Decision Theories in Transportation Planning

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•THE PURPOSE of this paper is to present a very brief survey of some of the decision theories that may be applicable to transportation planning. These techniques have been developed in various fields, ranging from architecture to industrial management, economic planning, and statistics. Our use of the plural—decision theories—emphasizes that there is not just one single technique, but a variety of different techniques that come from many different disciplines and are applicable to transportation planning.

Several good survey articles have been written on decision theories and their applications (1, 2, 3, 4); only those most relevant to transportation are discussed here. Four groups of techniques are discussed: statistical decision theory, hierarchical structure, search techniques, and evaluation procedures.

STATISTICAL DECISION THEORY

We live in a very uncertain world. We tend to forget this, and become fascinated by the numbers produced by systems of complex models, such as the urban transportation planning systems, and elaborate calculations, such as benefit-cost analyses. In truth, however, we must concede that there are always uncertainties in every transportation analysis.

Uncertainties in transportation are of 3 types: demand, technology, and goals. No matter how elaborate a demand model we build or how much data we collect, there will always be uncertainty about our predictions of the future demand for transportation, because we do not understand very well the internal dynamics of the social and economic system with which we are concerned. In addition to the uncertainty about demand is the uncertainty about technology, not only about the pavement life and other characteristics of the particular highway or transit line we design but also about the transportation technologies that may be available a few years from now. Recent studies of urban transportation sponsored by the U.S. Department of Housing and Urban Development indicate that a variety of systems might be available in the near future. We are also uncertain about goals. In designing a metropolitan transportation plan or specific highways, we attempt to make decisions from the point of view of the body politic, but whose point of view? How are the interests of different groups balanced? The objectives of our society are continually evolving, and no single individual or group is able to fully express those objectives. We do our best, but inevitably the goals we use are uncertain.

Because the sources of uncertainty in transportation planning are many, they must be explicitly considered in our recommendations about specific actions. This is the task of decision theory: to provide a basis for reaching decisions in the face of uncertainty. The decision theory approach is indicated in the payoff matrix given in Table 1. To construct a payoff matrix, we first list all the alternatives open to us, in this case, an expressway, a high-level arterial, or the existing 2-lane road. Then we identify those things about which we are uncertain by listing the alternative "states." For example, we may be uncertain about the volume of the demand for a particular route; therefore, the alternative states are the alternative levels of demand that we consider might occur. Next, we determine the utility or desirability for each possible combination of an action and a state. For example, for each action and each level of demand, we can compute total annual cost (first cost plus user costs).

Such a table summarizes the decision problem: For each action, the utility or payoff depends on which particular state occurs. How should we choose an action in the face of uncertainty about which state will occur? There are a number of approaches

TABLE 1
PAYOFF MATRIX

Alternative State: Demand Levels	Alternative Action: Expressway	Arterial	2-Lane	Probabilities
	Expected Utility			
1,000	1.7	2.2	3.0	0.3
5,000	1.9	2.5	2.5	0.6
10,000	2.0	2.2	1.5	0.1
	Expected Value			
	1.9	2.4	2.6	

to this problem (5). Here we will treat only one, the statistical decision theory approach (6, 7, 8). In this approach, we assume that it is possible for the decision-maker to estimate a probability for each of the states.

These probabilities may be objective or subjective. Objective probabilities are derived from actual data; for example, we may have statistics on the variability of strength of pavements of a certain type. Subjective probabilities are derived by judgment; they reflect the engineer's estimation of the relative likelihood that a particular state will occur. For example, uncertainty about future demand may come from uncertainty about the growth rate of population and automobile ownership. Therefore, based on various estimates of population and automobile ownership growth rates, we can make judgments about the relative likelihood that future demand will be at certain levels. Then, we express our judgments in the form of probabilities 0.3, 0.6, and 0.1 for the 3 levels of demand in Table 1. Expressing professional judgments over a range of values as probabilities should be more satisfying than simply using a single best-estimate value. It is certainly a sounder basis for design.

To use the probabilities, we now compute the "expected value" of utility for each alternative in the payoff matrix. The expected value for any alternative is the sum, for all states, of the probability of that state times the utility of that alternative if that state occurs. For example, the expected value of the expressway is $(0.3 \times 1.7) + (0.6 \times 1.9) + (0.1 \times 2.0) = 1.9$. We then compare the alternatives on the basis of their expected utilities and choose the action that has the highest expected value of utility.

