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TRANSPORTATION SYSTEMS EVALUATION

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TRANSPORTATION SYSTEMS EVALUATION

1.0 INTRODUCTION

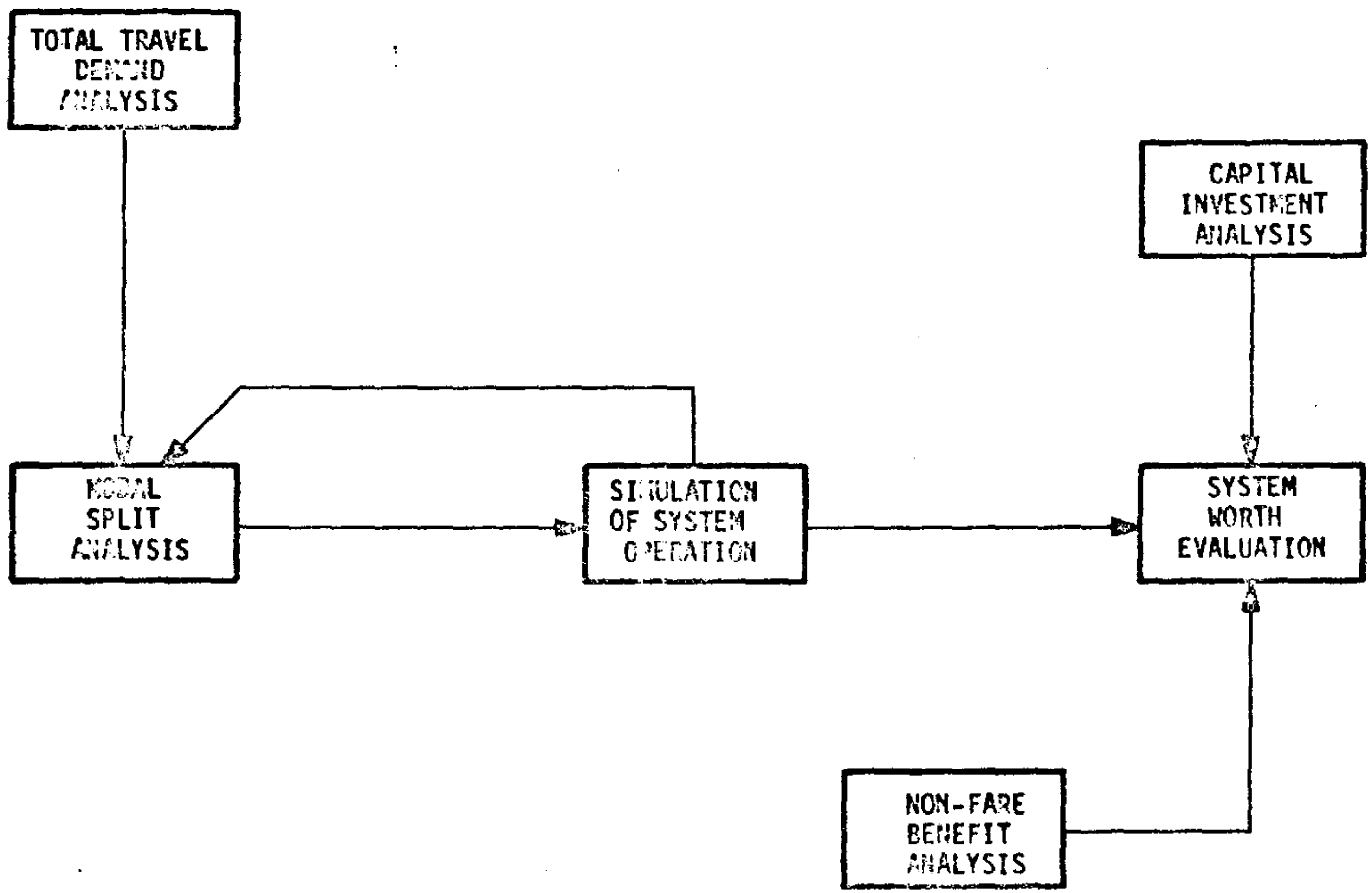
For a number of years, the Operations Research/Management Sciences staff of Boeing Computer Services, Inc., a wholly owned subsidiary of The Boeing Company, has been actively engaged in the development of analytical tools for analyzing transportation requirements and associated systems. The purpose of this paper is to present a framework for analyzing transportation systems which accounts for the interaction between demand and system performance. This framework is applicable to systems ranging from intraurban Personalized Rapid Transit System (PRT) networks to trunk airlines. It has evolved from and been used in studies of inter and intra urban air, ground, and water transportation systems to move both commodities and people.

In order to illustrate the flexibility of this methodology, intra and inter problems will be discussed in what follows. In Section 2 the framework is presented; Section 3 consists of a lengthy example showing how the approach was used to study an intraurban commuter air system. Finally, in Section 4 a proposed study using the approach to investigate Personalized Rapid Transit (PRT) is described.

2.0 ANALYTICAL FRAMEWORK

The steps required to analyze a transportation system are shown in Figure 1. The procedure begins with the calculation of travel demand. Then, based upon assumed performance, the demand is split between travel modes. Next, the system is simulated and performance is calculated. This performance level is fed back and a new modal split is calculated. When assumed performance and calculated performance are equal, the cost and revenues of the system are calculated. Capital costs and non-revenue benefits are also calculated. Finally, the system is evaluated based upon accurate estimates of service level, capital costs, non-revenue benefits and operating costs and revenues. Each of the above functions will now be described in more detail.

TRANSPORTATION SYSTEMS ANALYSIS



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2.1 TOTAL TRAVEL DEMAND ANALYSIS

The first step of the analysis is to calculate total demand for travel for the region under study. Past and forecasted demographic and geographi characteristics of the study areas together with current travel patterns form the basis of the analysis. In particular, land use forecasts may enter the analysis at this stage.

To begin the demand analysis for the intraurban problem, the study region is broken into analysis zones by the analyst. Information describing each zone is fed to the program. Base year travel information from a travel survey (if available) is also given to the model. The model calculates total travel (by all modes) between all zone pairs. The analyst produces time of day and day of week distributions of demand.

The intraurban demand model consists of two parts; Trip Generation and Trip Distribution. The former creates a forecast of total trips produced in and attracted to each analysis zone. The trip distribution portion spreads the trips (calculated in the trip generation phase) over all zone pairs. It is this trip table which is needed by the modal split model.

Demand forecasts for the airlines are based upon the CAB traffic surveys and econometric forecasts of basic economic variables. For the domestic trunks, for example, the first step is to calculate total RPM for the desired year from the forecast of GNP and other economic variables. Next, the demand is assigned to city pairs. The assignment for a given city pair depends upon the share of the total RPM carried by that city pair in the past. Different growth rates are forecast for different city pairs depending upon whether the market is new or mature. The result of the assignment is total origin and destination travel for each city pair.

