generated demand from surface modes.

Flight Assignment—Step 4

As the scale of operations grows through the process of adding more and more flights, system earnings will follow a pattern similar to that shown in Fig. 7. During the first phase of flight assignment, the computer is continually asked, Which flight with which aircraft, if added, will produce the maximum increment of earnings? This question is repeated until no flight with any aircraft on any route can be added which will increase earnings. Thus, the point of maximum system earnings is determined by computer.

Airlines normally conduct their business on a much larger scale of operations than that which would provide maximum system earnings. Otherwise, average load factors on the order of 75 to 80% would be achieved, resulting in a considerable amount of unserved demand. During peak periods, such as Friday afternoons, passengers seeking service would not be served. Further, people in low-density markets might receive no service at all. Thus, competition and government

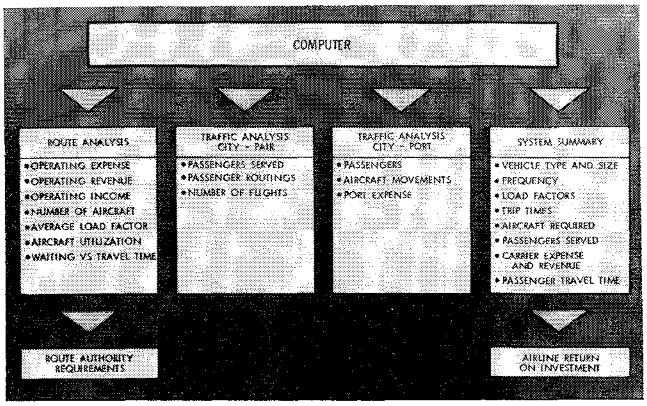

Fig. 8 Short-haul-system simulation outputs.

regulations, designed to provide adequate service, require expansion of the scale of operations beyond the point of maximum earnings.

In this phase of the computer program, the question is continually asked, which flight with which aircraft, if added, will produce the largest increment of revenue compared to the added increment of cost? Flights are added until some specified level of operations is reached, such as a predetermined rate of return on average total fleet investment or the assignment of all available aircraft.

System Analysis and Summarization—Step 5

Various input criteria for levels of operation that can be selected, either individually or in combination, are maximum earnings, fleet limits, load factor, and return on investment. To establish realistic conformance with regulatory and competitive forces, the scale of operations is usually expanded past the point of maximum earnings. The point at which all available aircraft of a particular type are fully utilized is called the "fleet limit" stop. This can occur before or after the maximum earnings point, depending on the number of aircraft available. The scale of operations can be expanded to produce a selected load factor for any specific aircraft fleet. The scale of operations can also be expanded until each of seven specified returns on investment is obtained. Results that would be obtained, should the scale of operations be stopped at each of these points, are printed out and summarized. Thus, it is possible to determine up to ten points on the scale of operations curve, and this curve may then be used to determine a realistic scale of operations.

IV. Outputs

A summary of the outputs is presented in Fig. 8. A description of these outputs follows.

Route Analysis

The printout consists of a listing of operational traffic results for each input route. For each type of aircraft assigned, the following data are included: 1) trip distance from port to port, 2) trip time from port to port, 3) passenger time portal to portal, 4) passenger load factor, 5) number of flights, 6) total capacity, 7) passengers served, 8) total revenue, 9) total direct operating expense, 10) direct operating expense per available seat mile, 11) number of aircraft required for route, and 12) average amount of cargo per trip, lb.

Traffic Analysis—City-Pair

This printout consists of a listing of each input city-pair. For each city-pair all available input routings serving the city-pair are listed, together with the number of flights and passengers served on that route by each aircraft type. The data are totaled by aircraft type and for the city-pair. The total demand, percent business traffic, and airline market share are listed.

Traffic Analysis—City-Port

This printout consists of a listing of each input city-port. For each city-port all available routings operating from the port are listed, together with the number of operations and passengers by aircraft types. The total number of operations and passengers is totaled by aircraft type and city-port. Port expenses paid by the carriers are shown.

System Summary

The system operational and economic results for each aircraft type and for the total fleet are listed in this printout. Data included are 1) average flight distance, 2) average passenger load factor, 3) number of passengers served, 4) passenger miles, 5) passengers transit time, 6) revenue received, 7) direct operating expense, 8) direct operating expense per available seat mile, 9) aircraft utilization (block hours), 10) number of aircraft required, 11) cargo tons carried, 12) cargo ton miles, 13) number of flights, 14) depreciation, 15) total earnings, and 16) system return on investment.

