The Inseparability of Operational Control Policy Analysis and Strategic Planning: An Experience With U.S. Airports

by
DAVID G. SMITH
U.S. Department of Transportation, Office of the Secretary
The University of Virginia, McIntire School of Commerce

DANIEL P. MAXFIELD
U.S. Energy Research and Development Administration, Division of Transportation

STAN FROMOVITZ
The University Maryland
College of Business and Management, Department of Management Science

INTRODUCTION

Transportation planning research appears to be proceeding along two distinct and seemingly divergent methodological paths. The analytical developments of shorter range operational control methodology seems to be incompatible with analytical techniques being developed to evaluate long range transportation policies and plans. Yet these operational control policies are causing significant changes in the cost structure of transportation. In this paper we

1. define the analytical difficulties encountered in simultaneous consideration of long range capital investment planning and short range operational control policy.
2. describe our methodology for combined short and long analysis in airport investment planning.
3. summarize our findings in analysis of sixty-eight U.S. airports.
4. demonstrate the potential benefits that may result from continued research in this area.
5. indicate future research directions and areas of application.

Our methodology, at this point has been developed for the particular problem of airport system planning and applied to the sixty-eight largest airports of the United States. Selected results of these applications have been reported in the *1974 National Transportation Report* [1] and in the long range planning document *National Transportation: Trends and Choices*[2] for the Office of the Secretary, U.S. Department of Transportation. The existence of trade-offs between operational policy that affects the demand for capacity and strategic investment policy that affects the future supply of capacity is established. A method is described that approximates long run marginal costs of capacity that are defined in terms of the appropriate short run marginal cost functions. In the case of airports, short run marginal cost approximation involves the solution of a peak load pricing problem where peak period activity may substitute off-peak capacity until the marginal cost of this substitution just equals the incremental cost of a new capacity increasing project. The short run operational problem is inseparable from the longer run investment problem. We show that these are the costs appropriate to strategic investment and facility planning.

Our experience in airport system planning suggests that when the inseparability of short and long range planning is explicitly recognized and dealt with in the planning methodology, requirements for future capacity are significantly reduced. When the two are separated, long range plans tend to perpetuate operational inefficiencies. We summarize our findings in support of this observation.

THE SHORT RUN: OPERATIONAL CONTROL POLICY ANALYSIS

For many years, economists have recognized the inseparability of short and long run analysis. The economist's long run cost functions required for investment decisions are developed by collecting the short run cost functions for alternative investments. The problem encountered is in the specification of the appropriate short run cost functions. The economic paradigm assumes that a productive facility is managed optimally with respect to input factors leaving price and quantity to be determined. In reality there are additional managerial dimensions to short run costs. In fact, some of these dimensions are substitutes for investment in increased capacity.

Skirting the semantics of what is the short and what is the long, these management options must be associated with short run cost functions in the same fashion as are investment alternatives. However, this demands that all of the variables that are controllable in the short run must also be controlled in the long. A difficult problem results.

New techniques emerging for optimal control of transport systems offer great potential for altering short run costs. This is especially true for management of transient conditions such as peak loads at airports or congestion on urban road networks. These new techniques have greatly enlarged the number of manageable variables but in doing so has restricted scope to analysis at a single point in time for all practical purposes. Examples of this result abound in transportation planning. The examples here are from the airport system planning area where investment and operational control decisions are to be made in anticipation of future traffic growth.

The analysis of short run airport costs typically begins with an average cost related to airport utilization and a direct cost related to congestion delays. Aircraft operations (arrivals or departures) are considered to be the output of the airport. Figure 1 shows the cost structure facing an aircraft of a particular weight classification at a U.S. airport.

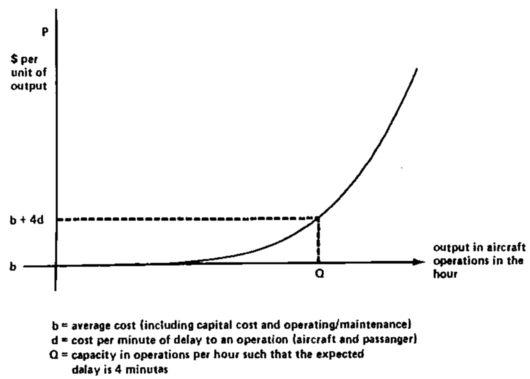

Figure 1 - Short Run Cost Curve

For simplicity, airport capacity is shown as constant, although it is somewhat variable even in the short run. Knowledge of the types of aircraft and the distribution of activity over time (hourly, daily, weekly, monthly, etc) results in a simple arithmetic operation to determine the annual cost to users of a given airport at its existing capacity.

