Search and Choice in Transport Systems Analysis

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•THE SUBJECT of this paper is the problem of searching out and choosing among transportation system alternatives. We first describe the essential features of transportation systems analysis, as a substantive problem. In the next section, we review a very popular model of the design process, the "rational model," and discuss its limitations; we then present a more complete model of the design process, the PSP model, and explore its implications. Next, we demonstrate the applicability of the PSP model to transportation planning and illustrate systematic analyses of transportation alternatives. In the last section is described specific operational techniques that have been developed to implement or extend the PSP model in the light of issues raised by the prototype analysis.

This paper builds upon initial concepts proposed earlier (15, 19). A fuller exposition of the ideas and techniques summarized here can be found in several current research reports (1, 18, and also 2 through 17).

THE PROBLEM: TRANSPORTATION SYSTEMS ANALYSIS

Options

A wide spectrum of aspects of a transportation system can be varied. Not all of these aspects are open to a single decision-maker, nor are all open at the same time. This spectrum of options, or "decision variables," may be summarized as follows:

1. Technology—Development and/or implementation of new combinations of transportation components enable transportation services to be offered in ways that were not previously available. Examples include containers, containerships, and piggyback trucks and rail cars; supersonic transport; new urban mass transportation concepts such as the Westinghouse Skybus and the various types of dial-a-bus systems featuring dynamically routed and scheduled vehicles (20, 21). In general, we are dealing with systems containing several different transportation technologies, i.e., with multimodal systems.
2. Networks—Options about networks include the general configuration pattern of the network as well as the approximate geographic location of the links of the network.
3. Link Characteristics—Networks consist of links as well as nodes; links correspond to routes, such as highways, airways, rail lines, and urban streets, and to terminals, interchanges, and other physical facilities.
4. Vehicles—There are options regarding the number and characteristics of vehicles in the system.
5. Operating Policies—Operating policies include the full spectrum of decisions about how the transportation system is operated: routes and schedules of the vehicles; types of service to be offered, including various services auxiliary to transportation (passenger meal services; diversion and reconsignment privileges for freight); prices to be charged (both general pricing policy and specific pricing decisions); subsidies; and taxes.

This set of transportation options fully defines the space of possible transportation plans and policies. However, these options are exercised not in a vacuum but in the context of a system of social and economic activities. We define such an activity system as all the social, economic, political, and other transactions that take place over

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space and time in a particular region. These transactions, both actual and potential, determine the demand for transportation, and, in turn, the levels and spatial patterns of these interactions are affected in part by the transportation services provided.

Therefore, in addition to the options about the transportation system itself, we must clearly identify those options in the activity system that will be expressed as the demands on the system:

1. Travel—These are the options open to every potential user of the transportation system: whether to take a trip at all, where to make it, when, and how, i.e., by what mode and route. The aggregate result of all the individual decisions about travel is expressed as the demand for transportation.
2. Activity System—Each of the social, economic, and political actors in the activity system has a wide range of options about how, when, and where it will conduct its activities. Over the long term, these options profoundly influence the demand for transportation. For example, as major changes in a transportation system are made over time, the spatial pattern of population and economic activity will change, as actors exercise their options for changing the location and/or scale of their activities. Forces within the economy external to the transportation system, such as housing subsidies or mortage policy, may impact on the spatial pattern of activity, and thus affect the demand for transportation.

These options are in the hands of a large variety of public and private decisionmakers. In many transportation analyses, most of these activity system options must be treated as exogenous, completely uncontrollable by the transportation analyst. Still other options are controllable to some extent in explicit coordination with nontransport options such as control of land use through zoning and land development incentives.

Whether controllable or not, however, the full set of transportation and activity system options must be considered in any analysis.

Impacts

When evaluating alternative transportation systems, one would like to consider all relevant impacts. Any change in the transportation system can potentially affect a large variety of groups and interests. The prospective impacts can be grouped as follows:

1. Users by location within the region, by trip purpose, and by socioeconomic group. Examples are suburban resident commuting to central city job and low-income, noncarowning resident of center city traveling to health facilities.
2. Operators by mode, by link. Examples are air carrier, trucker, highway maintenance agency, port authority, and toll bridge operator.
3. Physical by type of impact, by link. Examples are families, jobs, and taxable values displaced by new construction; and pollution of immediate environment through noise, fumes, air pollution, and ground water changes.
4. Functional by location within region, by type. Examples are changes in retail sales areas of shopping center, changes in production costs, and changes in land values.
5. Governmental by location, by level. Examples are local, state, or national representatives and citizen groups (22, 23, 24).

An essential characteristic of transportation is the differential incidence of its impacts. Some groups will gain from any transportation system change; others may lose. Therefore, transportation choices are essentially sociopolitical choices: The interests of different groups must be balanced.

Prediction: Basic Concepts

Any proposed change in a transportation system (or a completely new system) can be expressed in terms of the options identified above. The problem of prediction is to anticipate the impacts that a particular proposal will have: That is, we need procedures for predicting the impacts associated with any set of options (Fig. 1). In transportation, the impacts depend on the pattern of flows in the network that will result from the particular set of options.

The core of the transportation analysis problem is the prediction of network flows: Specification of the transportation system, T, and the activity system, A, implies the pattern of flows, F. Once the options with respect to transportation and the activity system are specified, the flows in the system are a consequence of those options. Prediction of these flows is necessary for evaluation of the impacts.

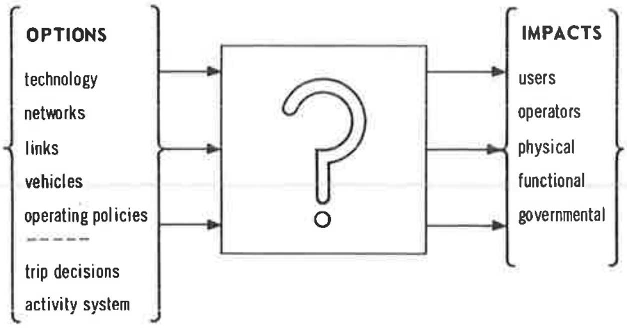

Figure 1. The prediction problem.

The general framework for the prediction of network flows is that of the equilibrium between supply and demand (25, 26, 27, 28, 29, 30, 31). All the transportation system options, T, can be expressed in a set of supply functions, S, and all the nontransportation options, A, in a set of demand functions, D. Then, within the constraints of the transportation channels specified as part of T, the equilibrium of S and D is a pattern of flows, F. The elements of this pattern, F, are the volumes and characteristics of the flows over each link of the transportation network: What flows over a link, from what origin zones, to what destination zones, at what speed, and cost?

The key concept allowing this formulation to be workable is that of a vector, L, of service variables. The level of service, L, that a particular set of transportation facilities provides can be expressed in terms of travel time (mean and variance), trip costs (fares and other out-of-pocket costs, as well as indirect costs such as car ownership), safety, comfort (real and psychological), and other characteristics. These service variables both characterize the transportation system and serve as the basis for the demands for transportation. The difference between perceived and actual service characteristics may be large and significant. Here, we shall make no distinction (25).

The general structure of this analysis problem can be expressed concisely (these variables are all vectors, matrices, or n-dimensional arrays).

Definition of variables:

T = specification of transportation system, in terms of full set of options;
A = specification of activity system (including exogenous characteristics);
F = pattern of flows in the system;
L = service characteristics of a particular flow or set of flows; and
V = volume of flows.

Supply Functions:

$$L = S(T, V)$$

Demand functions:

$$V = D(A, L)$$

Equilibrium:

$$\begin{Bmatrix} L = S(T, V) \\ V = D(A, L) \end{Bmatrix} \longrightarrow (V_O, L_O)$$

$$\text{i.e., } (T, A) \longrightarrow F = (V, L)$$

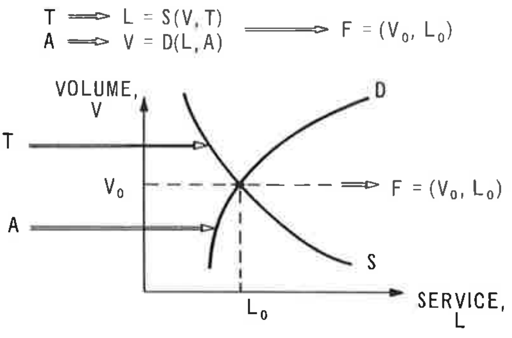

Figure 2. Simple equilibrium.

In words: The level of service, L, that the transportation system supplies is a function, S, of the transportation options, T, and the volume of flow, V. The volume of flow desiring transportation is a function, D, of the activity system options, A, and the level of service, L. The pattern of flows, F, defined as the volumes and the service levels that will actually occur for given (T, A), is the equilibrium solution to the supply and demand relations.

The graphical interpretation of this formulation is shown in Figure 2. In this figure V and L are assumed one-dimensional. Specification of T and A implies supply and demand functions, S and D. These in turn imply an equilibrium flow pattern, F, comprising a volume, V, and trip cost or "negative" level of service, L_0.

The value of this formulation is illustrated in Figure 3. S_0 is the supply function of the previous system, with corresponding equilibrium flow pattern $F_0 = (V_0, L_0)$. Consider a possible improved system S_1. If we assume the existing volume of travel, V_0, will occur on the new system as on the previous, we would anticipate a service level, L_E, i.e., a lower trip time because of the improved facility. However, assuming a constant volume level is erroneous, for the travel volume will increase because of the increased level of service (decreased trip time). The extent of this increase in travel is given by the demand function, D. Thus, the actual flow pattern resulting will be that given by the equilibrium of D and S_1: $F = (V_1, L_1)$. That is, the traffic volume will increase, and the level of service will be intermediate between L_0 and L_E.

Of course, because it takes time to implement transportation system improvements and because population and travel continue to increase, the demand curve, D, may meanwhile have shifted upward and to the right. Thus, the new equilibrium (V_1, L_1) may actually occur such that L_1 is greater than L_0. The level of service over the new system is actually worse than the level of service over the previous system at the initial period, but is better than the level of service that would have resulted from the old supply function and the new demand function.

The prediction of flows in a network is based, in principle, on this theory of equilibrium between supply and demand. In practice, prediction of equilibrium flows in networks is generally difficult and expensive; and, as discussed later, most present techniques for predicting network flows leave much to be desired.

The major, but by no means only, difficulty in translating this conceptual framework into practice is the role of the network in constraining the equilibrium flow pattern (10, 26, 28, 29).