2.2 MODAL SPLIT ANALYSIS

The function of the modal split module is to apportion the total demand, previously calculated, to the various travel modes available. Required inputs are user costs and times for each mode to be considered, and users attitudes towards the competing modes. Output of the module is a market share forecast for each mode. This forecast is based upon assumed performance levels and hence is a preliminary estimate of market shares. After the system is simulated and true performance calculated, a new modal split must be performed.

2.2.1 INTRAURBAN MODAL SPLIT

A marginal utility approach forms the basis of the intraurban modal split model. The utility of a mode to a given user is calculated as a function of its time and cost and the income of the user. Attitudes toward travel modes can be incorporated into the model. The marginal utility of one mode over another is simply the difference between the two utilities. The percentage of travellers taking one mode instead of another is calculated from this marginal utility.

To calculate the market share for each mode, the marginal utility analysis is applied to each zone pair separately. Access and egress times and costs, waiting times, parking costs, line haul times and costs are all calculated for each zone pair. From these, the utilities of each mode and hence the market shares can be determined. In addition to market share, the model calculates demand for transit by station pair. This is the information needed by the simulation model. This approach is used for intraurban systems as well as short haul air systems in which auto, bus, and train are significant competitors. For long haul air systems a different approach is taken.

2.2.2 INTERURBAN MODAL SPLIT - PASSENGER PREFERENCE ANALYSIS

For nearly all interurban markets the total demand for air service can be calculated from the CAB surveys, as was described in the demand analysis section. The modal split problem in this case involves assigning demand to the competing airlines. Historically this was done according to number of frequencies offered. With the advent of significant differences between equipment (e.g. wide and narrow bodies) simply using relative frequencies to calculate market share produced incorrect answers. Our technique involves carrying out surveys to obtain passenger reaction to the equipment and then calculating market share from these ratings, airline image and frequency. To finish the demand calculation, the market share must be multiplied by the true O & D traffic previously computed, to obtain daily O & D traffic for each airline for each city pair. The final step is to convert the O & D into segment flow.

In order to calculate the type and effects of passengers equipment preferences, we have carried out several surveys. These include in-flight as well as mock-up surveys on several different airlines. Over 14,000 people have responded to these surveys.

The basic tool we have used to quantify peoples' subjective feelings is a survey form which asks a respondent to rate certain aspects of his trip on a scale from 1 to 9. Descriptors are furnished for each aspect to define the scale. For example, when rating seat comfort, a rating of 1 is defined to mean narrow, cramped and hard, 5 means moderate width and leg room and 9 means ample width and leg room. The resulting ratings are amenable to statistical analysis. This technique has been used in situations other than travel surveys. For example the Air Force uses it for personnel evaluation, as does BCS, and it has been used in the white goods industry.

Our surveys have covered a wide range of equipment, both wide and narrow aircraft in many configurations. The mock-up surveys tested reaction to characteristics such as seat comfort, spaciousness, and cabin appeal as well as many other aspects of an aircraft. The in-flight surveys tested these reactions as well as the reaction to flight experience variables such as smoothness and service.

The mock-up and in-flight surveys produced similar results. The relative importance of the characteristics common to both sets of surveys were the same. In particular, it was found that seating comfort, spaciousness, and cabin appeal ratings were sufficient to predict overall flight ratings in the mock-up survey. To these, service and flight smoothness need to be added to predict overall ratings for the in-flight survey.

In order to rate equipment for which no survey has been conducted, relationships between physical characteristics and passengers attitudes have been produced from survey data. For example for a given pitch, seat comfort ratings corresponding to various seat widths used in the surveys are used to produce a curve of rating as a function of width. Such curves can be produced for several pitches. When a new airplane is being considered, its seat comfort rating can be obtained from its seat width and pitch by using the curves.

One of the questions asked on the in-flight surveys requested the time interval within which a passenger was willing to re-schedule his flight in order to fly on the particular aircraft he chose. From the responses to this question we produced curves showing the percent of people willing to re-schedule their flights as a function of the deviation from the desired departure time. Different curves apply to different aircraft. These curves allow one to predict flight loads for different equipment given the schedule and the passengers arrival rate curve.

One main purpose of the surveys was to produce data allowing more accurate market share calculations. A computer program was written including time of day demand, variations, equipment preferences, and airline image in the market share calculations. This program gives roughly the same answer as the simple formula shown in Figure 2. In the formula P_A is the preference for flight A, including the equipment rating and airline image.

The formula and simulation model were both applied to a market (JFK-LAX) for which on board load data was available. Both the simulation and the formula gave answers which differed from the observed loads insignificantly.

Using either the formula or the computer simulation one calculates the market share for each airline in each market. These percentages are multiplied by the total O & D air travel, previously calculated, for each city pair. The resulting O & D demand can then be converted into segment flow (on board loads) using our segment flow model.

TO DETERMINE MARKET SHARE

- FOR COMPETING AIRLINES WITH SIMILAR IDENTITY & ABOUT EQUAL SCHEDULE ADVANTAGE:

MARKET SHARE FOR ONE FLIGHT OF TWO

$$= \frac{P_A}{P_A + P_B}$$

MARKET SHARE FOR ONE FLIGHT (A) OF SEVERAL

$$= \frac{P_A}{P_A + P_B + \ldots\ldots\ldots P_N}$$

- IF CLOSEST FLIGHT SEEKERS (C%) ARE INCLUDED:

MARKET SHARE FOR ONE FLIGHT (A) OF SEVERAL

$$= (1 - C) \frac{P_A}{P_A + P_B + \ldots\ldots P_N} + \frac{C}{N}$$

- FURTHER CORRECTIONS CAN BE MADE USING AIRLINE IDENTITY FACTOR

FIGURE 2

.3 SYSTEM SIMULATION

So far we have shown how demand can be calculated and split between competing transport modes for a variety of transportation systems including intraurban transit and airlines. The process described produces an interim estimate of modal split based upon assumed system performance. The system must be simulated to get actual performance. This information is then given back to the modal split module. The process ends when assumed and actual performance coincide.

The market share forecast produced by the modal split module, in addition to the specifications of the system are the inputs required by the simulation module. For a new system, the simulation must be done by actually having the computer assign passengers to vehicles, move the vehicles to their destination, etc. For existing systems, an analytical approach may be satisfactory. The result of the simulation is a set of operational data showing how the system performed. This includes vehicle requirements, loads, and utilization. Another result is the cost and revenue information required to calculate operating profit. The average time a passenger was forced to deviate from his desired departure time is also calculated. This "average passenger waiting time" must be compared with that assumed in the modal split calculation.

Once the simulation has been run, complete information regarding system operation is available. This information includes: average vehicle utilization, number of vehicles used and vehicle loads, among other operational statistics. For a transit system, labor requirements are calculated from the operational data and then labor and non-labor costs are calculated. Finally, G & A costs are added to get full system operating costs.