To compute values required for Figure 1, the method of Warskow, et.al. [3] has been refined. The procedure (Delay Algorithm) determines the delay incurred in shifting all aircraft scheduled in excess of capacity to a later time. To demonstrate this delay computation, let

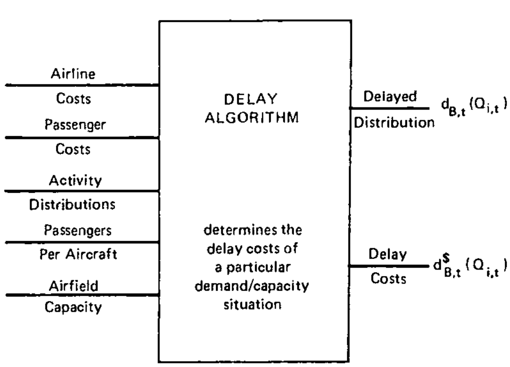

Figure 2 - Delay Algorithm Input-Output Diagram.

$d_{B,t}(Q_{I,t})$ = total daily delay for the busy day in year t as a function of the capacity of the $_I$-th configuration (see Figure 3.17) if implemented in year t, as a function of system capacity ($Q_{I,t}$).

$d_{A,t}(Q_{I,t})$ = total daily delay for the average day in year t as a function of $Q_{I,t}$.

Where

$Q_{I,t}$ = capacity of configuration i in year t.

$d\$(Q_{i,t})$ = delay cost associated with having configuration i in place in year t.

The method assumes that the three classes of aircraft are uniformly mixed in order within the hour. Figure 3 shows a typical distribution, where the profile obtained shows for hour h, the summation

$$\sum_{c=1}^{3} D^{c}_{B,h,t}$$

In the figure, only the portion of the distribution in which delays occur are shown.

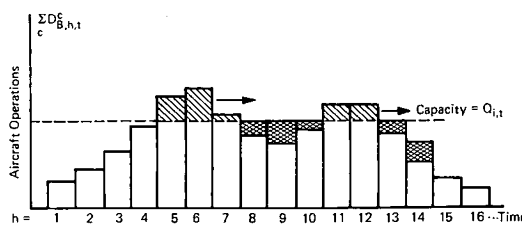

Figure 3 - Typical Hourly Distribution of Aircraft Operations and the Effect of Delay Procedure

The shaded area above the $Q_{I,t}$ capacity line represents over capacity operations at the airport. In calculation of delay by this method, all of the aircraft above the capacity line in hour 4 and all aircraft to the right up through hour 11 must be shifted (delayed) to the right such that the resultant distribution is everywhere below the capacity line.

Given the input for the average day, the average day delay and costs are also computed using the Delay algorithm. These must be combined to allow approximation of the annual costs. Experience with the Delay algorithm suggests that the delay $[d_{x,t}(x;Q_{I,t})]$ as a function of the peak hour demand magnitude x is approximately exponential in process. Given $d_{B,t}$ and $d_{A,t}$ with knowledge of the maximum over h of both $d^{c}_{B,h,t}$ and $D^{c}_{E,h,t}$ at time t, the function

$$\delta(x) = \alpha e^{\beta x}$$

can be fit by regression techniques. With this average delay function, the total delay lost function can be derived.

Now let,

$P_t(x)$ = the proportion of the 365 days of the year when peak magnitude is x.