In the preceding example, the alternatives considered were immediate actions regarding particular highway alternatives. In general, however, the decision-maker also has the option of deferring implementation of an action in order to acquire more information about the problem. For example, if there is a great deal of uncertainty about demand, it might be more efficient in the long run to delay construction of a new highway for a period in order to collect sufficient information to reduce this uncertainty. Information can be collected by several alternative ways such as traffic counts or origin-destination surveys. Thus, the more general problem has 2 basic sets of alternatives: immediate actions such as highways, or actions that involve collecting additional data first and then making a choice among immediate actions.

Statistical decision theory is particularly appropriate for this more general problem. Data collection programs such as origin-destination surveys or traffic counts can be evaluated not only in terms of cost but also in terms of their role in reducing uncertainty. Then, the decision as to which kinds of data collection programs to conduct can be based on a careful economic calculation. In such a calculation, the costs of deferring action and of data collection are balanced against the "costs" of uncertainty if action were taken immediately. Johnson (9) has done pioneering work in applying statistical decision theory to transportation data collection.

An even more general formulation is that of a sequential decision process. There are significant time lags in implementation of transportation systems alternatives. It takes at least 7 years to plan, design, and construct a new highway. A comprehensive transit and expressway plan for 1985 is not implemented instantaneously, but as a series of stages. Meanwhile, the world continues to change. Transportation planning takes place in a context of continuous change in demand, in technology, and in goals.

Transportation planners need to deal with strategies; each alternative strategy is composed of a sequence of actions staged over time. For example, consider a 20-year comprehensive metropolitan plan. Such a transportation plan might be divided into five 4-year stages. Each stage might consist of several actions such as particular highway links, transit extensions, data collection activities, and community decision points. We can expect that by the end of the first 4-year period things will have changed.

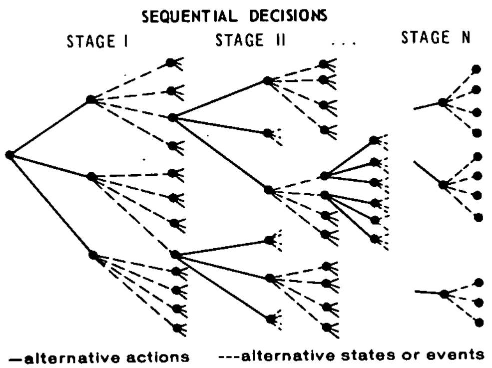

Figure 1. Simple decision model extended to multiple stages via decision tree.

Demand patterns will have changed; new technologies will have been developed, or problems or advantages in existing technologies will have been uncovered; goals and aspirations will have changed; data collection activities will have produced new information. We will have learned more. Because conditions will have changed, the strategy consisting of a sequence of stages should be reviewed and possibly revised at the end of the first stage. If change has been relatively minor, the actions to be implemented in the following stages of the strategy may stay the same; more likely, however, the later stages of the plan will be revised because of the changing world. To have an effective continuous planning process, we need to conceive of a transportation system plan as a sequence of staged actions; at the conclusion of each stage, we must open the door again to review and analyze the succeeding stages based on new information and the results of the preceding stages.

A formal basis for this continuous planning process is provided by the sequential decision model. Figure 1 shows the simple decision model extended to multiple stages via a decision tree. At each stage, the set of actions includes not only immediate actions, e.g., highways, but also information-collection actions, e.g., traffic survey. The optimal strategy, or sequence of actions, is determined by a procedure very similar in outline to that of the simple single-stage decision model. For every possible sequence of actions and combination of events, a utility, e.g., total discounted annual cost, is determined, and the probability of various events is established objectively or subjectively. Then, the net expected utility for each sequence of actions in the face of uncertainty is computed by summing the probabilities times the utilities. The best action is the one that has the greatest net expected utility.

In principle, this calculation has a straightforward logic, but, in practice, it is complicated by a number of factors. [Relatively tractable techniques exist for standard statistical processes such as often occur in standard sampling approaches (8).] First, there is generally a large number of combinations of actions and events. Second, the probabilities at different stages of the decision tree are different, because information is acquired at different stages, and the information depends on which actions were taken at earlier stages. Third, the utilities at future periods are different from the utilities at the initial stage. Fourth, and perhaps most significant, to evaluate the utility at any point in the decision tree may require running a complex simulation model, such as the urban transportation package. Clearly, this is impractical for several hundred points in the tree. Therefore, to apply the sequential decision process model to transportation planning requires that special techniques be developed and adapted to the transportation problem. Research has begun on such techniques (10). The objective of this research is to develop practical techniques for treating transportation planning as a sequential decision process in the face of uncertainty.