V. Data for Other Programs

Airline Return on Investment

When the simulation is computed on a yearly basis, economic inputs necessary for calculating discounted cost flow rate of return are obtained from the system summary. For this purpose total costs by aircraft types are available without depreciation expense, so that the cash flow program can recalculate depreciation on any acceptable accounting method desired.

Route Authority Requirements

Any route pattern may be input to the program. If new routings are proposed, they may or may not be authorized. Therefore, all input routings that are assigned can be investigated through the use of the existing route authority program, from which needed new authorizations can be found.[7]

VI. Current Limitations

The operational program described does not consider time-of-day scheduling explicitly. It does assume, however, that flights assigned will be scheduled to accommodate the demand distribution. A time-of-day scheduling model is being developed to consider this important concept so that it can be incorporated into the simulation.[8]

The simulation, as described, will return only one solution for a given set of inputs. This does not allow various solutions for evaluating tradeoffs in system design, or economic restraints such as fleet retirement policies. Procedures already incorporated into the program for tradeoff analysis include the following:

1) Each aircraft type can be limited or unlimited as to the number of aircraft available to the system.

2) The aircraft types can be restricted from serving any airport or any routing.

3) A fixed frequency of flights by aircraft type and route can be initially input into the simulation; this system is computed and output results obtained. The simulation can stop at this point or continue from this input to optimize the system.

Procedures that are being investigated for future inclusion follow:

1) Time of day as referenced previously.

2) Minimum frequency restraints input by city-pair. With this modification, minimum service requirements and competitive influences can be added as restraints.

3) A variable share of the market procedure to be input by city-pair. With this modification the airline's current market share could be modified to agree with the flight frequency obtained in the simulation, in proportion to the frequencies of the competition.

4) Inclusion of air delay, especially to fixed-wing aircraft, to more adequately compute true trip times and utilization. Air delay is becoming of increasing importance and realistic data are now becoming available.

Current analyses obtained from using the simulation have produced creditable results but have, as usual, produced additional questions for research in various areas, including a more refined value of time formulation and a better approach to the criterion function after maximum earnings with respect to possible flight removal.

The city-port analysis section has not been fully implemented since the system envisioned for the 1970's is not now in existence. This area of vertiport systems costs is being investigated and will be added to the program when feasible data are premised.[9]

VII. Conclusions

V/STOL operations described by this paper are not in operation today. It is the purpose of the simulation analysis to determine the problem areas that will be encountered and help in finding adequate solutions. If the commercial air transport industry is to continue to grow into the 1970–1980 time period, solutions to the ground and air congestion problems about the major airports must be resolved. The moving of the large-demand short-distance intercity flights away from conventional airports to easily accessible V/STOL ports is a step forward towards the solution. This economic simulation is geared toward determining costs and benefits of introducing V/STOL systems which are the concern of the aircraft manufacturers, airline operators, local and national agencies, and most of all, the air travelers.

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Advanced-Composite-Material Application to Aircraft Structures

CHARLES W. ROGERS*
General Dynamics Corporation, Fort Worth, Texas

The initiation of flight testing of aircraft structures utilizing advanced composite materials in January 1967 marks a major milestone in the development of this new material concept. Specific developments in the boron fiber-reinforced plastic tape systems leading to this accomplishment will be discussed, together with design, analysis, and fabrication techniques. Composite test results emphasize the need for fiber spacing control and matrix toughness. Data through the 420°F temperature range demonstrate the advantages of this material over other materials. Analytical procedures for predicting laminate stiffness and yield strength have demonstrated satisfactory results with an assumed yield surface theory. A digital program has been written to aid the designer in selecting the minimum-weight laminate for a given point load or stiffness requirement. The flight-test component design features and static test results will be discussed.

I. Introduction

A TEST airplane flew a routine flight-test mission on January 3, 1967 utilizing a component made with an advanced fibrous-reinforced composite. The part used was the left-hand inboard airflow director door, a 1- × 6-ft × $\frac{1}{2}$-in.-thick actuated panel located on the lower surface of the wing. The composite constituents were boron fibers produced by the halide process within an epoxy matrix.

This flight mission, the first in an environmental test program of one year's duration, marks a major milestone in the development of advanced composite materials for aircraft. Under the direction of the Advanced Fibers and Composites Division of the Air Force Materials Laboratory, the Fort Worth Division of General Dynamics Corporation, in conjunction with IIT Research Institute and Texaco Experiment

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* Program Manager, Research and Development of Advanced Composites. Member AIAA.