Then

$$d_t(Q_{i,t}) = \sum_{x=0}^{\infty} P_t(x)\,\delta(x)$$

Of course infinity can be replaced by the peak magnitude of the busiest day distribution. Finally, $d_t^{\$}(Q_{I,t})$ is approximated in a similar fashion using the total user costs components. The following equations define the average cost per minute of delay to an aircraft operation and an aircraft passenger.

$$\lambda A = \sum_{C=1}^{3} C^c_{A,t} \frac{\sum_{h=1}^{24} D^c_{B,h,t}}{\sum_{C=1}^{3}\sum_{h=1}^{24} D^c_{B,h,t}}$$

$$\lambda p = \sum_{C=1}^{3} C^c_{P,t} \, P^c_t \frac{\sum_{h=1}^{24} D^c_{B,h,t}}{\sum_{C=1}^{3}\sum_{h=1}^{24} D^c_{B,h,t}}$$

where

$C^c_{A,t}$ = cost per minute of delay to aircraft of type c in year t.

$C^c_{P,t}$ = cost per minute of delay to passengers on aircraft of type c in year t.

$D^c_{B,h,t}$ = hourly distribution of aircraft operations of type c for hours (h= 1,2,...24) on the busiest day of year t.

P^c_t = average number of passengers per aircraft of type c in year t.

Then using the total minutes delay for the average and busy day, the average and busy day costs are computed by

$d_{B,t}\,(Q_{i,t})\quad(\lambda A + \lambda p)$

$d_{A,t}\,(Q_{i,t})\quad(\lambda A + \lambda p)$

and ultimately used to calculate an annual user cost,

$$d^{\$}_t(Q_{i,t}) = \sum_{x=0}^{\infty} P_t(x)\,\delta(x)\quad(\lambda A + \lambda p)$$

To obtain an approximation of marginal delay costs, the original average delay curve

$$\delta(x) = \alpha e^{x}$$

would be converted to a cost function by use of λA and λp. Hence total delay cost as a function of x would be approximately

$$\delta^*(x) = \alpha e^{\beta x}(\lambda A + \lambda p)\quad x$$

The approximate short run marginal delay cost is then

$$\frac{d\delta^*(x)}{dx} = \alpha(\lambda A + \lambda p)\, e^{\beta x}(\beta x + 1)$$

This can become quite high in relation to marginal capacity cost and, as will be shown later, is responsible for much of the perceived airport capacity investments of the future. However, the use of this cost relation ignores the substitution of off-peak capacity at a cost lower than the cost of additional capacity.

In the short run scenario, with no expansion in output capacity, it is possible to modify this cost structure. An approach that has been suggested [4,5] would institute a pricing policy that would charge the incremental unit of output with the incremental change in costs incurred by all others, ie. a variant of the marginal cost price. Observing Figure 1, it is clear that an additional aircraft operation during a congested period increases the delay cost incurred by all other aircraft operating in that period. Even here the cost arithmetic is simple employing the above short run marginal delay cost function approximation. The problem lies in predicting the response of demand to the increased charge. To the extent that there is any price elasticity of demand, there will be a decrease in activity during the peak period.

Faced with the increased cost, an aircraft operator will either pay the price or seek a substitute. In the short run, substitutes include a shift to an off-peak period or a shift to a different airport. An airline engaged in multiple flight markets may reduce frequency. A non-scheduled flight may be cancelled entirely. Of course, purchase of an increase in capacity may be the choice in the long run.

With little information about price elasticity and practically no information about time elasticity, a model of the substitution process became a necessary replacement for time variant demand functions. The short run model [6] begins with the hourly distribution of aircraft and seeks to redistribute the activity at minimum cost. It spreads the peak periods to attain a more uniform utilization of the airport. The assumption is that the aircraft operator will seek the least cost substitute. In the case of carriers competing in the same market at low load factors, it is assumed that the airport authority will enforce a suitable compromise.

The analytical procedure (Peak Spreading Algorithm) calculates the cost of rescheduling the demand such that no hour contains scheduled demand in excess of existing capacity. Figure 4 shows the concept.

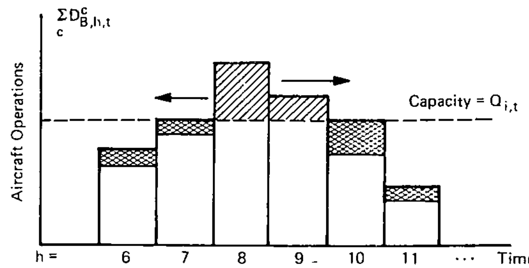

Figure 4 - Typical Hourly Distribution of Aircraft Operations and the Effect of the Peak Spreading Procedure

The diagram shows over capacity operations being rescheduled to the left and right of the peak period. This is in contrast to the delay procedure shown in Figure 3.