For an airline, the routing and scheduling done by the simulation model allows accurate cost calculations. Cash DOC (excluding hull insurance and depreciation) is calculated from the ATA or some similar formula for each flight. Depreciation and insurance are calculated for each aircraft. Thus no utilization assumption is required. Further, having all details of the system operation (e.g. number of peak hour movements at each airport) allows one to base the IOC calculation upon system elements which actually cause IOC.

2.4 CAPITAL INVESTMENT

The capital investment module determines the cash required for debt service for each year the system operates. The vehicle requirements have been determined by the operating simulation. Other capital expenses, (e.g., guideway construction, computers, station construction) are required inputs to the model.

For a municipally owned transit system, this module balances capital requirements against available funds. During the construction phase, any capital expense not covered by specified grants is assumed to require municipal bonds. The capital investment module "issues" such bonds when needed. For the operating period, the module calculates yearly operating surpluses necessary to cover debt service. The module also calculates the present value of this stream.

For an airline we have available a financial analysis program which treats taxes, fleet additions and retirements, investment tax credit and all other financial aspects of airline operation.

2.5 SYSTEM WORTH EVALUATION

The results of the previous four modules together with the results of the non-fare benefit analysis come together in the system worth evaluation. This process is not computerized. It requires an analyst and must be specially tailored to each application. Usually several different transportation systems are compared with respect to some criterion, e.g., maximum profit, within certain constraints, e.g., adequate service level and sufficient transit ridership. The aim is to find a balanced transportation system for the study region. Usually many systems need to be processed through the model before an adequate system worth evaluation can be made.

The economics of a transit system don't tell the full story. In some cases community values will be better served by a system with poorer economics but better non-fare benefits. In some cases the non-fare benefits are directly measurable economically, e.g., taxable real estate retained rather than lost to parking. In some cases the economic benefits are harder to measure. Where possible, these benefits are evaluated economically by the non-fare benefits module.

Figure 3 shows how the results of the capital investment and simulation modules interact. The capital investment module gives the operating surplus required, whereas the simulation module shows the operating surplus achieved. If an insufficient operating surplus is achieved, some aspect of the system must be modified, e.g., fare level, number of vehicles, size of vehicles, station locations. This modification will effect modal split, so that an entire new analysis is required.

2.6 SUMMARY OF FRAMEWORK

Figure 4 shows the structure of the entire model. Any transportation study must cover all the elements shown in this chart. The major advantage of TSEM (Transportation System Evaluation Model) is that all the elements are linked together so that interactions between the elements is considered. The fine level of detail treated by TSEM allows accurate systems evaluation, which in turn makes possible intelligent transportation planning.

3.0 EXAMPLE - INTRAURBAN AIR SYSTEM

A study which Boeing performed for NASA shows clearly how the methodology described previously can be applied. The purpose of the study was to test the feasibility of using V/STOL aircraft in commuter service. All aspects of the system were to be studied. In addition to the base case results, many sensitivity studies were to be conducted. Important areas for future research were to be identified.