One of the advantages of this sequential decision process formulation is that it places in perspective the role of experimentation in the transportation planning process. A variety of information-gathering experiments is possible. For example, demonstration programs such as in public transit or high-speed rail transportation are experiments to get information about demand as well as technology performance. It is essential to analyze such experiments explicitly (11); they are as important a part of the set of transportation planning options as the construction of new highways or new transit lines or other physical facilities. The sequential decision process model of transportation planning emphasizes this perspective by including explicitly such information-gathering activities, as well as physical actions, in the context of staged strategies.

HIERARCHICAL STRUCTURE

We now turn to an extension of the statistical decision theory model to represent the analysis process through the concept of hierarchical structure (12). Figure 2(a) shows a hypothetical highway route location problem. The objective is to locate a highway between 2 termini roughly 15 to 40 miles apart. In a typical process, the engineer will not immediately start developing a detailed design for a single highway location between 2 termini. Most often, there will be a series of steps in the analysis process, successively narrowing down the range of alternatives under consideration.

In the example, we have assumed that there are 3 such steps in the location process. The first step involves bands of interest or approximate areas of highway location, such as "generally on the north of the valley" or "the easterly side of the ridge." The engineer will begin the location process by developing several possible bands of interest based on general surveys of the terrain. Then, he makes a judgment about which band of interest should be studied in more detail and shifts his focus to location bands. A location band is an approximate location for a highway, perhaps within a range of several hundred feet. In the example, the engineer generated 2 bands of interest, A and B, and then decided to work with band of interest B; within that he generated 2 alternative location bands, C and D, which he evaluated. Finally, he selected location band D, and developed a single detailed location, E, within that location band.

This process of progressively narrowing the space of alternative locations can be modeled explicitly. Consider the set of all possible locations between these 2 termini, as shown in Figure 2(b). What is a location band? It is simply a symbolic designation for an even larger set of specific locations, and it also represents a number of location bands. Thus, in the process of solving a particular location problem, we progressively narrow the set of possible locations. First, we look at large sets, bands of interest; then at smaller sets, location bands; and then at locations, the basic elements of the set.

To visualize this, consider a particular stage in the location process. Prior to this stage, we have generated 5 actions; 2 bands of interest, 2 location bands, and 1 single location. The relationships of these actions as sets is shown in Figure 2(c). At this point, there are a number of possible things we might do next. We can generate either (a) a location in location band D, (b) a location in location band C, (c) a location not in any of the previously generated location bands, (d) a location band within band of interest B, (e) a location band within band of interest A, (f) a location band not in either of the previously

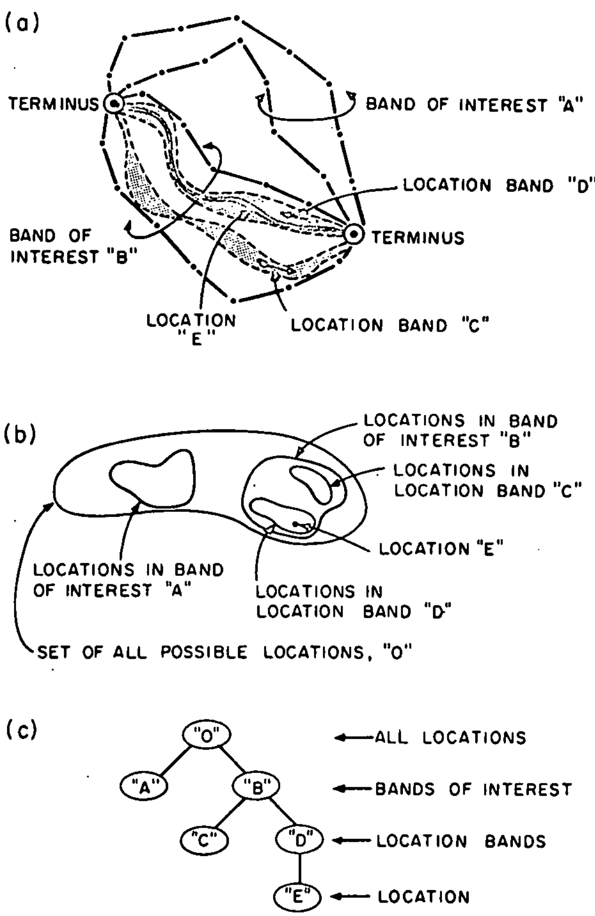

Figure 2. A history of a location process.