The Peak Spread Algorithm requires the same inputs as the Delay Algorithm. Its output is a measurement of the magnitude of passenger time and aircraft operating cost losses due to rescheduling and a monetary evaluation of these. Figure 5 displays the inputs and outputs of the procedure where the output activity distributions are constructed by type of aircraft.

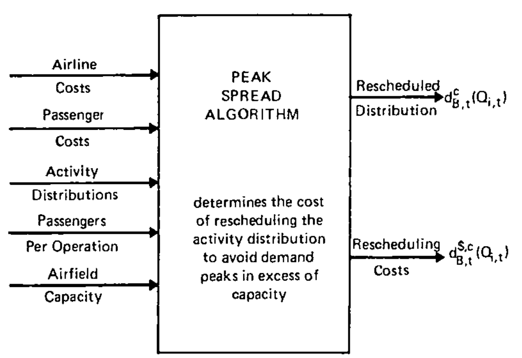

Figure 5 - Peak Spreading Algorithm Input-Output Diagram

Rescheduling is accomplished under a discipline which orders aircraft with priorities

1) Air Carrier Aircraft
2) Commuter Aircraft
3) General Aviation Aircraft

This represents the generalization that, with respect to airport system public productivity, social value of the flight types are ranked in this order.

The algorithm begins by solving the rescheduling problem for the air carrier distribution. Having solved this problem, it then adds (by horizontal summation) the commuter distribution to the original air carrier distribution and a second solution is obtained. The general aviation distribution is then added to the first two input distribution and a third solution is obtained. Costs are assigned to each aircraft type as the added cost of successive solutions; e.g., air carriers are assigned the cost of the first solution, commuters the difference between the second solution and the first, general aviation the difference between the third and the second. This is shown in the flow diagram of Figure 6.

In solving the rescheduling problem, the Peak Spreading Algorithm operates as follows: (see Figure 7)

1. Searches the input distribution locating *chains* (or sequences) of hours of activity that define peak and off-peak periods.
2. Establishes the *central points* (mean, mode) of each chain and determines the number of aircraft involved in the peak periods (chain value).
3. Assesses off-peak periods for their ability to *absorb* aircraft operations being rescheduled.
4. Locates the *weighted center* of each peak period. These centers depend upon the steepness of the peaks and valleys of the activity distribution. Aircraft in a peak period are rescheduled to the right and left (in time) of the weighted center of each peak.
5. Employing empirically derived probability functions, the location (in time) of unused capacity during off-peak periods is determined by Monte Carlo procedures. This reflects the observed preferences of airline schedulers for certain times within the hour.
6. At this point, each peak period is treated independently. Before rescheduling can begin, a search must be made to locate off-peak chains that are to receive a greater number of aircraft than can be accomodated. This can occur when two peaks are close together. When it does happen, the two peaks (chains) are said to *intersect*.
7. If chain intersections exist, then an iterative procedure is executed that adjusts the assignments until a feasible allocation occurs.
8. Assignments are completed producing the rescheduled distribution.
9. The time duration of aircraft rescheduling is computed.
10. Costs are computed.
11. At this point, the peak spreading is either complete, requires another iteration to resolve intersecting peaks or there is not enough off-peak capacity available to reasonably apply the procedure. Reasonableness is defined in terms of rescheduling time in step 9. This usually occurs when total daily demand is in excess of 80% of total daily capacity.

Using the Peak Spreading Algorithm, the value of off-peak substitution is established.