CASH FLOW ANALYSIS

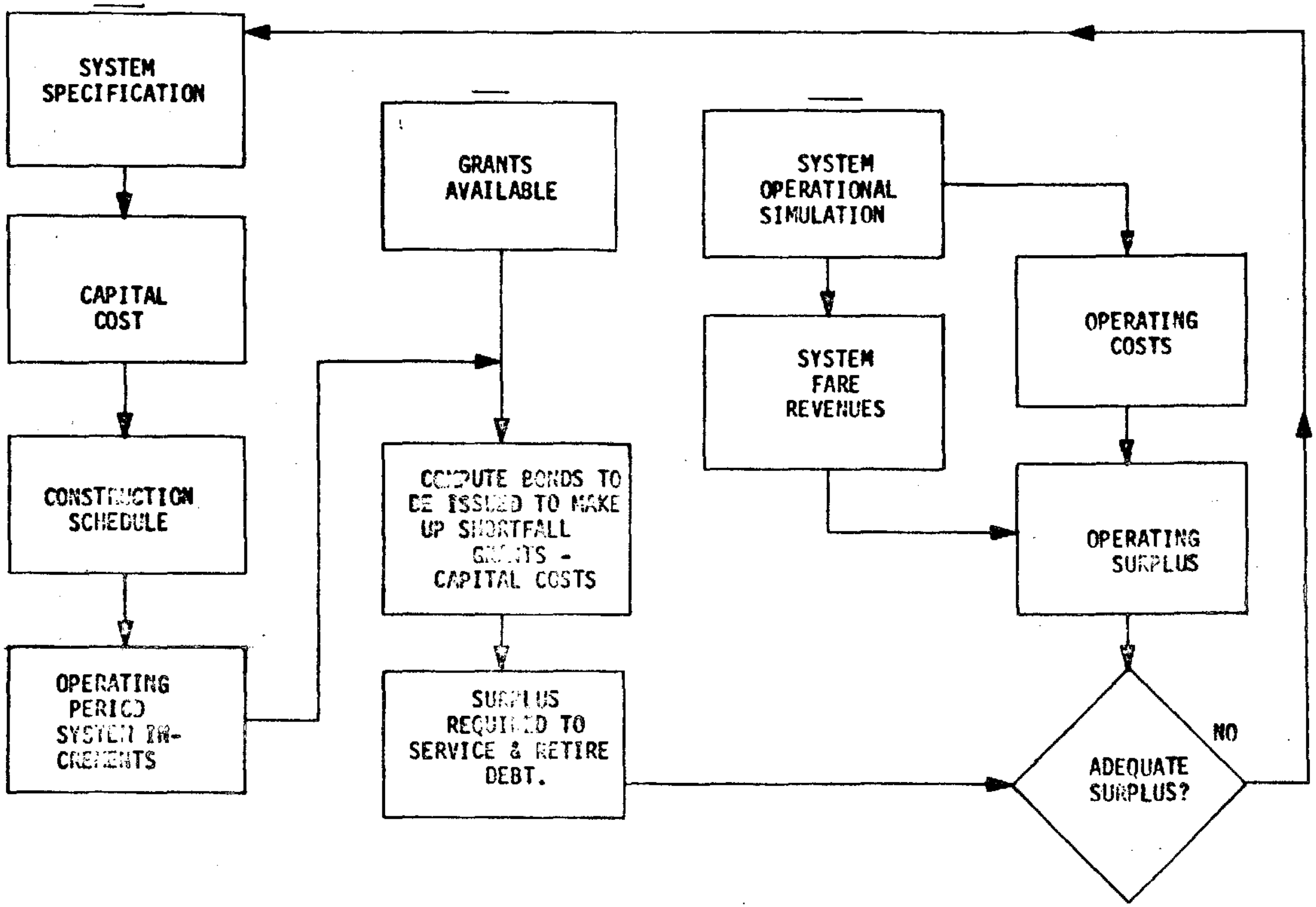

FIGURE 3

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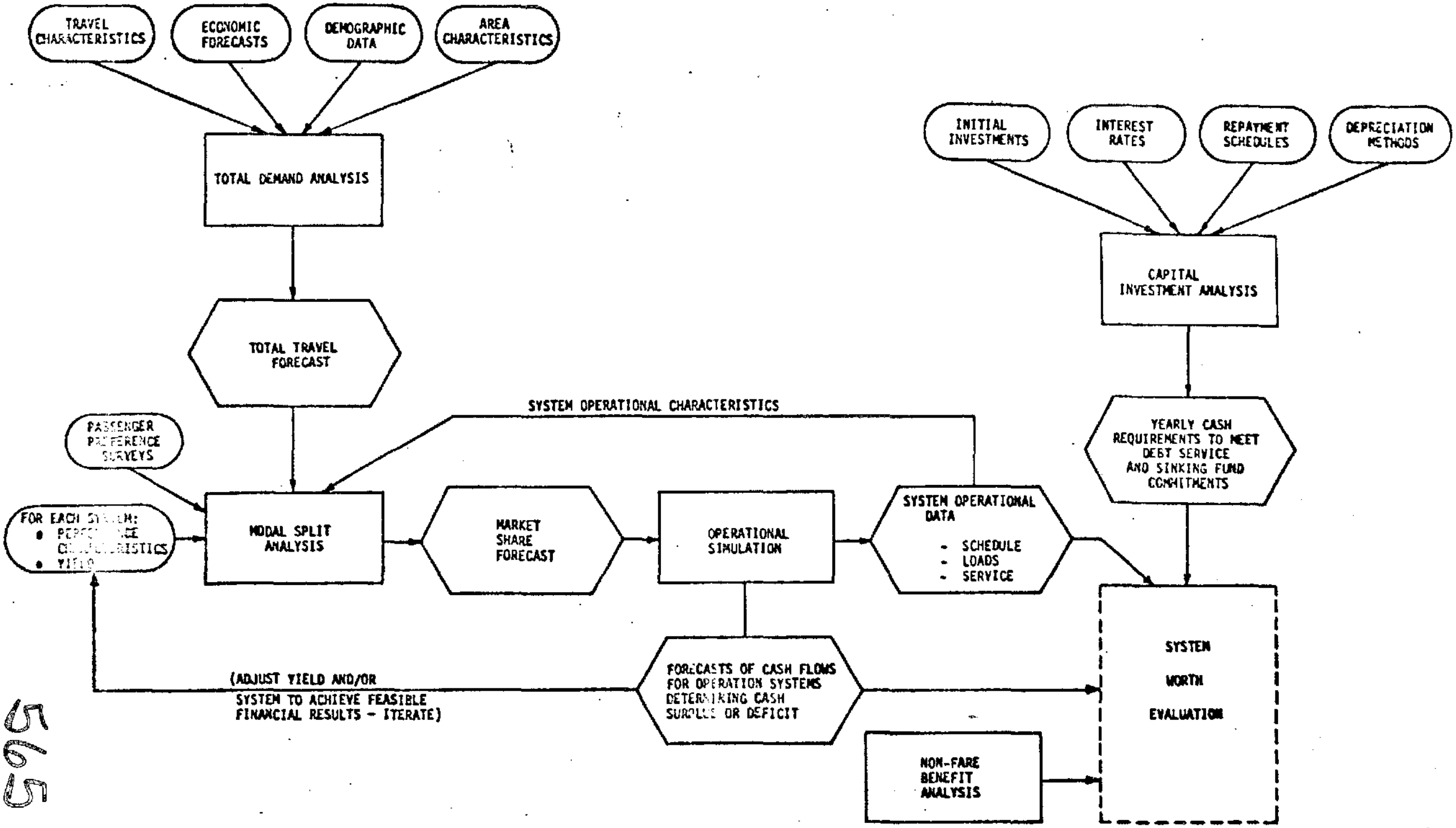
TRAVEL CHARACTERISTICS
ECONOMIC FORECASTS
DEMOGRAPHIC DATA
AREA CHARACTERISTICS
TOTAL DEMAND ANALYSIS
TOTAL TRAVEL FORECAST
PASSENGER PREFERENCE SURVEYS
FOR EACH SYSTEM:
SYSTEM OPERATIONAL CHARACTERISTICS
MODAL SPLIT ANALYSIS
MARKET SHARE FORECAST
OPERATIONAL SIMULATION
SYSTEM OPERATIONAL DATA
- SCHEDULE
- LOADS
- SERVICE
INITIAL INVESTMENTS
INTEREST RATES
REPAYMENT SCHEDULES
DEPRECIATION METHODS
CAPITAL INVESTMENT ANALYSIS
YEARLY CASH REQUIREMENTS TO MEET DEBT SERVICE AND SINKING FUND COMMITMENTS
(ADJUST YIELD AND/OR SYSTEM TO ACHIEVE FEASIBLE FINANCIAL RESULTS - ITERATE)
FORECASTS OF CASH FLOWS FOR OPERATION SYSTEMS
OR DEFICIT
SYSTEM WORTH EVALUATION
NON-FARE BENEFIT ANALYSIS

FIGURE 4

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The study covered the nine county San Francisco Bay area. Two time periods, 1975 and 1985 were studied. In each time period 2 STOL and 2 VTOL concepts were investigated.

The scope of the study was quite broad covering all aspects of an air transportation system. Aircraft design, travel demand, modal split, aircraft operation, and economic evaluation were the major tasks of the study.

These are also the basic blocks in the methodology presented earlier. Vehicle design wasn't mentioned in the methodology, but in order to choose a design the analytical procedure must be applied to each candidate.

In some respects the intraurban system resembles a domestic trunk airline. Characteristics of a typical intraurban system are listed below:

Daily Passengers Carried	48,551
Total Daily Flights	2,292
Average Passenger Trip Distance	23.4
Aircraft Required	73
Average Load Factor	.45
Number of Terminals	24
Number of One Way Segments	65

Both in passengers carried and daily flights the system rivals such an airline. Of course, the fleet size is much smaller than that of an airline, showing the large number of daily flights made by each aircraft. The largest difference between the intraurban and trunk airline is, of course, the average segment length.

Figure 5 is a picture of one of the STOL aircraft designed for the study. Its most interesting feature is the large number of doors. The plane is configured like a European train without any aisle. Each compartment has a door on each side of the aircraft. This design came about as a result of simulations showing that gate time was a critical variable in the system. The weight penalty caused by multiple doors was more than paid for in the reduced gate time they allowed.