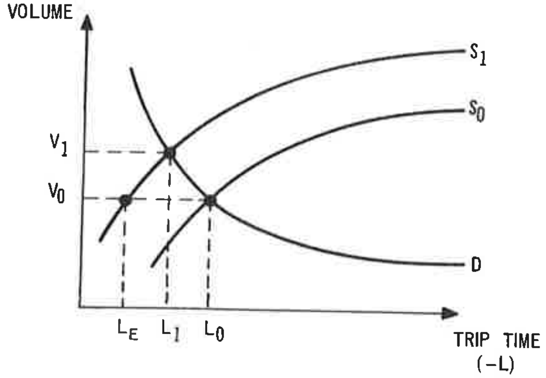

Figure 3. System improvement.

1. Multiple demand functions: The area to be studied is divided into zones; there is a different demand function for each pair of zones (origin and destination), for different groups of prospective trip-makers, and for different trip purposes (passengers) or commodity types (freight). Further, the demand for each zone pair is a function of the level of service vector, not a single "price."

2. Multiple supply functions: Each link of the network is represented by a different supply function. Note that

because L is generally a vector with time, cost, or safety as components, both the supply and demand functions are potentially very complex.

3. Finding the equilibrium pattern of flows: Instead of a simple graphical exercise, the calculation of the equilibrium flows is a difficult problem. Some of the conceptual and computational difficulties are (a) the level of service perceived by a trip between two zones depends upon which path is taken through the network; (b) the level of service over any path is a function of the levels of service over each of the links in that path (e.g., trip time equals the sum of the times over each link in the path); (c) the level of service over a link is a function of the total volume over that link (as given by that link's supply function); (d) the total volume over a link is composed, in general, of flows between many different zone pairs; (e) the actual computational procedures may be difficult and expensive; and (f) the equilibrium flow pattern is not unique. [A mechanism of trip behavior must be assumed in order to determine a unique equilibrium. One set of assumptions leads to the traffic-assignment approach of urban transportation studies; other types of assumptions lead to various mathematical programming formulations (2, 10, 26, 28, 29).]

Prediction Models

To fully implement this analysis approach, the following five major types of models are required:

1. Supply models to determine for any specified setting of the options what the level of service will be for various flow volumes. Examples are travel time over a rail link as a function of train length, schedule frequency, roadway, and volume of passengers; volume-travel time curves as used in traffic assignment procedures.
2. Resource models to determine the resources consumed—land, labor, capital—in providing a particular level of service with specified options.
3. Demand models to determine the volume of travel demanded, and its composition, at various levels of service.
4. Network equilibrium analysis to predict the volumes that will actually flow in a network for a particular set of supply and demand functions; short-term equilibrium.
5. Demand shift models to predict the long-term changes in the spatial distribution and structure of the activity system as a consequence of the short-run equilibrium pattern of flows, the feedback effect of transportation on land use.

These five are the basic prediction models in transportation. The interrelationships among them are illustrated in Figure 4.

This structuring of the transportation systems analysis problem incorporates several hypotheses. The first hypothesis is that this is a complete and useful summary of the types of options and impacts. The second hypothesis is that it is meaningful to model transportation technology from two perspectives: in terms of the service perceived by prospective users, the supply functions; and in terms of the resources consumed in providing that transportation service, the resource functions. The third hypothesis is that it is useful to separate short-term and long-term equilibrium: the short-term responses of transportation users in a transportation market with the activity system fixed, as represented by the demand functions; and the long-term responses of users and others in a larger, more general market (the total

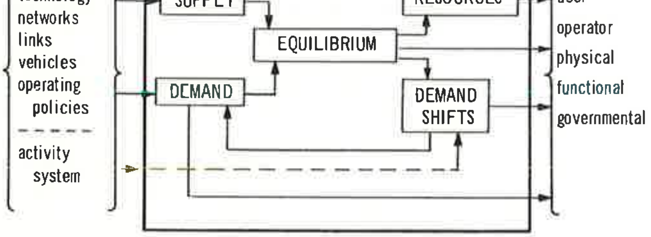

Figure 4. Basic prediction models.

economy), as represented by the demand shifts. The fourth hypothesis, which in a sense is the operational test of the second and third hypotheses, is that valid predictive models can indeed be constructed.

At present, in addition to the modest set of models developed at M. I. T. for the prototype analysis (1, 2), there are several transportation systems analysis activities in which this framework is being applied, implicitly if not explicitly. Three major areas are (a) urban transportation planning, (b) Northeast Corridor Project, and (c) Harvard Transport Research Program.

The prediction portion of the urban transportation planning process, as it has been established in almost all the metropolitan areas of the United States, consists of variants of the following sequence (32): (a) project land use, population, and employment changes; (b) predict trip ends generated in each zone; (c) predict interzonal distribution of trip ends (e.g., using gravity or opportunity models); (d) predict modal split; and (e) predict distribution of flows over the proposed network. As pointed out by Wohl and Martin, Deen, and others (25, 33, 34), there are serious internal inconsistencies in this sequence of steps, from the point of view of an equilibrium analysis. For example, the estimation of trip ends assumes implicitly a general level of service in the system, and a level of service is assumed explicitly for input to the interzonal distribution calculations (e.g., using a gravity model). The last step of the process, traffic assignment, predicts an "actual" level of service, or set of travel times, for flows in the network. However, the initial estimates of level of service used for trip generation and distribution are rarely revised to be consistent with the travel times that are predicted by the traffic assignment.

In spite of these inconsistencies, and other limitations, the structure implicit in urban transportation planning is fundamentally that of the supply-demand equilibrium framework. The supply functions are represented as volume-travel time functions or simply link capacities and travel times. The demand functions are represented by the sequence of predicting trip ends, interzonal distribution of trips, and modal split. The network equilibrium model is the traffic assignment process, with the various capacity-restraint formulations representing explicit attempts to find equilibrium in the network, given fixed demands. (All-or-nothing assignments are obviously very difficult to justify as a meaningful prediction of equilibrium flows.) The resource requirements models are represented in a variety of ad hoc calculations: right-of-way, construction, and operating costs. Demand shifts models are sometimes explicit, as when land use models are used to predict the effects of differential changes in accessibilities on the location of population and economic activities.

Perhaps one of the most significant needs in urban transportation planning is to revise the models and procedures to incorporate the equilibrium approach more explicitly. The present procedures represent a series of ad hoc approximations, as a pragmatic approach to the problem of predicting flows in networks. A new generation of urban transportation models should be developed on the sounder theoretical basis of explicit supply-demand equilibrium analysis.

In the Northeast Corridor Transportation Project's system of models, this structure is more explicit. Although not yet fully operational, this system of models is described in several documents (35, 36). There are explicit interregional and intraregional demand models for passengers and freight (37); technology models to produce supply and resource functions; a network simulator to predict network equilibrium (although it is not yet clear whether this will be a consistent equilibrium, i.e., something other than all-or-nothing); and demand shift models for forecasting changes in interregional and intraregional location and intensities of economic activities as a function of changes in transportation and other factors (38).

The Harvard Transport Research Program models are designed for use in planning investment in transportation in developing countries (39). Several explicit technology models are used for predicting cost-service characteristics of highways, rail, and intermodal transfer points. Demand is derived from a macroeconomic model, containing an interregional input-out model; these are also used to predict demand shifts. Network equilibrium is found with a modified traffic assignment approach.

These are very cursory descriptions of highly sophisticated systems of models; they simply point out how the basic framework outlined above underlies several major transportation analysis efforts. Yet, in spite of the magnitude of effort that has gone into development of the model systems described, there are still major difficulties with implementing this framework in a thoroughly satisfactory way. Constructing demand models is always difficult, particularly because of the lack of good data for model calibration, as was demonstrated in Plourde's efforts to test the Baumol-Quandt model for metropolitan travel (12, 40, 37, 41, 32). The understanding of the structure of transportation supply functions and resource requirements models, particularly with respect to basically new technologies, is very elementary, and many difficult problems remain (6, 31, 42, 43, 44, 45, 46, 47, 48). The problem of computing supply-demand equilibrium in networks was described above. There is a significant amount of effort under way in exploring various computational approaches to this problem, ranging from simulation approaches to mathematical optimization applications for certain special cases (10, 26, 28, 29). The problems become even more complex when equilibrium is to be determined for multiple time periods, where vehicle schedules may be adjusted to meet the transient fluctuations in demand (49).

Predicting demand shifts, that is, changes in land use, population, and the structure of social and economic activity generally, is perhaps the most difficult problem of all. This requires not only understanding the basic structure of the social and economic system and the influence of a variety of policy levers on that system, but also identifying the specific role of transportation in modifying growth patterns. Even in urban land use model development, an area of significant activity in the past, there is still a great gap between what would be desirable in terms of land use prediction models and what has actually been implemented (50, 39, 38).

The Problem of Search and Choice

The system of basic models discussed in the preceding section is the core of the analysis problem, but not the whole of it. The framework of equilibrium analysis provides a basis for prediction of the impacts associated with a particular set of options. However, there still remain several major issues.

1. The problem of search: how to generate a set of options in the first place, that is, how to formulate a complete, meaningful, well-specified transportation system strategy, which is worth testing in the complex system of prediction models.
2. The problem of choice: given the predicted impacts of several alternative specifications of options, how to evaluate the impacts and choose among the alternatives. The difficulties in choice arise because an essential characteristic of transportation is the differential incidence of its impacts. Some groups will gain from any transportation system change; others may lose. In a realistic network context, there are many user, operator, and other groups, and the interactions among them are complex.

Therefore, transportation choices are essentially sociopolitical choices: the interests of different groups must be balanced. This does not mean that negative impacts of a system on some group are inevitable. It may well be possible, particularly with complementary programs, such as relocation subsidies, industrial development, and job training, to develop a concerted strategy such that no single group is hurt unduly (51). The development of a real-world, implementable transportation plan or policy requires more than just the prediction of impacts of one or two alternatives. Feasible, desirable solutions can be developed only through a careful and sensitive analysis, in a systematic way, of a variety of alternatives and their impacts.