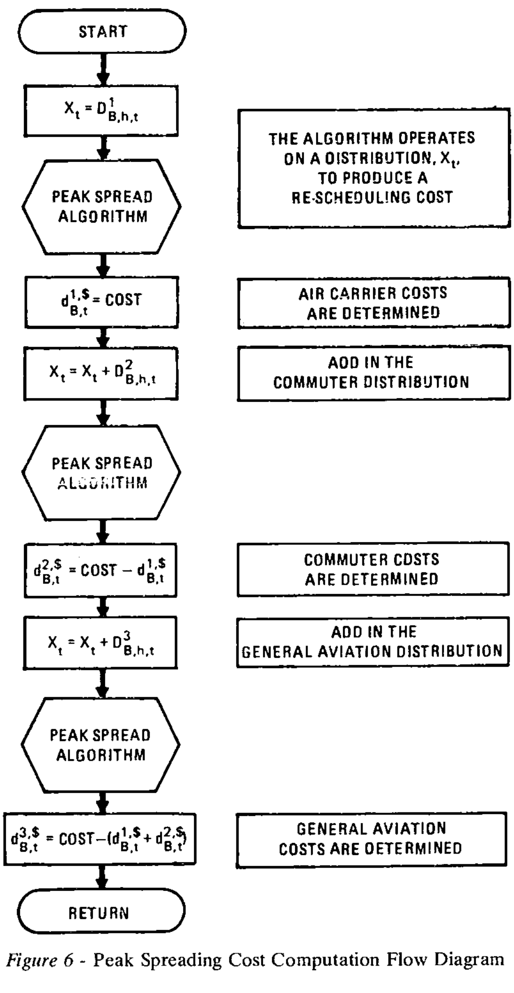

Figure 6 - Peak Spreading Cost Computation Flow Diagram

THE LONG RUN ANALYSIS: STRATEGIC INVESTMENT PLANNING

The short run model considers the systematic substitution of off-peak capacity for peak capacity. In the long run, construction programs can be implemented that increase the physical capacity of the airport. Figure 8 shows a segment of the long run cost curve for airport expansion along two airfield expansion paths. The solid short run curves define average incremental costs of capacity and delay to individual operations in peak periods. Expansion possibilities are arranged in a tree structure [7]. Each path has a long run cost curve associated with it. The appropriate path, and hence cost curve depends upon the demand for additional capacity. Movement along a path represents the investment of successive increments of capital in airfield and passenger facilities. Extending the analysis to the long run brings an additional option to the aircraft operator faced with the relatively high marginal cost based charges. This additional option associated with an increase in peak period capacity completes the components of the cross-elasticity of demand between peak and off-peak periods.

Recall that the first component of the cross-elasticity is the value differential between peak period airport use and off-peak use as measured by the differences between the cost of rescheduling to an off-peak period and not doing so. The aircraft operator has the option of having his effective price increased by congestion delay during peak periods or reexamining his preferences and perhaps reschedule to an off-peak time. This cost differential, over all levels of output, defines one component of the cross-elasticity.

The long run option is a contribution to the purchase of additional capacity. A capacity increasing project may be selected that will insure sufficient capacity to eliminate certain congestion costs. The fundamental criterion for this selection is cost minimization. However, the existence of this alternative affects the magnitude of the

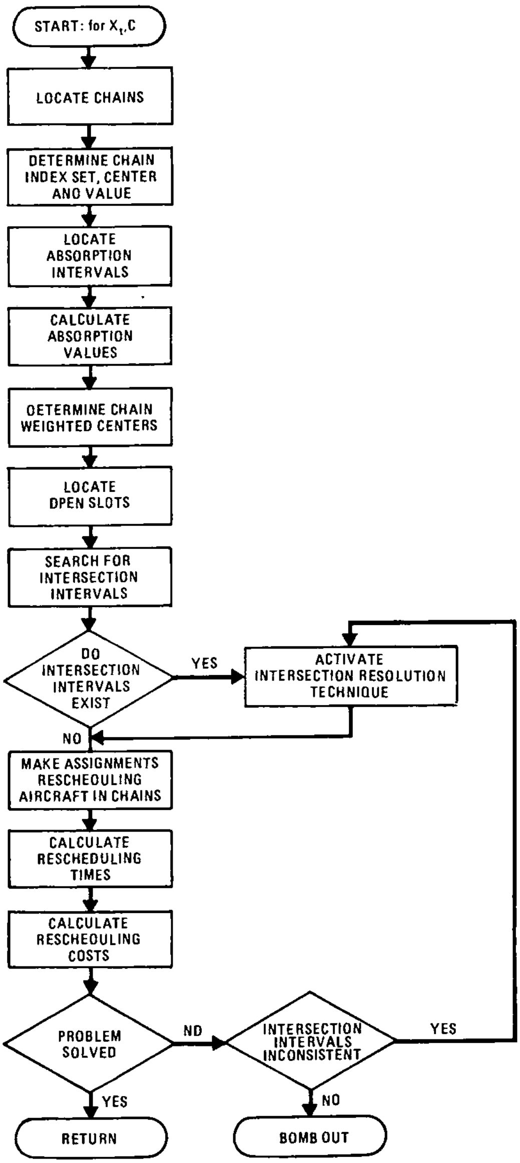

Figure 7 - Peak Spreading Algorithm Procedural Flow Diagram

first cross-elasticity component and conversely, the economic attractiveness of the project is affected by the potential for a shift in the timing of demand. Thus, the second component of the cross-elasticity is the effect that capacity increasing projects, i.e., their present valued cash flows, have on the first component.