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AUGMENTOR WING STOL

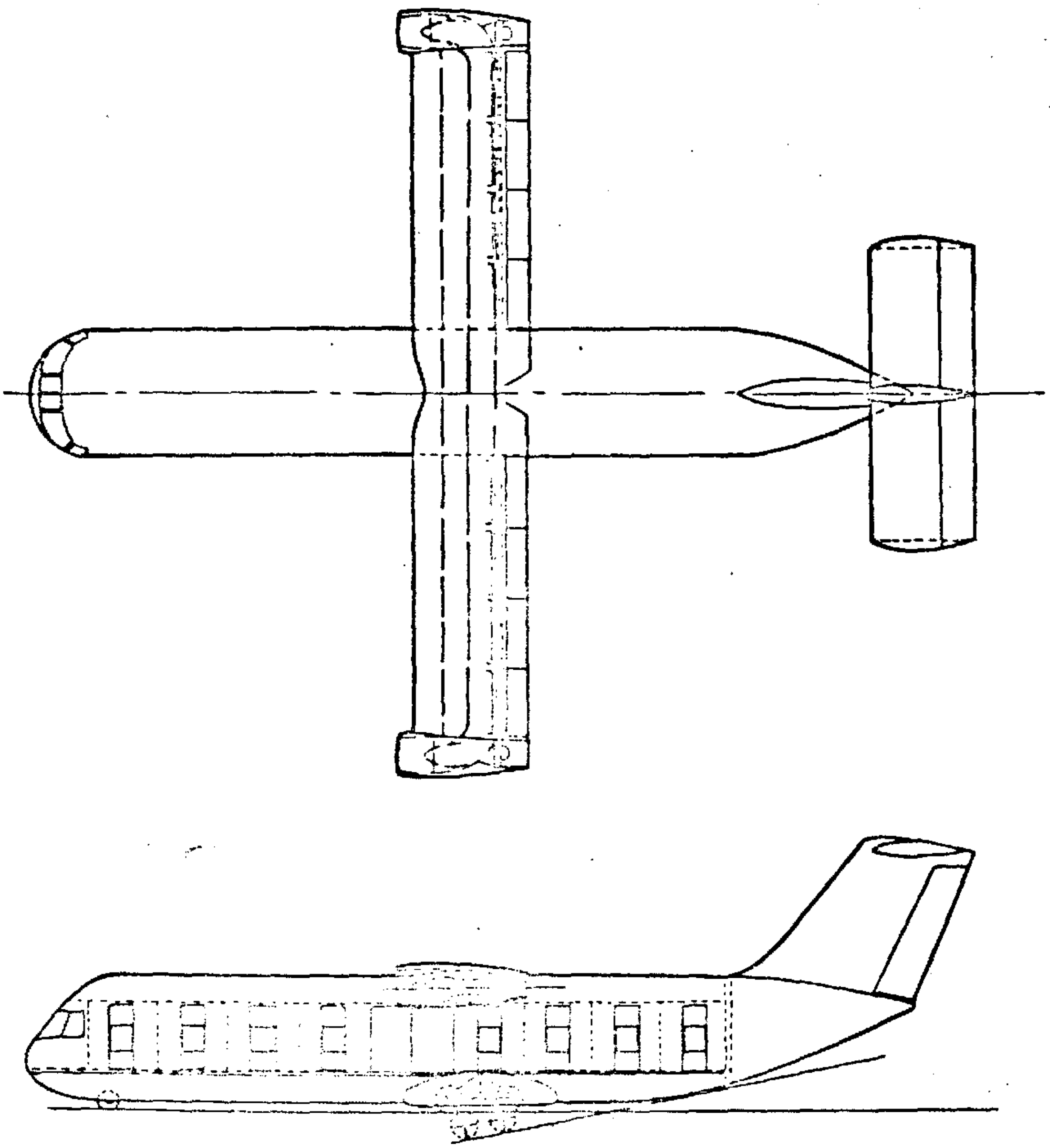

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FIGURE 5

3.1 MODEL STRUCTURE

Since little historical data exists for intraurban air systems, a detailed simulation of the system was required. A demand/modal split model was built to calculate station pair demands. A routing and scheduling model was produced to simulate the operation of the aircraft within the system. An economic module was created to take the routes, schedules, and flight loads and calculate revenues and costs. This is exactly the process described in the preceding general discussion.

Figure 6 shows some of the data flow within the model. The traffic generator for this study was a set of input demands. The modal split will be described later. Note that the waiting time assumed in modal split (as part of the trip time) is compared with the waiting actually achieved by the scheduling module. If they don't match, a new modal split is performed and a new schedule produced. Once the two are equal the economic evaluation takes place.

The zoning of the study region and total demand for travel by all modes for each zone pair in the Bay area had been forecast by the Metropolitan Transportation Commission before our study began. These forecasts of total travel were used in our study. They had also conducted a home survey of transportation. From this survey we developed time of day demand curves.

A plot of demand by time of day was made for each zone pair from data collected in the home surveys. However, since there were only about 100,000 trips to distribute in more than 2 1/2 million time slots (using 1/2 hour intervals for each zone pair), most zone pairs had very sparse curves. A pattern emerged, however. One curve was used from all zone pairs to downtown S.F., a second was used from downtown S.F. to all other zones, a third curve was used between all other zone pairs. These 3 curves adequately represented the survey data.