Systematic analysis in transportation requires that a wide variety of alternative options be explored and their differential impacts traced out explicitly. In Figure 5 we illustrate the systematic exploration of the range of options for a single link. We assume that this link is of sufficient length and importance that we in fact have the full range of decision options open to us. We can choose alternative technologies for this link, for example, mass transit, highway, automatic bus on separate right-of-way, or some new technology. We can change the network configuration in this area by introducing

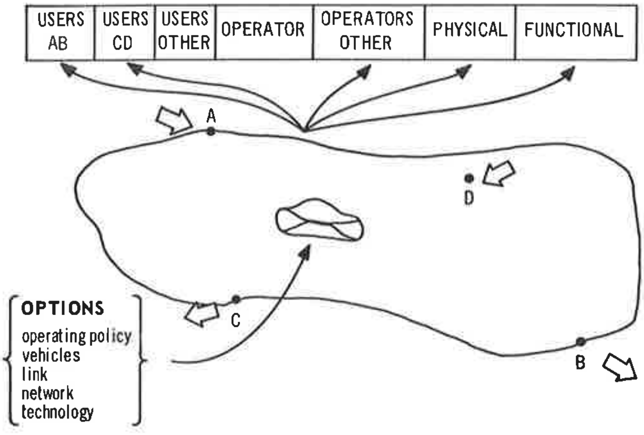

Figure 5. Changes in a network.

several links to supplement this one or change the relationship of this link with other links by adding or eliminating intersections between links. We can change the characteristics of the link itself by changing its physical location or widening it. We also have options regarding the number and type of vehicles that will run over this link, as well as speeds, schedules, stopping times, and fares.

Changes in this particular link will impact differently on each of the groups shown in the figure. In particular, we have identified several user groups, AB and CD, as well as the group of all other users, the operator of this particular facility, the operators of all other facilities, and the physical and functional impacts. In Figure 6, we show how changes in the options for this particular link, as reflected solely in speed over the link, might impact differentially on the various actors. (This is hypothetical; the actual variations would be a property of the network at hand.)

We may have already examined a particular set of options, and thus know its impact on each of the actors. However, in general, we are very uncertain about the changes in these impacts that will occur if we make relatively small changes in these options. This is precisely because of the complexity of the supply-demand interactions in the network.

This is the real difficulty in analysis of a large, complex, multimodal transportation system, such as that of the Northeast Corridor region (Boston to Washington, D. C.). Instead of changes to just one link, we have a potential of changes to, or introduction of, a very large number of links: interstate highways, other highways, conventional jet aircraft routes, and new high-speed ground transportation systems, such as tube trains

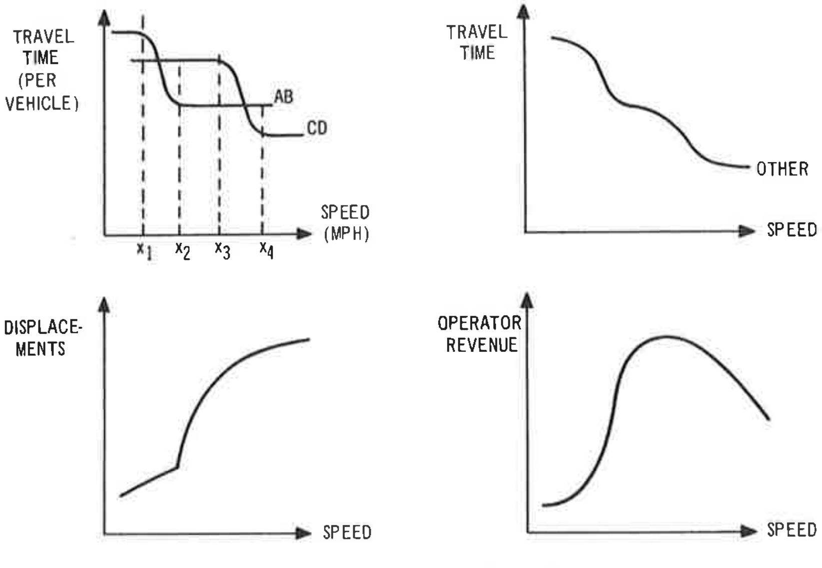

Figure 6. Differential impacts.

or tracked air-cushioned vehicle systems. Furthermore, we are concerned with the impacts on a correspondingly very large number of groups. Clearly, it is not a trivial problem to identify the set of options that has the most desired impacts.

What is required is a systematic exploration of the options that carefully traces out the differential impacts on each group. The set of prediction models serves as a vehicle for assisting in this; but additional techniques are required. Procedures are required for systematically searching out and choosing among transportation alternatives in order to develop equitable transportation system changes that explicitly recognize the differential incidence of impacts.

Summary

Many options are open for manipulating a transportation system, and many impacts must be considered. To predict the impacts associated with a particular set of options requires prediction of the corresponding pattern of flows that will occur in the multimodal transportation network. The basic logic of this prediction is that of supply-demand equilibrium. Making this logic operational in the network context requires a complex system of models. Thus, to predict the impacts associated with only one alternative transportation system requires significant effort.

The problem of search is to generate alternative transportation systems sufficiently attractive to be worth testing by predicting the impacts. The problem of choice is to rank the alternatives based upon evaluation of their predicted impacts. Systematic analysis in transportation planning requires that a wide variety of alternative options be explored and their differential impacts traced out explicitly.

Thus, the task is to systematically search out and choose among transportation systems alternatives, with careful consideration of the differential impacts on different groups, in a network context. Therefore, inevitably, the hard realities of alternative transportation technologies and complex computer models lead into the "soft," very subtle differences of impacts: Who gets better service with a prospective change? Who gets worse? Who pays? And how do they all change the way they work, live, and relax as a result?

THE ANALYSIS PROCESS

The topic of the preceding section was primarily the scope of the substantive problem of transportation systems analysis. Underlying this discussion was a second theme: a concern with how this substantive problem should be analyzed. Clearly, it is not sufficient to have a set of computer models for predicting impacts of a given alternative; there are a wide variety of issues involved just in the problem of generating good alternatives to test. Furthermore, if we examine the role of transportation systems analysis in the context of the political process within which transportation planning inevitably takes place, then we see that there is an even greater order of complexity involved. Thus, in order to understand how to conduct systematic analyses of transportation policy, we must step back from the substantive problem of transportation and focus on the process of analysis.

We do this, first, by pointing out some of the major issues by reviewing the rational model and its limitations. Then, we outline a conceptual model stimulated by this review of transportation systems analysis in the context of a political world. In the next section we then show the application of this PSP model to transportation systems analysis. This sets the stage for a discussion of specific operational techniques derived from the PSP model.

The Rational Model and Its Limitations

The essence of the rational model of decision-making is expressed in the very common prescription of systems analysis (52, 53, 54, 55, 56) that includes the following steps: (a) define objectives and formulate a utility function; (b) enumerate all the possible alternative actions; (c) identify the consequences of each action; (d) evaluate the consequences in terms of the objectives via the utility function; and (e) choose that action that best achieves the objectives.

This "synoptic" model (57, 58, 59) is very limited in its application to complex public policy questions, such as transportation, for many reasons:

1. We can never know completely all the alternatives.
2. We can never define all the relevant objectives consistently and completely. First, there are too many points of view, "actors," to get agreement on objectives (though as Lindblom points out, we may get agreement on actions without agreement on objectives). Second, objectives are difficult to formulate in the abstract, and they will be substantially revised and clarified through examination of the consequences of specific alternatives (58).
3. We can never completely identify the relative values of all possible combinations of the various objectives; that is, we can never get a fully defined utility function. Therefore, evaluation of the consequences of an action is not so simple. Most naturally, we prefer to examine alternatives explicitly and to evaluate the incremental differences between them (58).
4. There will always be uncertainty in the prediction of consequences. Many relevant consequences will be left out; because of the open nature of the socioeconomic system (i.e., not a closed system), consequences of actions such as transportation will "spill over" into other areas (e.g., functional and governmental impacts). Further, we can expect to find that actions that we have implemented do lead to unanticipated consequences (60).
5. The costlines of analysis are a severe constraint. Generation of alternative actions, formulation of objectives, anticipation of the consequences of actions (prediction), and determination of the most desired action all take resources. The resources of analysis are dollars, time, manpower, and computing capability (computer time). Analysis of policy alternatives generally suffers under very severe constraints on these resources, and so analysis is inevitably incomplete.
6. Analysis is dynamic. Problems are never solved completely; massive changes in the system, such as transportation, generally take time for implementation. As specific changes are implemented, the context of the problem will change. Within the analysis process itself, the conceptions of the problem held by analysts and decision-makers will evolve. Initial statements of objectives will be revised as successive alternative actions are generated and examined. Examination of previous alternatives will suggest new ones for analysis.

Perhaps the best way of summarizing the limitations of the rational model is that ". . . in the face of man's limited capacities, it offers simply a prescription: 'Be comprehensive! ' " (58). The comprehensive ideal fails to accept the realities of policy analysis: the costs of analysis, and the inability for cost and cognitive reasons of ever being comprehensive.

This does not mean, as some would argue, that systematic analysis must be discarded altogether, rather, that the simple five-step model of the analysis process must be replaced by a more subtle structure.

PSP: A Dynamic Model of Decision-Making

As a partial answer to the limitations of the rational model described above, a more complete model of decision-making is necessary. Such a model has been formulated, the problem-solving process (PSP) model (15, 4). Only a few of its major characteristics will be summarized here.

The first important characteristic of the PSP model is the role of time. The analysis process itself takes place over real time; to develop, evaluate, and choose among alternatives takes time. Further, the analysis process is itself embedded in the larger evolutionary process of the real-world system of interest; the actions selected by analysis are implemented, their results observed, and new analyses lead to new, revised actions.

The second important characteristic of the PSP model is the distinction between generating and choosing among actions. We emphasize this distinction by defining search and selection as the procedures that perform these functions. Search designates any procedure used to produce one or more alternative actions. Search may be intuitive, as in the sense of design, or may be formalized, as in a linear programming model. Selection designates the process of choosing among several alternative actions. The input to selection is a set of alternative actions. The output of selection is a preference ordering, or ranking, of the actions by desirability.

To actually accomplish selection requires three basically different kinds of procedures. Prediction models are used to anticipate the consequences that an action would have if implemented in the real world, for example, to predict volume of travel on a particular transportation link. Evaluation procedures operate upon the predicted consequences to yield statements of the valuations, or relative desirabilities of those consequences of a particular action, for example, the values of user costs and benefits associated with a particular flow volume on a link, or the relative desirability of a particular regional growth pattern. Because all predicted consequences cannot be represented adequately by a single measure of value, or valuation, we do not assume that evaluation summarizes all the valuations into such a single measure. For example, we do not assume that construction dollars, loss of recreation land, and regional development patterns can all be lumped into a single measure of value, such as dollars or some overall utility measure. Therefore, after evaluation there must be choice. In choice, two or more actions are compared on the basis of the set of valuations for each—dollar costs, recreation land acreages, quality of regional pattern—and a decision made about the rankings of the actions. Choice is difficult, but necessary. (At this point, we will not distinguish between choice executed by the analytical staff and choice executed by a small group of decision-makers or the larger political process.)