Figure 9 depicts the situation where peak period price (P_1) is equal to short run marginal cost (SRMC) which is constant and equal to to (b) for peak period demand (Q_1) up to capacity (Q_c). For demand in excess of (Q_c), the SRMC increases by a congestion component cost expressed functionally as $D(Q_1)$. (P_1) is determined by the congestion component as a function of (Q_1). Peak/off-peak cross-elasticity can be written as the partial derivative ($\partial Q_2/\partial Q_1$) and plotted as a function of (Q_1). The rate increases from (Q_c) as a function of $D(Q_1)$ up to the point (Q_c^* ,r) where a capacity increasing project of size (Q_c^*) is cost justified and reduces $D(Q_1)$ to zero. Because capacity increments can only be purchased in large blocks, the cross-elasticity is discontinuous.

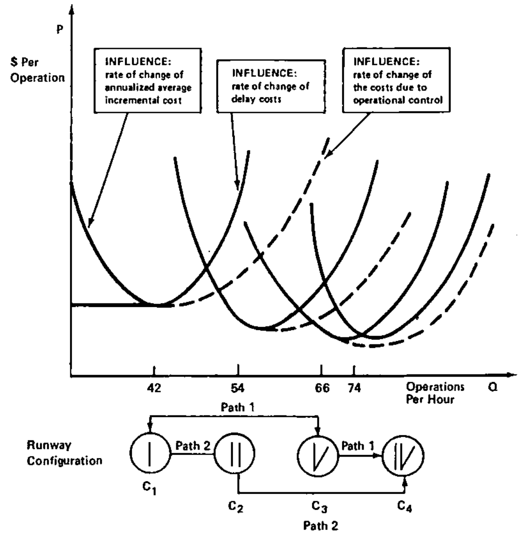

Figure 8 - A Segment of the Long Run Cost Curve

From here, a standard construction sizing and staging procedure can be applied to develop a strategic investment plan. For example, discrete variable dynamic programming procedures were employed in the study described. below. A severe problem arises, however, in that the short run cost structure is not simply a function of hourly output but of a complete distribution of interrelated demands over the time of day. As a result, the Peak Spreading Algorithm must be executed for every state variable-stage combination in the enumeration. Computation time can become excessive depending upon distributional characteristics. By any standard, the expense is too great for effective sensitivity analysis typically demanded of a planning methodology.

The short run operational policy analysis for the airport strategic planning problem employs a heuristic technique. The procedure recognizes certain characteristics of daily demand distributions, produces expected

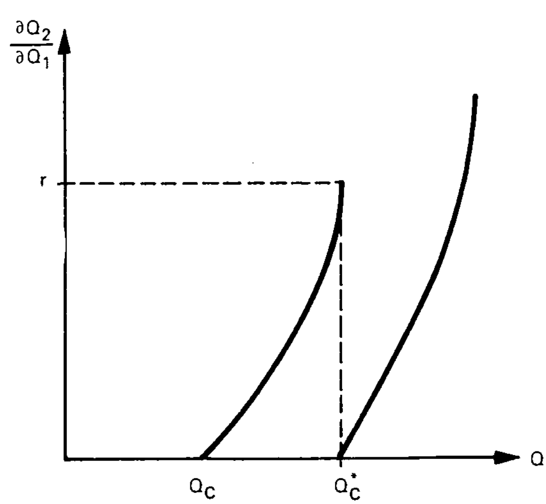

Figure 9 - Peak/off-peak Cross-elasticity

schedules and proceeds iteratively toward an optimal redistribution of that demand. A natural possibility for reducing computational expense is the development of an approximation method. Dependent variables are the cost of peak spreading and the output rescheduled distribution. Independent variables are selected properties of input activity distributions and certain search parameters of the Peak Spreading Algorithm. Using the results of Peak Spreading Algorithm applications on several representative demand distributions, a set of linear statistical models were developed.