TRANSPORTATION NETWORK MODEL

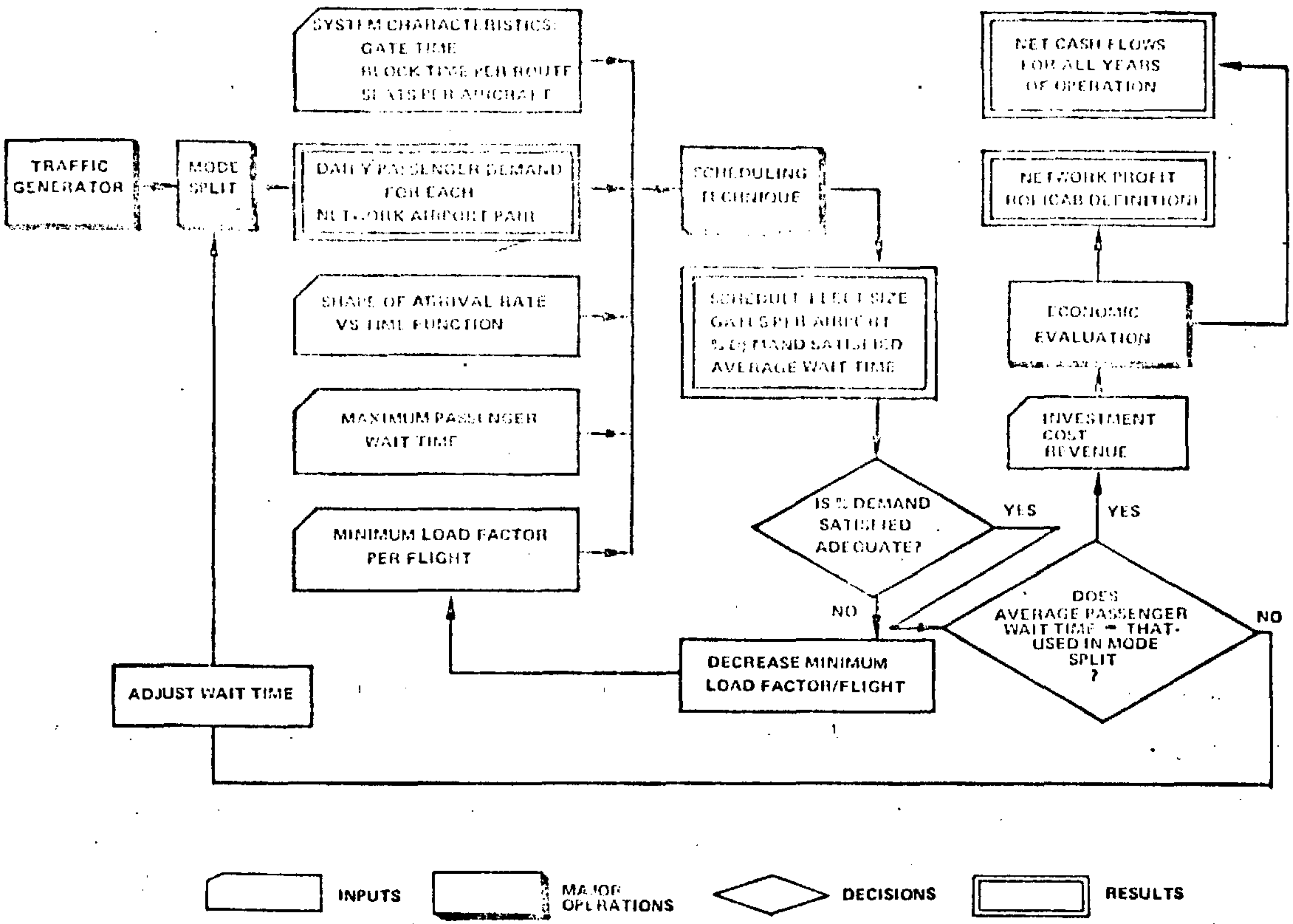

FIGURE 6

The demand (properly speaking modal split) model calculated demand for V/STOL between each port pair. The model works exactly like the intra-urban modal split model described earlier. Each zone pair is treated in order as follows: nearest V/STOL ports to the centroid of origin and destination zones are found, costs and times for auto and V/STOL trips are calculated and a diversion curve is entered with the cost and time differences to calculate the percentage of demand choosing V/STOL. This percentage is multiplied by the total zone pair demand and the result is added to the appropriate V/STOL station pair demand.

The diversion curve used in this study was a plane, with cost difference and time difference as independent variables, percent diverted the dependent variable. Of course, negative diversion and diversions of over 100% were excluded.

The demand model calculated travel demand between all V/STOL port pairs. Figure 7 shows the length distribution of these trips for the base case (1975 augmentor wing STOL aircraft with 49 seats). Also shown is the demand fed to the simulation model. This consisted of all port pairs with traffic of 250 passengers per day. The demand actually carried during the simulation is also plotted. The model only carries demand when it makes some sense to do so. The requirement was that all aircraft achieve at least two hours of utilization per day.

Because the system was being simulated, all aspects of the operation were calculated. This allowed the IOC to be assigned to variables which caused IOC to be incurred such as number of gates. For each cost category (e.g., aircraft servicing, ground facilities) coefficients were determined for each independent variable (terminals, departures, gates, etc.). The cost for each category was the sum of these coefficients multiplied by the variables. Total IOC is the sum of all cost categories. Cash DOC curves were produced for each design to be evaluated.

DAILY PASSENGER DEMAND

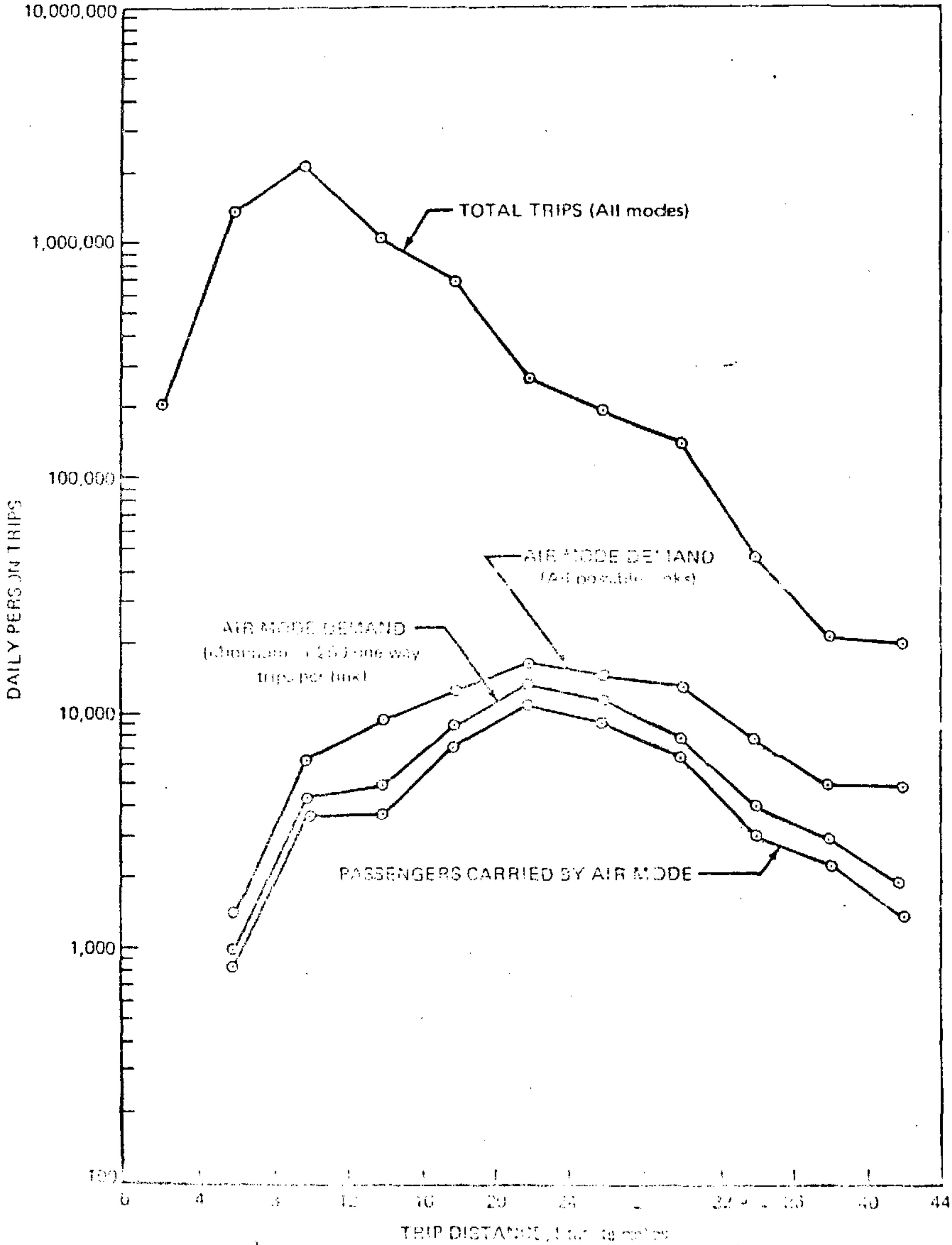

FIGURE 7

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3.2 RESULTS AND SENSITIVITIES

The results for the 1975 aircraft are shown in Figure 8. The small STOL aircraft make an operating profit but the debt service requirements cause substantial losses. The helicopters lose less because of the reduced land requirement for ports.