The third important characteristic is a distinction between the state of the analysis process at any particular time, and the procedures that may be used to change that state. The state of the process expresses the analyst's current view of the problem. The problem-solving system contains a variety of procedures to be used in the problem-solving process when and as appropriate. Each time a procedure is used it changes the state of the process in a way appropriate to the procedure: the use of a procedure changes the analyst's view of the problem.

From the point of view of our present discussion, the major variables describing the state of the process are the actions, A, the goals, G, and the current ranking of the actions, R. The major procedures for changing that state are search, selection, and goal formulation and revision. Additional state variables include consequences, valuations, raw information, and probability distributions over uncertain variables. Additional procedures include information analysis, model construction and revision, decomposition and restructuring procedures, and metaprocedures (15). All these procedures involve some reference to the current set of goals, G.

The basic view of the problem-solving process that this implies is shown in Figure 7. Alternative actions are generated, and then a preference ordering is established over those alternatives. If the most desirable alternative is sufficiently attractive, then the problem-solving process ceases and that most desirable action is implemented in the real world; if not, then search is repeated and new actions are generated. These new actions may or may not be related to the previous actions. The sequence is repeated again and again, until finally there is one action sufficiently attractive for implementation in the real world.

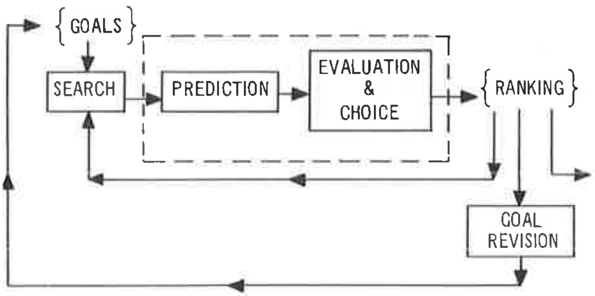

Figure 7. Basic cycle.

This image of a trial-and-error process, basic to the PSP concept, is completely contrary to the image of a problem for which the optimal solution is obtained directly by solving a mathematical (or other) model. Such optimizing methods do have an important role in the broader PSP, but such real problems as transport systems planning are too complex for such techniques to carry the whole burden. A particular optimizing method corresponds to one search-and-selection sequence; but many kinds of search and selection procedures are required in addressing the total problem.

Evolution of Actions and Goals

The focus of PSP is on actions. Because search and selection procedures concern the basic processes of generation and selection of actions, these procedures are at the heart of the PSP. However, there are a variety of other activities that must occur in PSP to allow search and selection to operate, and to revise the context in which they operate (15). Particularly important are goal formulation and revision procedures.

The purpose of these procedures is to formulate and revise the statement of goals, G, as new actions are generated and their consequences are examined. That is, each cycle of search and selection potentially may trigger goal revision; for example,

1. An initial statement of goals is formulated.
2. The search procedures are executed, one or several times, producing one or more alternative actions.
3. The selection procedures are executed, identifying and evaluating the consequences of the actions and their performance with respect to the goals; the result is a ranking of the alternatives.
4. In the basic cycle, steps 2 and 3 may be repeated a number of times, until an action sufficiently desirable for implementation has been found, or analysis resources have been exhausted.
5. The mutability of goals must be recognized, however, and so step 3 or even step 2 may be followed by goal revision.

Goal revision may follow search immediately, particularly when the results of search are either very disappointing (it proves very difficult to generate actions that achieve the goals) or very successful (the goals are set so low it is not at all difficult to achieve them).

By this simple model, the analysis process is typified by continued and parallel evolution of the set of actions, A, and the set of goals, G. The ranking of the alternative actions will change, not only by addition of new actions to the set, but also by revision of the goals.

Search and choice interact heavily in the sociopolitical arena. To account for this interaction, a model of the analysis process more subtle than the static, rational model is required. The evolution of goals as well as actions is an important facet of the more complete model.

Implications of the PSP Model

In this brief exposition, we have touched only quickly upon the characteristics of a more general model of the problem-solving process. Let us now explore some of its implications. Once we shift from a static conception of the analysis process to an evolutionary one in which actions and goals change over time, our perception of the interaction of search and choice changes in fundamental ways.

For one thing, we need no longer search desperately for a utility, or social welfare, function. Such functions are used to reduce a multi-dimensional set of goals to a single dimension (for example, benefit-cost ratio). In an evolutionary process, we can accept a less well-structured set of goals, because all that we require at any time is sufficient information about goals to reach a choice over alternatives, not a function over all conceivable combinations. (In fact, we may not need to have a completely consistent goal structure to produce agreement over alternatives; as Lindblom points out, actors may reach agreement on actions even though they are striving for different objectives.) Thus, a much looser, more flexible structure of goals is appropriate and useful. The concept of a "goal fabric" has been proposed to serve this purpose; it is discussed later in this paper.

A second important implication is that alternatives need not be single, massive-system proposals, but can and should be formulated as staged strategies over time. The typical urban transportation study chooses among a small number of alternative transportation system plans for a target year (1985, say). Instead, there should be a much richer number of smaller actions, each one being the building of a specific part of the network in a particular year (or other options, such as buying additional transit cars). Then the major alternative 1985 plans could be composites of a number of the specific time-staged facility actions. However, the whole approach to analysis would be different. Instead of choosing among single packages, the emphasis would be upon choosing among sequences of actions staged over time. In this way, there would be a great deal of flexibility for revision of both actions and goals as each stage of the system selected is implemented. Furthermore, the decision about appropriate facilities to construct at each successive time period could be revised as changes in the real world are observed, or changes in the goals or the available actions as new technologies are developed. Models for searching out and choosing among sequential decisions in transportation planning are under development (61).

A third implication is more emphasis on the value of information. That is, instead of collecting all the information necessary for constructing demand models and the other analysis models in one single survey, there can be a much more efficient use of resources through continuous sampling over time, with a flexible readjustment of data acquisition as new issues are identified for study. This is an important consequence of the time-staged strategy approach. Further, this implies that there should be an economic analysis of the value of information in its relevance to the search and choice issues at hand; as the actions and goals change over time, the value of different types of information will also change. Models for optimal information collection strategies in networks are under development (16).

Finally, and perhaps most important, the evolutionary image of the analysis process leads to a major new perspective on the relationship between the analysis team and the political environment (51).

The evolution of actions and goals takes place at several different levels. First of all, consider the technical analysis team actually doing transportation systems and related studies for a particular area. Within this team, the sets of actions and goals will evolve fairly rapidly: the team is engaged in day-to-day development and testing of alternatives, and as it learns more about the problem, it will be almost continuously revising its assumed goals. At a second level, this analysis team will interact periodically with the political decision-makers or other responsible public or private officials for whom the analysis team is acting as staff. As a result of these (more or less frequent) interactions the actions and particularly the goals will be further refined and revised. These decision-makers, in turn, will interact with the body politic: the variety of actors, individuals and interest groups, who comprise the full set of interests impacted by transportation systems alternatives. As a result of their interactions with the body politic, the decison-makers will revise their conceptions of actions and, more particularly, goals, and will pass these revised conceptions on to the analysis team. But also, the results of the analysis team, as communicated through the decision-makers to the public at large, will help to change and broaden the perceptions of the decision-makers and of the body politic.

The interactions in search and choice among analysis team, decision-makers, and polity should be exploited explicitly. Perhaps the most important role of a technical analysis effort is to clarify public objectives, even more than the development and implementation of specific actions. For example, one of the major contributions of the highway transportation program may have been to create a public awareness of the choice issues that need to be addressed in the core of the metropolitan area. The threat of highways through the centers of cities has set in motion political forces that have helped to raise serious discussion about the competing objectives of groups in the metropolitan area and have stimulated the search for new transportation technologies as well as new methods of highway planning.

EXAMPLE: THE "PROTOTYPE" ANALYSIS

The preceding sections have laid out the scope of a comprehensive systematic analysis of transportation, and a theoretical model of the analysis process. The feasibility and utility of these ideas have been demonstrated by conducting a prototype analysis of passenger transportation in the Northeast Corridor region. (Clearly, the models could be used for many other contexts as well.) To the maximum extent feasible, realistic data were used. The result demonstrates how the analytical approaches and techniques can be applied to improve policy decisions. However, the result is not of sufficient detail or comprehensiveness to be used for policy decisions without further calibration and modifications of the models and substantial additional data.

TRANSET II, a Laboratory

To do this prototype analysis, it was necessary to develop a set of models for transportation systems analysis. These models, in the form of computer programs, provided a "laboratory" for experiments in systematic analysis in transportation.

This laboratory was implemented as TRANSET II, a new subsystem of ICES, the Integrated Civil Engineering System (62). This subsystem is a problem-oriented, command-structured language for transportation system analyses, and thus is designed for ease of use by analysts without computer training. The development of TRANSET II is based upon additions and changes to an earlier subsystem for urban transportation analysis, TRANSET I (63). For example, to create a new regional transportation network by adding a link to a network previously stored in the computer, the analyst might give the computer this problem-oriented language command:

```
MODIFY NETWORK 'BASE' FORMING 'NEWRAIL' ADD LINK FROM
56 TO 97, DISTANCE 37.2, LANES 6, VOLUME/DELAY 4.
```

In this example, BASE is the previously stored network, NEWRAIL the name to be given to the new network. The modification consists of adding a link from node 56 to 97, with the indicated length, number of lanes, and supply function (volume/delay curve number 4). Such problem-oriented language capabilities enable the analyst to use the computer models in a much more flexible and efficient manner than do the more traditional forms of programs.

As a system of computer models, TRANSET II provides the capability to analyze transportation problems by predicting supply and demand equilibrium in a multimodal transportation network (2). Some of the particular features of TRANSET II are (a) the capability to express transportation policy options through technology choices, network configuration, link characteristics, fares, frequency of service, subsidy, and tax policy; (b) the use of the Baumol-Quandt abstract mode demand model; (c) incremental assignment techniques as an approach to calculating equilibrium; and (d) explicit evaluation routines for tracing out impacts on different groups.