Current use of these models is restricted to a relatively small range of independent variable values. Outside of this range, the Peak Spread Algorithm is used. This has resulted in a computer cost reduction in the 50 to 80 percent range. One observation bearing note is that due to the very large cost of even minimal capacity increasing projects, the pattern of project selection and staging is not highly sensitive to moderate approximation errors. The poorest statistical model in use has coefficients significant at the 20 percent level based on standard t-tests but produced long run analytical results that compare reasonably well with results using the Peak Spread Algorithm. These models are probably not acceptable for detailed short run analysis of energy consumption and pollution. They do, however, capture the significant effects of short run operational policy upon long run costs.

Our plan for modification of the relationship between the linear models and the Peak Spreading Algorithm is to implement a statistical model building subroutine. This subroutine will maintain a data base independently of any particular application. Depending upon the characteristics of the demand distribution being operated upon, the subroutine will select, revise or build models based upon predefined conditions or will execute the Peak Spreading Algorithm as necessary and append the results to the data base.

ANALYSIS OF THE POTENTIAL OF SHORT RUN OPERATIONAL CONTROL POLICIES TO REDUCE INVESTMENT IN AIRPORT CAPACITY

Air carrier airports can be described as being in one of several activity categories that define the levels and types of congestion present. An airport will typically track through these categories in succession as air carrier traffic increases:

1. High peaking and a high percentage of general aviation (HP-HG).
2. Moderate peaking and a high percentage of general aviation (MP-HG), as general aviation begins to avoid the air carrier peaks and spreads itself into the off-peak hours.
3. Moderate peaking and a low percentage of general aviation (MP-LG), general aviation begins to decrease as a percentage of total operations and eventually in absolute terms as much of this demand will shift to other airports.
4. Low peaking and a low percentage of general aviation (LP-LG), as air carrier peaks begin to spread to other parts of the day.
5. Pressure is applied for the construction of a new airport. The tendency is for a previously congested situation with low peaking and a low percentage of general aviation to result in two highly peaked airports.

The alternatives analyzed for management of this cycle and to reduce investment requirements include various combinations of reducing general aviation activity in peak periods, spreading of air carrier peaks by rescheduling and, in certain multiple airport hubs, reallocating the traffic among the air carrier airports. [8]. These alternatives are each variants of the peak spreading process.

The sixty-eight airports were analyzed in two groups. [9,10]. The first group consists of the twenty-seven large hub airports that each represent at least one percent of the total enplaned passengers at U.S. airports. The remaining forty-one airports are the medium hub air carrier airports. The large hub results are best summarized by consolidation into three distinct situations:

A. Airports in the high peaking categories where a new airport is not actively being planned.

B. Airports in the medium or low peaking categories where a new airport is not being planned.

C. Airports in hubs where a new airport is actively being planned.

For airports in the first situation, the analysis has shown that reducing general aviation demand in the peak periods is generally more effective than either the construction of additional capacity or the spreading of air carrier peak demands. Reducing peak period general aviation activity would result in reductions in peak hour capacity requirements ranging from 43 operations per hour to 95 operations per hour between 1974 and 1990. Congestion delay cost savings would range from 5% to 90% for airports in these high peaking situations. It should be noted that high peaking is almost always accompanied by high general aviation percentages except in the cases of multiple airports.

For seven of the airports in situation A, there would be no capacity related airfield investments required if the operational control policy reducing peak period general aviation were applied. For two of these airports, there is no problem of capacitation. For all but one of the remaining airports of situation A, a combined reduction of peak period general aviation traffic and the spreading of air carrier peaks, would eliminate the need for capacity related investments through 1990. The State of Colorado reports that the remaining one airport (Denver) is planning a policy of general aviation diversion to other airports. The data reflects this and indeed no further application of the policies were indicated in the analysis. The combined plans reported by the States include a total of $717 million in airfield investment through 1990 at the large hub airports in situation A. Our analysis indicates that the implementaion of operational control policies and the elimination of nearly all of this capacity related investment is economically justified.