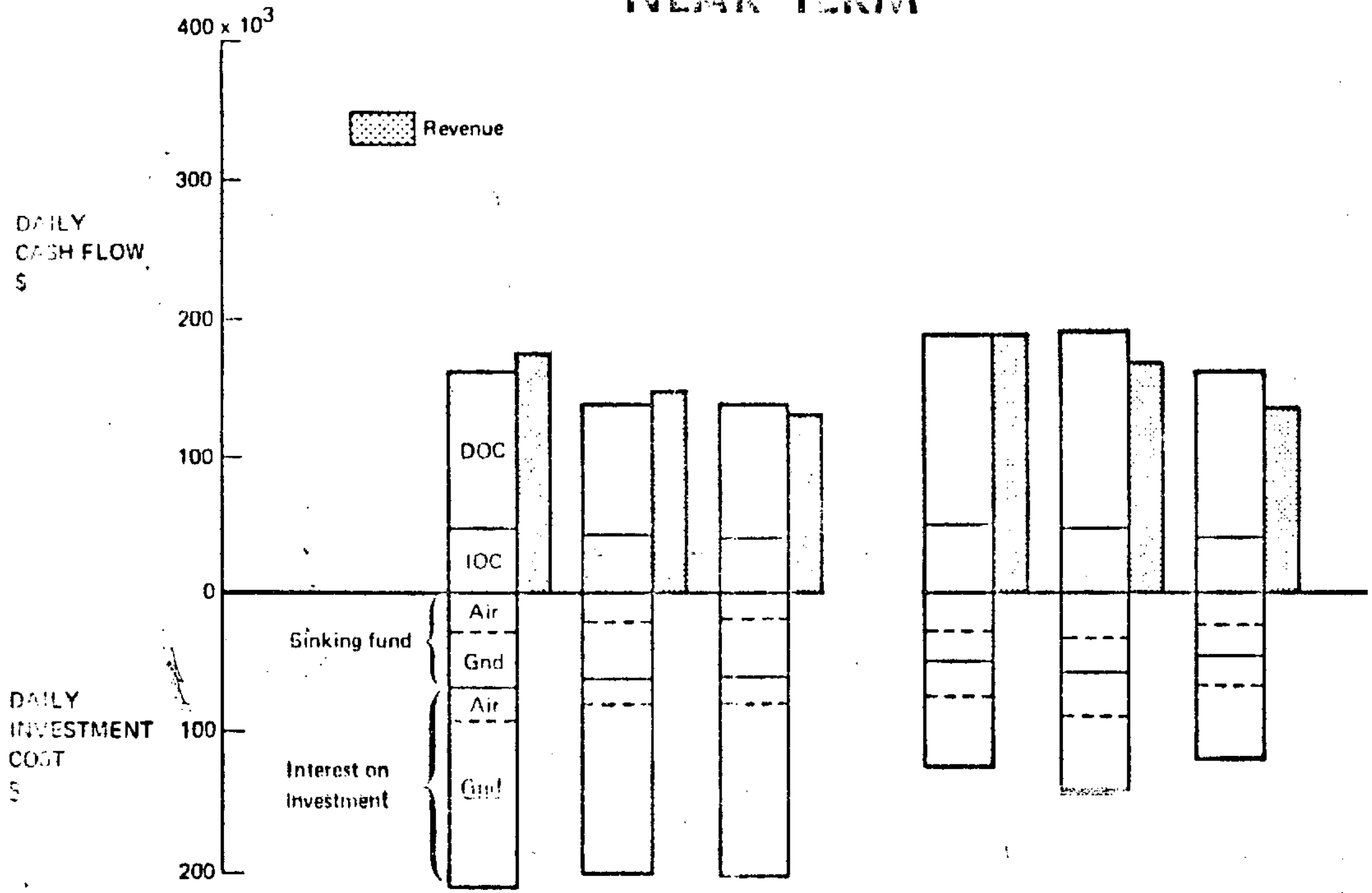
Figure 9 shows cash flows for the best aircraft. Profits from concessions located in V/STOL ports have been included in revenues. In 1980 both VTOL and STOL aircraft require subsidies, 19 million per year for the helicopter and 25 million per year for the STOL. By 1990 the STOL subsidy is 16 million and the VTOL makes a profit.

A number of simulations were run using time of day demand curves with different peaking characteristics. The results show that both fleet size and profit are quite sensitive to the peaking characteristics. A flat time of day demand curve led to a requirement for 51 aircraft and an operating profit $23,000 per day. The standard case required 76 aircraft and produced an operating profit of $2,000 per day. If the peaking were three times as severe as in the standard case, 82 aircraft would be needed and a $5,000 per day operating loss would be sustained.

The demand and simulation models were run for several different fare levels. The demand grows rapidly as fares are reduced and the loss per passenger decreases. The total loss increases slightly as the fare is reduced. At 70% of the base fare the system carries 173,000 passengers instead of 49,000 and the loss per passenger is $1.53 instead of $4.05.

The 1975 aircraft were flown in the 1990 market and the results compared with the 1985 aircraft in the market to measure the effect of technology change. Both the 1975 and 1985 STOL aircraft experience the same demand; a slight reduction in loss per passenger is achieved by reduced DOC in the 1985 aircraft. The 1985 helicopter has a faster block speed than does the 1975 vehicle and hence attracts more demand. This in addition to the lower DOC of the 1985 vehicle more than offset its higher purchase price. The 1985 helicopter loses almost half of what the 1975 vehicle loses per passenger.