With the cooperation of the Northeast Corridor Project of the U. S. Department of Transportation, data were obtained through which the Northeast Corridor network was modeled in two forms: 5-district and 29-district versions with the networks modeled at corresponding levels of abstraction. The resulting models then served as the basis for a number of analyses. The TRANSET II model system was used as a laboratory to conduct numerous experiments with the 5-district data. These experiments demonstrate (a) the feasibility of developing a supply-demand equilibrium model for transportation analysis; (b) the difference between equilibrium and nonequilibrium approaches to the problem; (c) how different options and impacts can be included in a single model so that their interactions can be explored systematically; (d) how trade-offs between options can be explored; (e) the technique of differential impact analysis through tracing out impacts among different actors as the options are varied; (f) sensitivity analyses; and (g) effects of alternate time-staging of actions.

Space does not permit summary of all of these experiments here (1, 2). The major points we will discuss in the following sections will be the applicability of the PSP model, as illustrated by TRANSET II, and the systematic analysis of options and impacts.

Applicability of the PSP Model

To see the applicability of the PSP model to transportation systems analysis, we can refer to the specific problem-oriented language capabilities of TRANSET II, as now operational.

Search—No explicit search procedure is provided in TRANSET II at this time, although several are under development. At present, the analyst must generate a policy alternative, execute search, through his own judgment. He may generate a completely new action, or use parts of one or more previously generated actions as stored in the computer files (i.e., on disc). If he uses stored components of an action, he may modify them if he wishes. One particularly powerful capability of TRANSET II is the ability to name data files. Thus, the analyst may store several transportation networks under arbitrary names such as '1956-1,' 'RAIL-2,' and 'HWAY.'

To generate a completely new transportation system alternative, or new components of an alternative, to save portions or all of an alternative in computer storage, and/or to create a new alternative through modification of a previously stored component, he uses the following commands:

1. Transportation Options
   a. READ NETWORK, for general network characteristics
   b. LINKS, for network connectivity and link characteristics
   c. READ VOLUME DELAY SET, for generalized supply functions
   d. INPUT MODAL SERVICE DATA, for interzonal fares and frequencies for each mode
   e. INPUT MODAL COST DATA, for cost parameters for each mode
2. Activity System Options
   a. INPUT DISTRICT DATA, for population, incomes, and holding capacities, for each zone
   b. INPUT MODAL SPLIT PARAMETERS, for demand model parameters

In addition to specifying a completely new alternative, it is also possible to generate an action by using portions of another action previously stored in the computer, as follows:

3. To modify an action, previously stored on secondary storage as a permanent file, to create a new one
   a. MODIFY NETWORK + name of network to be changed

ADD LINK DELETE LINK CHANGE LINK	specification of changes

   b. REVISE MODAL DATA + name of data to be changed

MODE COST MODE FREQUENCY	specification of changes

   c. REVISE DISTRICT DATA + name of data to be changed

DISTRICT	specification of changes

Selection-Prediction—The prediction procedures of TRANSET II are based upon the supply-demand equilibrium concept. The commands to accomplish prediction of the consequences for a specific alternative are as follows:

1. PREDICT POTENTIAL TRIPS, generate estimated trip demands
2. PREDICT ACTUAL TRIPS, predict actual network equilibrium flows
3. PREDICT DISTRICT DATA, predict future population and income for each zone, based upon predicted network flows

Selection-Evaluation—The evaluation components of TRANSET II are relatively simple. For any particular alternative action, its predicted consequences can be displayed in a variety of ways for intuitive evaluation by the analyst. User, operator, and government costs can be computed and aggregated in a variety of ways through the EVALUATE COSTS commands. Accessibilities can also be evaluated as measures of functional impacts (i.e., potential changes in the activity system). There are no capabilities at this stage for predicting physical or governmental impacts explicitly.

1. Display flow pattern consequences
   a. REQUEST FINAL LINK DATA, MINIMUM PATHS, TRAVEL TIMES, SYSTEM TRAVEL DISTRIBUTION, INTERZONAL TRIPS
   b. PRINT TRIP MATRIX
   c. In graphical form, by plotter or other display device, PLOT NETWORK; DISPLAY LINK VOLUMES, TRAVEL TIMES, SPEEDS; DISPLAY INTERZONAL VOLUMES, TRAVEL TIMES, SPEEDS
2. EVALUATE COSTS, for user, operator, and governmental impacts
3. EVALUATE ACCESSIBILITY, for functional impacts

Selection-Choice—Choice involves the comparison of alternatives to determine a preference ordering. In TRANSET II, no automatic choice capability is provided. However, a very simple but powerful set of commands provides the analyst information that is extremely useful in his judgmental decision about preferences between alternatives. These commands compare two alternatives, displaying the differences between them. Then the analyst can examine the incremental differences between the two alternatives, as well as the absolute levels of the impacts.

1. COMPARE TRIPS, for summary of the differences in flow volumes between two alternatives
2. COMPARE SURPLUSES, for differences in user benefits as provided by consumer surplus measures
3. COMPARE ACCESSIBILITIES, for differences in functional impacts

The problem-oriented language capability is particularly useful in commands such as COMPARE TRIPS, ALTERNATIVES 'AIR' AND 'RAIL'.

Utility Commands—In addition to the above, there are available in TRANSET II a variety of utility commands for editing data, obtaining intermediate results during the course of the computations, or filing data on computer disc storage (2).

The use of TRANSET II commands is illustrated in Figure 8, which shows typical computer input and output for a single selection cycle. Substantial improvements and additions to these capabilities have been made since the completion of TRANSET II (64).

Systematic Exploration of Options and Impacts

Often, when computers are used for problem-solving, far too much emphasis is placed upon getting the computer model running; not enough attention is given to how the model is to be used once it is running. A major objective of the prototype analysis was to demonstrate how prediction models should be used in transportation systems analysis.

The basic issues are these: What different combinations of options can achieve the same impacts? What different combinations of impacts (on different groups) can be achieved (by any combination of options)? TRANSET II was used as a laboratory to conduct a number of experiments to trace out such trade-offs. These are illustrated in Figures 9 through 12. The relationships in these figures were derived from data produced by a series of computer runs. In these runs, three levels of fare and three of frequency were explored, resulting in nine combinations. This sample provided the basis for inferring the relationships shown in the figures (except Fig. 12, as noted).

Figure 9 shows how, as frequency of service between two points is increased, fare must also be increased to maintain the same volume of trips in the system (e.g., 1.10 = 1,100,000 trips per day). Thus, this figure shows how two options—fare and frequency over one single route—must be manipulated together to achieve a constant level of one impact—total trips. In Figure 10, this same approach is extended to consideration of

```
$     EXAMPLE RUN 5 -- EQUILIBRIUM AND IMPACTS

TRANSET

$     RETRIEVE DATA PREVIOULSY FILED

LOAD NETWORK '5X3,1965'

LOAD TRIPS 'BASE'

LOAD VOL/DELAY SET '3MODES,2'

LOAD GEN/RATE SET 'BASE'

GET DISTRICT DATA '5CENTERS'

GET MODAL DATA '5X3 NO.1'

$     DEFINE VARIABLE INCREMENT

USE INCREMENT 50 PERCENT

$     SPECIFY NAME OF NETWORK WHICH WILL INCLUDE THE EQUILIBRIUM CONDITIONS

SAVE ASSIGNMENT RESULTS IN NETWORK 'BASE'

$     START THE INCREMENTAL APPROACH TO EQUILIBRIUM COMPUTATION

PREDICT ACTUAL TRIPS

                              THE NETWORK IS COMPLETELY ASSIGNED AFTER   420 ITERATIONS

                                   TIME USED SINCE START OF RUN IS   1.65 MINUTES


                             ASSIGNMENT RESULTS HAVE BEEN STORED ON DISK IN NETWORK BASE

$     OUTPUT ACTUAL AND ESTIMATED TRIP DEMANDS

$     CONTRARY TO HEADING, TRIPS ARE IN PASSENGERS PER DAY

PRINT TRIP MATRIX 'BASE'

                                             INTERZONAL TRIP STATUS


                                          TRIP MATRIX NAME IS BASE


                          THIS IS THE TABLE TO CONVERT MACHINE ZONE NUMBERS TO USER ZONE NUMBERS

      MACHINE NUMBERS          1         2         3         4         5         6         7         8         9        10

   0   USER NUMBERS         1001      1002      1003      1004      1005      2001      2002      2003      2004      2005
  10   USER NUMBERS         3001      3002      3003      3004      3005
                                    THE FOLLOWING MATRIX USES MACHINE ZONE NUMBERS.

$     OBTAIN COST DATA BASED ON ACTUAL FLOW PATTERN

EVALUATE COSTS TIME VALUE 2.00 WAIT FACTOR .50

                             COST SUMMARIES FOR NETWORK BASE

                                  AND TRIP MATRIX BASE



                                         DAILY USER DATA BY MODE AND ORIGIN


                      TOTAL       USER FARES         USER TRAVEL TIME       USER WAIT TIME        WEIGHTED COSTS
                      TRIPS
   MODE    ORIGIN                TOTAL    AVERAGE     TOTAL     AVERAGE      TOTAL     AVERAGE      TOTAL      AVERAGE
          DISTRICT (PASS/DAY)     ($)    ($/TRIP)    (HOURS)  (MIN/TRIP)    (HOURS)  (MIN/TRIP)      ($)      ($/TRIP)

   AIR        1       1552   0.28861E 05  18.60   0.39947E 04  154.   0.99343E 03  38.41   0.38837E 05  25.02
   AIR        2       1618   0.24215E 05  14.97   0.36320E 04  135.   0.10535E 04  39.07   0.33586E 05  20.76
   AIR        3       3054   0.46437E 05  15.21   0.69187E 04  136.   0.17284E 04  33.96   0.63731E 05  20.87
   AIR        4        974   0.14885E 05  15.28   0.22902E 04  141.   0.11386E 04  70.14   0.21742E 05  22.32
   AIR        5       1844   0.31603E 05  17.14   0.44475E 04  145.   0.10327E 04  33.50   0.42564E 05  23.09


   RAIL       1       1426   0.13982E 05   9.81   0.61999E 04  261.   0.85517E 03  35.98   0.28092E 05  19.70
   RAIL       2       4676   0.31738E 05   6.79   0.13401E 05  172.   0.21759E 04  27.92   0.62891E 05  13.45
   RAIL       3       5922   0.41680E 05   7.04   0.18018E 05  183.   0.31044E 04  31.45   0.83925E 05  14.17
   RAIL       4       2020   0.15598E 05   7.72   0.65330E 04  194.   0.16744E 04  49.73   0.32013E 05  15.85
   RAIL       5        672   0.71588E 04  10.65   0.34545E 04  308.   0.83411E 03  74.47   0.15736E 05  23.42


   ROAD       1       7968   0.36145E 05   4.54   0.42515E 05  320.   0.99600E 03   7.50   0.12317E 06  15.46
   ROAD       2      18470   0.58890E 05   3.19   0.90952E 05  295.   0.23087E 04   7.50   0.24541E 06  13.29
   ROAD       3      29900   0.95604E 05   3.20   0.13415E 06  269.   0.37375E 04   7.50   0.37136E 06  12.42
   ROAD       4      22580   0.63044E 05   2.79   0.84587E 05  225.   0.28225E 04   7.50   0.23806E 06  10.54
   ROAD       5      13004   0.45721E 05   3.52   0.59450E 05  274.   0.16255E 04   7.50   0.16789E 06  12.91
                                         DAILY USER DATA BY MODE


                      TOTAL       USER FARES         USER TRAVEL TIME       USER WAIT TIME        WEIGHTED COSTS
                      TRIPS
          M O D E                TOTAL    AVERAGE     TOTAL     AVERAGE      TOTAL     AVERAGE      TOTAL      AVERAGE
                   (PASS/DAY)     ($)    ($/TRIP)    (HOURS)  (MIN/TRIP)    (HOURS)  (MIN/TRIP)      ($)      ($/TRIP)

          AIR         9042   0.14600E 06  16.15   0.21283E 05  141.   0.59468E 04  39.46   0.20046E 06  22.17
          RAIL       14716   0.11016E 06   7.49   0.47606E 05  194.   0.86439E 04  35.24   0.22256E 06  15.13
          ROAD       91922   0.29940E 06   3.26   0.41177E 06  269.   0.11490E 05   7.50   0.11459E 07  12.47

      T O T A L S   115680   0.55556E 06   4.80   0.48066E 06  249.   0.26081E 05  13.53   0.15690E 07  13.56



                                          YEARLY COSTS AND REVENUES BY MODE

   M O D E     TOTAL        USER        TOTAL USER     OPERATOR'S     GOVERNMENT   OPERATOR'S PROFIT  GOVT. REVENUE
               TRIPS        FARES         COSTS          PROFIT         REVENUE      PER PASSENGER     PER PASSENGER

   AIR        3300330   0.53290E 08   0.60138E 08  -0.26871E 08  -0.72335E 08         -8.14             -21.92
   RAIL       5371340   0.40207E 08   0.66797E 08  -0.55785E 08   0.0                -10.39               0.0
   ROAD      33551520   0.10928E 09   0.34378E 09   0.15690E 08   0.0                  0.47               0.0

   TOTALS    42223200   0.20278E 09   0.57270E 09  -0.56966E 08  -0.72335E 08         -1.59              -1.71
```