For four of the medium to low peaking airports in situation B, the analysis has indicated that no capacity related airfield investments would be justified through 1990 if peak period general aviation reduction and air carrier peak spreading were combined. For the remaining two airports it was found that the investments planned for the period prior to 1980 could be postponed to the period between 1980 and 1990. These airports reported a total of $558 million in capacity increasing projects was planned. About 75% of this investment could be justifiably replaced by the implementation of the operational control policies.

For the airports located in hubs where new airports are under active consideration, it was found that the use operational control policies and capital investment at the existing airport could satisfy the demands on capacity through 1990. Some redistribution of air carrier traffic to reliever airports would be required. One exception was Chicago, where forecast demand could not be satisfied there even with maximum investment. Midway would offer some relief through 1985 but after that time only a new airport or a major reorientation of connecting traffic flow would satisfy the forecast demand. Los Angeles was found unable to handle the forecast traffic at the present site. Rescheduling of activity could not be accomplished realistically. Inspection of neighboring suburban airports suggests that enough capacity exists to relieve Los Angeles International through the 1990 period. In the New York hub, sufficient capacity appears available without the new airport at Stewart Field. This would require fuller utilization of Newark together with diversion of general aviation and implementation of air carrier peak spreading at all three airports. In the large hubs that have new airports under consideration, the overall cost of these airports has been estimated at about 4.4. billion dollars, of which 1.3 billion would be for airfield construction. If these new airports (except at Chicago) were not built by 1990, further increases in existing airfield capacity would be required at a cost of about $680 million even when operational control policies are employed. Existing terminal facilities would need to be expanded as well. It is clear that major cost savings in new airport construction are possible through the more efficient use of existing capacity.

Terminal area capacity requirements are affected by the short run operational policies, particularly the gate processing facilities and airport access systems. For airports in the high peaking and high general aviation activity situations, reduction of peak period general aviation activity will increase the airfield capacity available to air carriers in their peak period. The increase in peak period passengers that results may produce a need for more terminal capacity. It is estimated that a reduction in peak period general aviation could lead to required new terminal capacity of from 10 to 40 percent. On the other hand, air carrier peak spreading will reduce terminal area capacity requirements. For airports in the moderate peaking situations, a decrease in new terminal capacity requirements in the range of from 6 to 40 percent would result from implementation of the operational control policies.

The study indicates that, for major airports in large hubs, the economically justified level of investment is small in comparison with the investment levels being planned. This is the case because of the potential savings attributable to operational control policies for making better use of existing capacity in the short run.

Of the forty-one medium hubs studied, twenty-seven were planning no additional capacity, nor were they found to be in need of new capacity using our methodology. For the remaining fourteen medium hubs where major capacity additions are being planned, the composition of peak period demand is highly concentrated with general aviation. Spreading these general aviation peaks enables a reduction in capacity requirements of between 10 and 60 percent. The average reduction is about 35 percent. This reduction in general aviation traffic during peak periods was found to permit higher concentration of air carrier activity in peaks. As in the analysis of large hub airports, this tended to produce increases in the requirements for terminal capacity.

CONCLUSION

Potential results are significant for continued planning research recognizing the inseparable relationship between operational control policy and strategic planning. Terminal and link congestion problems that force capacity increasing investment exist in all modes of transport. Our methodology for airport system planning is directly applicable to other transport systems characterized by a high proportion of scheduled service or systems with predominant investment in terminal facilities, eg., water ports and rail yards. Applications in urban systems and on other problems where network structures are being analyzed probably will require methods of a different nature. The ability to incorporate the effects of operational control policy into long range planning analysis techniques will be essential.

In addition to the involvement of the U.S. Department of Transportation in investment planning research, several other agencies of the U.S. Government are interested in the energy and environmental impacts of operational control policies in the airport work. Short run inefficiencies often are responsible for resource waste having significant proportion. In reducing congestion delay and concentrations of activity, the operational control policies reduce fuel consumption and the level of engine emissions. The environmental impact of construction projects is often great. As we have seen, the operational control policies can be substitutes for capacity increasing projects. Their environmental impacts are certainly less, although their economic and political impacts may be strong. In guiding the process of transport planning, the application of operational control policy analysis should be encouraged. Techniques to implement this analysis must be developed and made available.

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