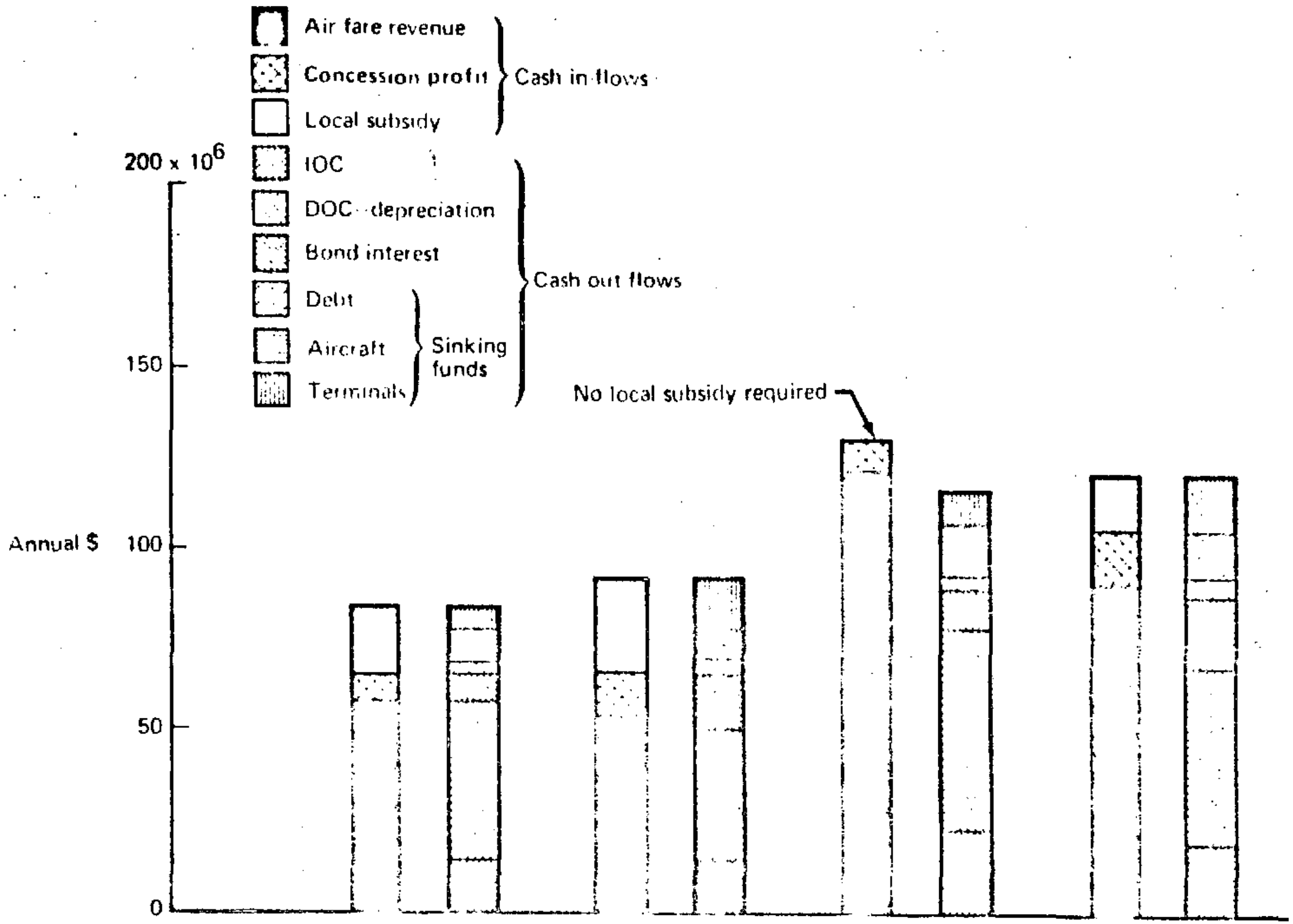
CONCEPT ECONOMIC COMPARISON
NEAR TERM



Vehicle	Augmentor wing STOL			Helicopter		
Passengers	49	95	153	50	98	150
Net loss per day	$194 000	$190 000	$2[illegible] 000	$128 000	$163 000	$147 000
Loss per passenger	$4.05	$4.70	$5.80	$2.42	$3.55	$3.85

FIGURE 8

ANNUAL CASH FLOW



Vehicle	Helicopter	Augmentor wing STOL	Tilt-rotor VTOL	Augmentor wing STOL
Passengers	50	49	50	49
Technology	1975		1985	

FIGURE 9

Simulation model runs were made using different gate times (turnaround times). The results were quite dramatic: going from 3 to 8 minutes of gate time increases the loss per passenger from 4 to 5 dollars. This effect is due to the lower peak period utilization of the aircraft which requires larger fleets to serve the same demand. The need for short gate times led to the multi-door design of the aircraft.

One run through both demand and simulation models was made including the BART system as well as the automobile as a competitor to V/STOL. Because of its low fare BART is a tough competitor. The demand for STOL shrinks and the loss per passenger climbs from \$4.05 to \$6.93.

Many sensitivity studies similar to those just described were carried out. Some of the results of the sensitivity studies were:

Low gate time is critical to the system
Cruise speed is important up to 250 KN
Commuter type peaking increases costs substantially
Downtown ports contribute most to the system
System cannot compete over the same segment with BART
Costs are lowest at very short field lengths
Lower fares (to a point) reduce the loss per passenger

Both the base case results and the sensitivity studies required the use of the demand and simulation models. This example shows the need for using the methodology described in Section 2, including all the interactions between elements. Had the analysis for this study been done in aggregate form, the base case results would have been suspect and the sensitivity studies could not have been performed.

4.0 APPLICATION OF TSEM TO A MAJOR CITY

A proposed study for a major U. S. city shows application of the methodology described in Section 2. In this case TSEM (Transportation Systems Evaluation model), our integrated intraurban model, will be used.

The objectives of the study involve preliminary design, evaluation of a PRT system, and a comparison of PRT and non PRT solutions to the transportation problem. Several transportation studies of this city have already been made. Zones have been created and 1985 trip tables (total demand) have been produced. The study will be based upon this data.

The first function of TSEM will be to aid in the preliminary design. A base case will be designed and run and then many modifications (different vehicle sizes, station locations, station capacities, headways, vehicle speeds) will be tried. The modal split and simulation modules will be cycled for each modification until convergence is obtained. All these runs will be made at a base fare level.

Once the system has been adequately refined, several fare structures will be tried. The service levels, ridership and operating profits will be calculated. The "best" fare will be chosen and the resulting system evaluated, including the non-revenue benefits.

Next, the service level, costs, and benefits of a freeway solution will be calculated and compared to the PRT solution.

The demand module will then predict demand for the future time periods. Modal-split and simulation modules will calculate system performance and costs in those years. The capital investment module will predict debt service requirements. Non fare benefits will be analyzed for each evaluation year. Finally, cash flows over the life of the system will be determined and this will permit final system evaluation.

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5.0 SUMMARY

We have presented a methodology for the analysis of transportation systems consisting of five major interacting elements. The analysis begins with the causes of travel demand: geographic, economic, and demographic characteristics as well as attitudes toward travel. Through the analysis, the interaction of these factors with the physical and economic characteristics of the transportation system is determined. The result is an evaluation of the system from the point of view of both passenger and operator. Service levels, economic and non-economic aspects of the system are ascertained.

The methodology was shown to be applicable to the intraurban transit systems as well as major airlines. Applications of the technique to analysis of a PRT system and a study of intraurban air travel were given. In the discussion several unique models or techniques were mentioned: i.e., passenger preference modeling, an integrated intraurban transit model and a series of models to perform airline analysis.

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