Figure 8. TRANSET II commands illustrated by typical computer input-output.

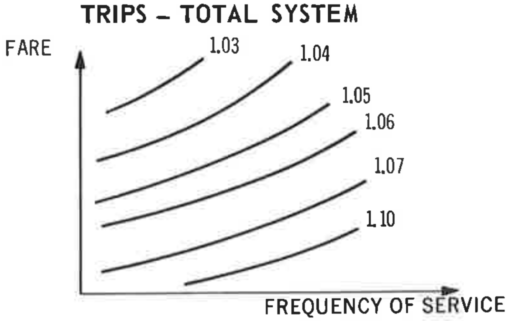

Figure 9. One impact.

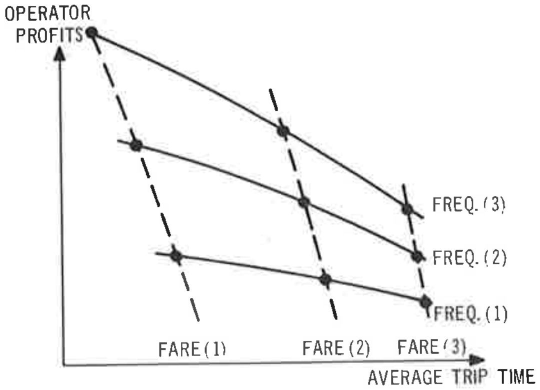

Figure 11. Trade-offs among impacts.

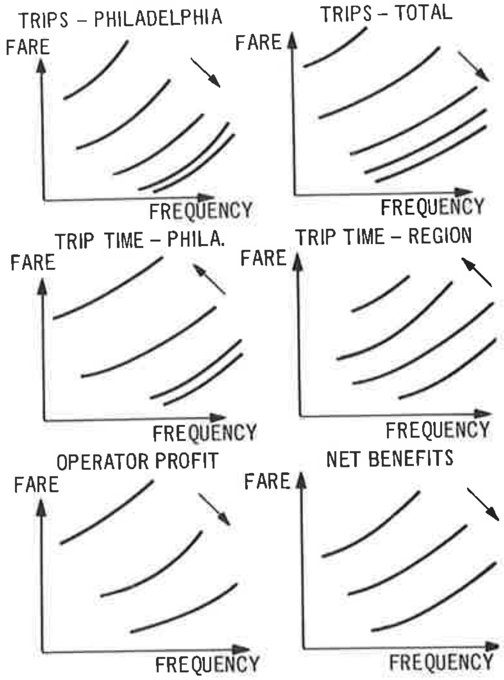

Figure 10. Differential impacts.

several different impacts simultaneously: total trips in the system; total trips to or from Philadelphia; average trip time, all trips; average trip time, Philadelphia trips; operator profit; and net benefit to the region as a whole.

In Figure 11 the impacts are shown on the axes. Thus, the same data are now shown as trade-offs among impacts, in this case, operator profit and average trip time (a user impact). All other things being equal (they are not), the point most to the upper left would be most desirable. Evaluation and choice deal with such trade-offs among impacts; whereas for search, trade-offs among options are needed.

In Figure 12, a third option, in addition to fare and frequency, is added: level of investment in the network. There are now 27 data points: 3 different levels of network and 9 combinations of fare and frequency for each. From this sample, we can now infer the locus of the most desirable alternatives, as indicated by the dotted line (again, everything else assumed equal!).

These examples illustrate how a number of runs of the computer models can be used to generate information. In this way, trade-offs among options and among impacts can be systematically analyzed. As these trade-offs are being developed in the analysis process, the information that is obtained can also be useful for search and choice. As systematic relations among the options are perceived, search procedures can concentrate on generating alternatives in the most interesting areas of the space of possible options. As achievable trade-offs among impacts are identified, the key issues of choice become clearer. It may be relatively easy to find options that produce desirable impacts for each of one group of actors; but there may be unavoidable conflict in the impacts that are achievable between two other groups of actors, for example, decreased travel time for suburban residents can only be achieved by displacing families from central city homes by freeway construction. It is precisely these differential impacts that must be traced out.

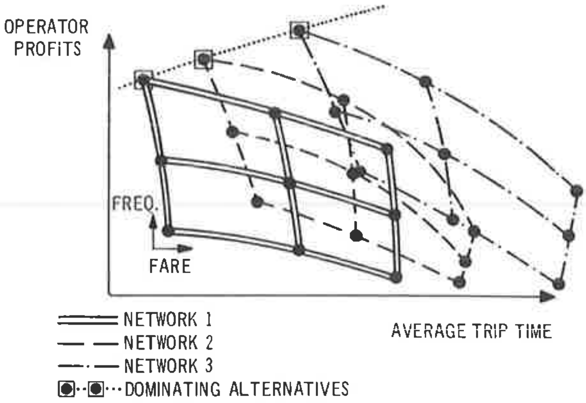

Figure 12. Dominating trade-offs.

Conclusions From the Prototype Analysis

The prototype analysis demonstrated the feasibility of network equilibrium analysis and the applicability of the PSP model. It illustrated the systematic exploration of options and impacts. However, it also emphasized the following problems, which are explored briefly in a later section:

1. Systematic analysis generates, and requires, a large volume of information from a number of computer runs. How can the analyst deal with, and understand, this model-generated information (particularly, to be able to infer such relationships as illustrated in the figures)?
2. If differential impacts among a variety of groups are to be considered explicitly, how can evaluation and choice be reasonably done without aggregating all the impacts indiscriminately?
3. What kinds of procedures can be developed to assist in search?
4. Each run of the computer models costs time, money, and other resources. Must all search and selection cycles be at the same level of detail? If not, what errors are introduced?

EXTENSIONS OF THE PSP MODEL

In the prototype analysis, the set of models and data was not highly refined. However, it illustrated some of the major issues in a systematic exploration of alternative transport systems. While showing the feasibility of systematic analysis, the prototype analysis also raised a number of issues about the difficulties in doing such an analysis. In this section, we will briefly summarize some of the techniques and approaches now under development to address these issues.

DODO: A PSP-Oriented System (4)

The prototype analysis uses a simplified set of models and a very simplified representation of the Northeast Corridor transportation system. Yet, even with this simplicity, the analyst finds it difficult to deal with the large volume of information produced in doing a systematic analysis of the alternatives. If only twenty different actions have been generated and compared, the analyst has real difficulty understanding the difference and similarities among the actions: Which actions are basically different in their impacts; which are very similar? What are the feasible trade-offs in impacts, and which actions produce the most desirable combinations? Even a single run of the model system results in large masses of data that are difficult for the analyst to comprehend. Given the results of analyses of a series of complex transportation systems alternatives, how can the analyst understand the differences between these alternatives, in order to establish a preference ordering among them and in order to identify fruitful areas to search for alternatives even more promising than those he has already examined?

What is needed is a way of storing all the relevant information generated in a series of model runs, such that questions meaningful to the decision problem can be asked of the data. Some of these questions can be identified a priori and built into the system; but many significant questions will occur to the analyst only as he is examining the specific data of a series of runs. Therefore, the information system must be designed for interactive use with flexible query capabilities.

The concept of DODO was developed in response to this need. DODO is an information system intended to provide the decision-maker and analyst with the capability to analyze and structure the large amount of data that may be generated in the analysis of a complex problem. The name DODO reflects this objective: Decision-Oriented Data Organizer. An initial operational version of DODO has been developed in the context of the TRANSET II subsystem of ICES, as developed and modified for the prototype analysis. Later versions of DODO will be more general, applicable to many other design problems as well as transportation.

The design of DODO is based upon the module suggested by the PSP model. This basic decision module (BDM) consists of the quintuple (A/P/C/U/V): action, A, consequences, C, valuations, V; with consequences conditional on a (data) parameter set, P, and valuations conditional on a set of (partial) utilities, U.

In an actual problem, each of these files may comprise large volumes of data. For example, in the prototype analysis, each action, A, corresponds to specification of the options of technology mix, network, fares, frequency of service, and costs and subsidies. The consequences, C, and valuations, V, may also be large files of data, e.g., the file of travel time for system users by trip purpose by zone pair by mode, for 5 purposes, 4 modes, and 50 zones contains 50,000 items, which can be aggregated a number of ways.

In outline, the basic capabilities of DODO are as follows:

1. It is designed as a command-structured, problem-oriented language, a subsystem of ICES. Thus, the commands are easy for the nontechnical analyst to use.
2. The basic files of the system are organized in terms of the basic decision module (BDM); i.e., the basic record is the quintuple (A/P/C/U/V).
3. Each step in the analysis process either initiates a new cycle, through initiation of a new BDM, or adds information to a previously initiated BDM. That is, a log of the analysis process is built up in the form of a sequence of BDM's.
4. Actions can be grouped into arbitrary subsets at will through a capability for defining sets of BDM's according to very general criteria. This set capability allows a wide variety of relationships among actions to be established. In particular, actions can be grouped so as to isolate and display trade-off relations as demonstrated in the prototype analysis.
5. By explicitly separating the parameters, P, sensitivity analysis is easy: simply designate a new P and repeat the prediction of consequences. Similarly, the sensitivity of the preference ranking to the statement of goals can be explored: designate a new goal statement (represented in DODO by a set of utilities, U) and repeat the evaluation and choice procedures.
6. The system is designed for browsing through the results of the analysis process. For example, the analyst may suddenly percieve a new issue and wish to define a new goal variable. He can do this, through the DEFINE GOAL VARIABLE command, at which time he also specifies how it is to be computed. The analyst may then "browse" the predicted impacts of actions previously examined with this new variable; if he decides it is a meaningful variable to use, he can add it to the system on a permanent basis, thus enlarging his set of goals.

The Goal Fabric Concept

The impacts of transportation alternatives are many. We can distinguish these impacts by their nature, the groups that are affected, and the time at which they occur. Some of these impacts are relatively easy to evaluate in quantitative terms, such as travel time and out-of-pocket costs. Others are difficult or impossible to quantify, such as quality of life, and change in regional growth pattern. Some impacts can only be ranked, i.e., placed in an ordinal scale, or perhaps given only nominal values, such as the numbers on the shirts of football players. Some impacts occur quickly and cause only short-term effect; others will not occur until a long time into the future. The groups that are affected must potentially include a number of examples of the basic types outlined earlier: users; operators; nonusers including physically impacted, functionally impacted, and governmental actors.

To define and operate upon goals, we must first formulate a list of goal variables; we must have a variable for each facet of the problem that will be relevant to the decision among alternative actions. In light of the earlier discussion, we will have goal variables for different groups that may be affected, for different kinds of impacts, and for different points in time. Once we have defined a list of goal variables, we may then attempt to use this list as a basis for choosing among alternative actions. The simplest way is to use the list as a checklist; if the level of every goal variable on the list is satisfactory, then that action is acceptable; it is unacceptable otherwise (65).

A more general approach is to establish some type of scoring scheme. Mathematically this can be expressed as

$$U_i = \sum_j a_{ij} w_j$$

where

w_j = relative weight of the j th goal variable,
a_{ij} = level on scale of j th goal variable achieved by action i, and
u_i = total weighted score for action i.

Standard economic criteria, such as total annual cost, net present worth, or benefit-cost ratio, are variants on this scheme, as is also utility theory.

The difficulties with such a scheme are as follows:

1. We never have a full, complete list of goal variables.
2. It is very difficult to get all the goal variables defined so as to be independent, mutually exclusive, and all at the same scale of relevance.
3. We can never completely identify the relative values, w_j, of all possible combinations of the various objectives.
4. We prefer to make decisions based upon the differences between alternatives, not the absolute levels. It is particularly important to know how much of goal j we must give up to achieve goal k.
5. Particularly in a sociopolitical context such as transportation, it is essential to examine the differential incidence. One alternative may score high on the goal variables important to group A but low on those important to group B, and therefore, the total score, U_i, hides the essential issues of choice.
6. Objectives change over time. It is sometimes as important to learn about the objectives as it is to develop new actions.

Recognizing the difficulties of the "scoring scheme" approach, we attempted to develop a looser, more subtle, more flexible approach to evaluating and choosing among alternatives. The concept developed is termed the goal fabric (66). It does not solve the problem completely, but seems a fruitful direction for development.

The basic ideas of the goal fabric are as follows:

1. A list of goal variables can be generated, but this list is never complete nor fully consistent and independent.
2. A number of relationships among goal variables can be identified and used to structure the list (means, ends, specification; value dependence or independence).
3. It is not necessary to get complete information on all possible combinations of values of the goal variables (e.g., by getting dollar equivalents, or by defining a utility function); the decision-maker need supply only sufficient information to indicate his preferences between the alternatives with which he is confronted, not all possible alternatives.

The basic impacts and consequences that are treated in the prototype analysis were briefly discussed earlier. Various aggregate measures of those impacts were constructed (see Fig. 5). For example, travel times are summed over origins, destinations, and/or modes to various levels of aggregation. In such a summation, all the goal variables are weighted equally.

The general structure of the goal variables in the prototype analysis is shown in Figure 13. This figure indicates how many different goal variables the analyst may wish to examine and the complex structure of their interrelationships.

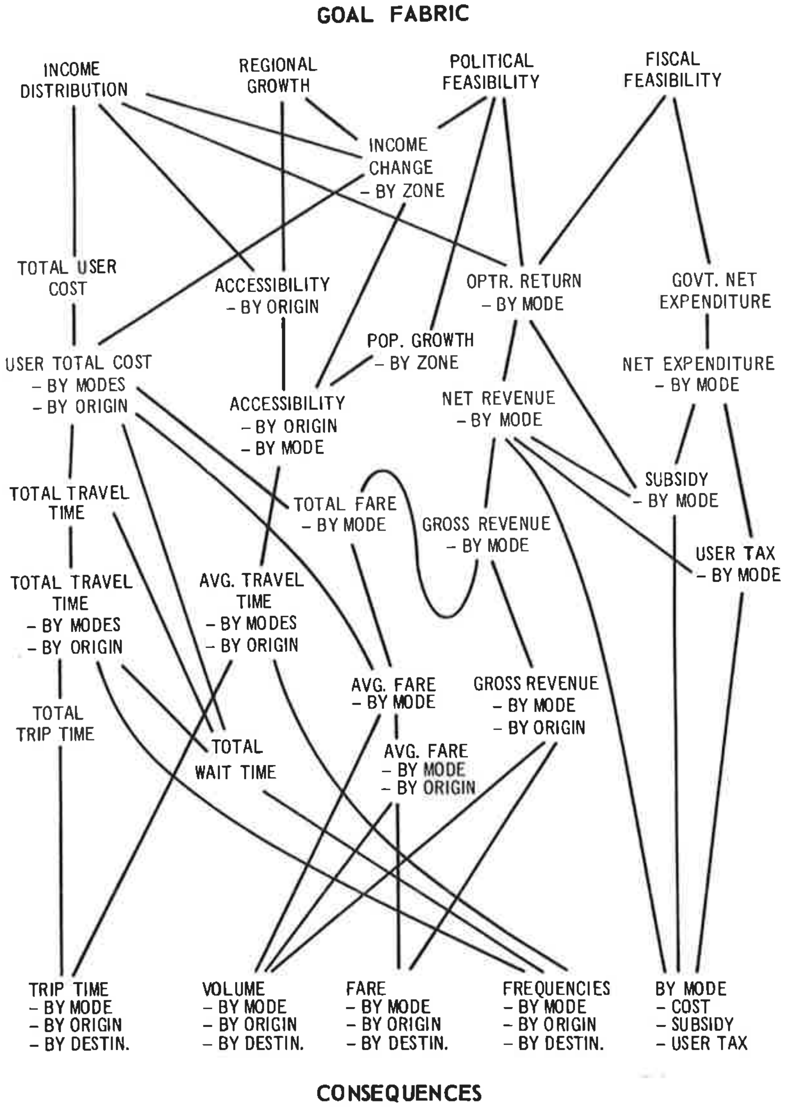

Figure 13. General structure of goal variance in prototype analysis.

The goal fabric concept is not fully tested. Capabilities for displaying and manipulating impact information in goal fabric form are being developed in DODO. Experiments with goal fabric analysis will be conducted in the context of systematic explorations of alternatives such as those outlined in the prototype analysis.

Search

The search problem is the following: Given a number of previously generated actions and their consequences and a statement of goals or desirable directions to go in to improve the impacts of these actions, what values of the decision options will achieve the desired levels or directions of change? For example, if we want to decrease travel time without decreasing operator revenue, how do we change the system?

In general, as indicated by the prototype analysis, the range of possibilities for any particular problem is immense. In practice, of course, we sample only a very small percentage of the large number of possible alternatives. In doing this, we use a variety of short-cuts: (a) We consider the existing system, and explore possible small changes to that system. (b) We focus on a component of the problem, we decompose the problem into subproblems and work only on a piece of it. For example, we design a better vehicle and ignore the terminal, the access links, or land use impacts. (c) We abstract and simplify from the detail of the real problem and construct a model that we can manipulate to get an approximate idea of the characteristics of the desirable alternative. Each of these approaches has its value.

In actuality, we want to build up our search strategy out of all of these. Because of the massive fixed existing investment in transportation systems, we will generally implement strategies that involve a series of small changes from the existing system. However, we want to make this series of steps part of an incremental path toward some target end state, which may be radically different from the present system. We will often take a piece of the problem and focus on some component if only to understand its properties better in relationship to the overall system. And, we will definitely attempt to abstract and simplify from the problem.

This suggests the general flavor that underlies our approach to search. There is no single all-powerful procedure to use for searching out transportation systems alternatives. Rather, what is needed is a variety of tools that can be used flexibly by the transportation systems analyst as he explores the shape of the problem.

In this exploration, we assume that the analyst uses a more complex system of models for predicting the impacts associated with each alternative action. This model system, of course, involves network equilibrium prediction. Because of the variety of options and impacts, and the complexity of their interactions as represented by the system of models, the analyst will attempt to systematically trace out variations of the options and impacts.

Every model abstracts from reality and imposes its own biases on the problem. We need to be careful about the limitations and biases imposed by the system of models being used. Thus, we can conclude that systematic analysis using the predictive model system is only a guide to the search process of the analyst.

The analyst uses predictive models and search techniques to stimulate his perception and understanding of the problem. Neither the predictive model system nor the "kit" of search techniques will specify the solution to a transportation systems problem. The systematic analysis of alternatives and the results of search procedures serve to build up the analyst's image of the issues in a problem. This understanding, conscious and unconscious, provides an experience base from which he will create intuitively (67) that synthesis of technical and political elements with which he will try to solve a transportation problem. The solution comes from the analyst's understanding and imagination, not the models; but the models are an important aid.

There are a variety of search techniques available in transportation systems analysis. If we make some fairly drastic simplifications in the problem, we can apply such powerful techniques as mathematical optimization, including linear programming, integer programming, dynamic programming, and other techniques based on calculus. Alternatively, direct search or other hill-climbing approaches may be used, as well as heuristic search techniques such as pattern recognition and network aggregation. Another important family of search techniques is to provide an effective on-line computer environment with graphic display such that the analyst is able to operate efficiently in rapidly searching out and evaluating a large number of alternatives.

None of the analytical search techniques, such as mathematical optimization, is yet computationally feasible for large real-world transportation systems. However, it should be fruitful to use these techniques as approximations for search, in the following way, via the concept of network aggregation (see further the following section). In this approach, an aggregate representation of the particular detailed transportation systems problem would be constructed using a particular aggregation rule. The result of applying this aggregation rule would be a formulation of the problem appropriate for some mathematical optimization technique. This mathematical optimization technique would then be used within the context of a gross representation of the problem to find an optimum. The results of this process would then be translated back to the detailed level. Thus, mathematical optimization formulations and other analytical search techniques may be useful in the context of a broader search strategy via the concept of network aggregation.

A rich variety of search techniques of different types will probably prove more efficient as a system than any single technique used alone. Furthermore, the judgment of the analyst can and should play a strong role throughout the search process. Therefore, it is appropriate to develop a variety of different search techniques, as well as a flexible environment in which they can be used. Work is proceeding in this direction.

Multilevel Problem-Solving: Network Aggregation

In human problem-solving, we rarely analyze real problems at only one level. It is a natural approach to problem-solving to operate at several levels of analysis. In some contexts, this corresponds to first doing preliminary design then detailed design.

When an analysis process deals with several levels, we say it is hierarchically structured. A model of hierarchically structured problem-solving processes has been proposed (68) that revolves around the concept of inclusion among actions.

By inclusion, we mean that one action may be a representation of a set of other actions. For example, a schematic diagram of a network and its associated regional development pattern (linear system, a polynucleated region) may represent a number of different detailed network and land use pattern alternatives. Conceptually, we can visualize the gross or higher level action as a set of more detailed, or lower level actions; all the lower level actions in the set differ in details but have the same basic characteristics, and so can be represented by a single higher level action.

The concept of hierarchical structure is defined by this inclusion relationship. Consider now the "basic operator," consisting of the sequence search-prediction-evaluation-choice (i.e., search followed by selection). Such a basic operator produces a characteristic kind of action. For example, in highway location, we might have three operators: one operator to produce bands of interest, a second to produce location bands, and a third to produce locations.

The purpose of multilevel structure is to enable us to search more efficiently by generating and evaluating gross alternatives as well as detailed ones. The inclusion relationship implies that only for the most detailed alternatives is it possible to predict impacts precisely. Of course, because at higher levels we are working with approximate characteristics rather than precise detailed characteristics, there is higher uncertainty about the performance of alternatives. In other words, if we are dealing with performance attributes of a particular system, then we can get a single-valued vector only at the most detailed level. At other levels, we can only deal with the distribution of these attributes (68). So what we gain in computational effort by dealing at the gross level, we lose in accuracy and certainty of results.

The complexity of the transportation systems problem suggests we may find it efficient to structure it as a multilevel process. A possible multilevel structure was initially proposed by Bruck, Manheim, and Shuldiner for the Northeast Corridor study (13).

To successfully use a multilevel framework, an understanding of the fundamental relationships among different levels is necessary. To develop this understanding in the particular context of network equilibrium in transportation, experiments are being conducted in network aggregation (8, 69).

A basic problem in the analysis of transportation systems is that of the detail with which networks are modeled. Very rarely can the analyst expend sufficient resources to model a transport network in full detail, with a link in the model for every link in the real-world network. Rather, the analyst must be satisfied with an approximate representation of the real network. For example in urban transportation systems analysis, usually the rail transit and expressway systems are represented in complete detail, but the arterial and local streets and bus lines are more usually approximated in some way. In megalopolitan or national transportation systems analysis, usually only the major intercity links can be modeled directly; the intraurban networks and secondary road systems can be represented only approximately at this scale of interest.

When modeling in full detail is not possible, the analyst must explicitly account for the uncertainties introduced by the approximation by a less-than-fully detailed (aggregate) network. The basic idea is that each link of an aggregate network corresponds to a set of links in the true network. More precisely, a subset of links at the aggregate level corresponds functionally to a subset at the "true" level (68). This simple notion implies that the aggregate link does not have a single value of travel time (length, capacity, or other parameters), but a probability distribution. The analyst should formulate and use this distribution and thus avoid possible serious errors that may result from using only the point estimate of the aggregate link's travel time (or length or capacity).

In general, many different levels of detail of network representations will be desirable. Each will have a corresponding uncertainty in analysis, consequent upon the degree of aggregation; but as aggregation and uncertainty increase, ease of computation for analysis should increase and computing cost (dollars, time) should decrease.

It is the task of the analyst to determine the desired level of detail for an aggregate network. To do so, he must estimate the relative benefits of increased accuracy associated with a detailed network versus the ease of computation and analysis effort permitted with an aggregate form. If a small number of alternative transport systems are being evaluated for a final decision regarding which alternative to implement, uncertainty in the network parameters should be minimized and the required aggregate network will retain a high level of detail. If preliminary studies are being performed on a large set of widely different transportation alternatives, then a higher level of uncertainty can be tolerated to permit many analyses, so that possible alternatives can be reduced to a small number for detailed analysis. The usefulness of aggregation in a transportation planning environment is reflected in the ability to analyze a larger number of alternative transportation systems for a given set of analysis budget and time constraints than would be possible if aggregation techniques were not employed.

SUMMARY

We began with a brief description of the problem of transportation systems analysis and emphasized the number and variety of options and impacts, the complexity of the system of predictive models, and the need to trace out differential impacts systematically. After review of the rational model, we then described a more general model of the design process, PSP, and its implications. To show the juxtaposition of these two themes, we next discussed a prototype analysis of the Northeast Corridor passenger transportation system. We showed the PSP structure in the computer language developed to do transportation analyses and illustrated the systematic analyses that could be done. There were many issues raised, however; and in the last section, we described extensions of the PSP model in the form of specific operational techniques to address these issues: DODO, goal fabric, search, and network aggregation.

Work is continuing to test, refine, and further develop the techniques and concepts described here. To summarize our basic conclusions: (a) The core of the transportation systems problem is the prediction of equilibrium flows in networks. (b) The systematic analysis of transportation problems requires careful, sensitive exploration of trade-offs among options and impacts. (c) The prototype analysis demonstrates the feasibility of this approach, but also raises issues. (d) It is useful to view transportation systems analysis as a problem-solving process. (e) A variety of specific operational techniques can be developed to make transportation analysis a more efficient process.

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This paper summarizes work to which many individuals have contributed, as indicated by the references and footnotes. The author expresses his appreciation for the stimulation and assistance of his colleagues and students, and particularly to Earl R. Ruiter.

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Discussion

STANLEY L. GORDON, System Analyst, Texas Instruments Incorporated—Professor Manheim has aptly presented two major themes in his paper. First, he has carefully described the multidimensional nature of transportation decision-making, i.e., options on the physical system, impacts on transportation subscribers, and prediction of impacts. Second, he has presented a well-thought-out description of the problem-solving process (PSP) that involves search (the generation of alternative transportation systems) and choice (evaluation and selection of alternatives).

Both topics, transportation and the PSP, are complex activities on which much attention has been focused. The unification of the many viewpoints that already exist about these two areas, in addition to fresh thinking on these subjects, present an exciting challenge to the analyst.

The major benefit of a fuller and more complete understanding of both transportation and the PSP as it applies to transportation is the greatly increased likelihood that a viable, adaptive transportation system will be selected to meet transportation requirements for the future. The need for a vast improvement in transportation decision-making exists because of the highly probable occurrence of gross suboptimization and the relative inability of anyone, individually or collectively, to significantly change a system once it has been implemented. It is because of the fixed nature of transportation systems and their enormous expense that calls for an advance in the state of the art in transportation system decision-making.

In this light, the major thrust of Professor Manheim's paper is the problem of search and choice—how alternatives are generated and how a best one (in some sense) is chosen. Professor Manheim has done well in "bounding" the problem of search and choice and in providing a framework for others to follow. Search is described as the generation of alternative transportation systems that appear to be sufficiently attractive for evaluation, given predicted impacts upon various transportation subscribers. Choice is the preference ranking of these alternatives based on an evaluation of the predicted impacts.

A model of the search and choice process consists of the definition of objectives or goals to be met and a utility function sufficiently well defined to render a preference ordering among alternatives. Next, enumeration of alternative transportation systems is performed. Third, the consequences of implementation of each transportation system are predicted. Fourth, the consequences are evaluated in terms of objectives through the utility function. Finally, one system that best achieves the objectives is chosen.

Additional flexibility in this model is achieved through appropriate iterations in which objectives and/or goals undergo revision. A very important concept is that of selective acquisition of input data for the model in which continuous sampling over time is preferred to an enormous single data-gathering effort. This ensures a flexible readjustment of data acquisition. Next, Professor Manheim acknowledges the fact that the model must account for multilevel problem-solving by generating and evaluating gross level alternatives as well as detailed ones. Finally, but most important, the model and the analysis team must properly interface with the social and political dimensions of transportation. The interface, in turn, serves to clarify public objectives.

I believe Professor Manheim has contributed something of much value to analysts dealing with decision-making problems in general and transportation problems in particular. His paper certainly establishes a point of departure for further work in transportation systems decision-making.