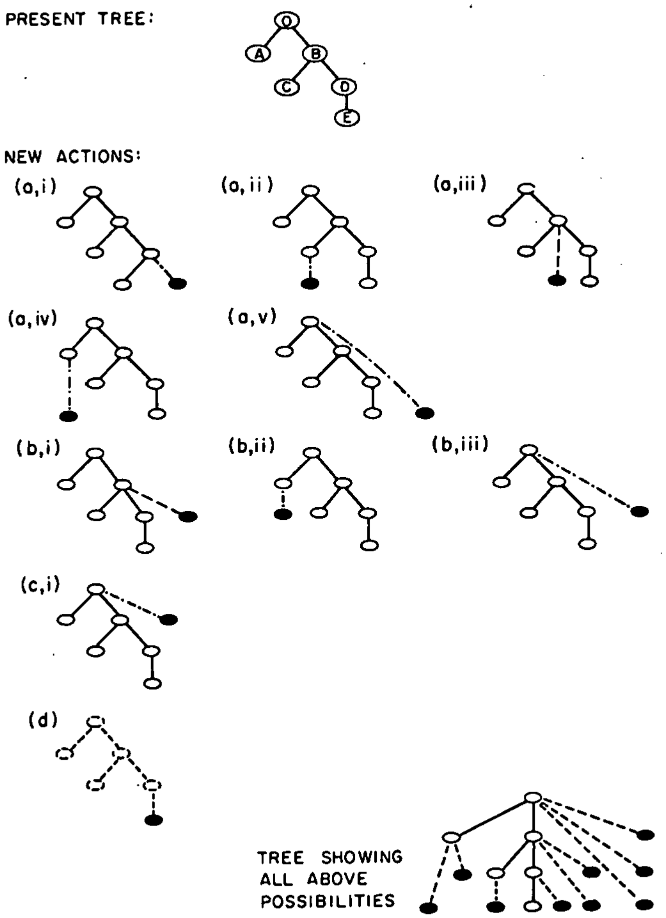

Figure 3. Possible new actions.

generated bands of interest, or (g) another band of interest; or, we can terminate the location process. These possibilities are indicated by the black dots shown in Figure 3. The problem is to know which of these is the best thing to do next in a location process. The hierarchical structure model provides a rational basis for the analysis of which of these possibilities is best.

The basic issue is the value of information versus the cost of acquiring it. To develop and evaluate a single detailed location design is relatively expensive; to develop and evaluate a band of interest is less expensive; and to develop and evaluate a location band costs somewhere in between. On the other hand, only specific, detailed locations are solutions to the location problem. The only value that bands of interest or location bands have is to serve as sort of intermediate way stations in the location process. By examining a particular band of interest or location band one gets some idea about specific locations represented by that band of interest or location band without spending all the resources required to develop and evaluate a detailed location. Thus, in the example, band of interest A has, so far, been rejected in favor of B without the cost of examining a detailed location in that band of interest.

The essential issue is to balance the costs of engineering against the value of information. One can spend a lot of money and get a lot of information through developing a detailed location, or one can spend relatively little money and get somewhat less information through developing and evaluating a band of interest. These kinds of tradeoffs can be modeled using the approach of a sequential decision problem.

The hierarchical structure model provides a rational procedure for guiding a design process such as route location. Several activities are possible, for example, (a) generating and evaluating locations, location bands, or bands of interest or (b) terminating the location process. Each activity is characterized by a cost or resources consumed and by its contribution to the engineer's information about the location problem. (More precisely, at any stage a set of actions, such as locations or location bands, has previously been examined, and over each the engineer has a prior probability distribution. Each activity is characterized by a cost and a conditional probability. There is a utility function over locations only.) The engineer's judgments are expressed as subjective probabilities. The logic of the sequential decision problem, modified to reflect the hierarchical structure of the location problem, provides a basis for calculating the best thing to do next in a location process (12). The hierarchical structure model is general, applying to problems other than route location.

In expressing the trade-offs between information value and information cost, the model also sheds some light on suboptimization. Note that we have not talked about finding the best location out of all possible locations; we have implicitly assumed that the location problem is not an optimization problem in the usual sense of finding the best of all possible. For example, we pick a particular band of interest, evaluate it, and then perhaps decide not to study it any further. The best of all possible locations may very well be in that band of interest. Once having rejected that band of interest, we have lost any chance of even finding that best location. However, given the limited resources of the engineering process and the information that the engineer has expressed in his judgment about the band of interest, we may be making a "reasonable" decision by rejecting that band. This is suboptimizing; we have not picked the best of all locations. Such suboptimization is in fact optimal, however, in the broader context of limited engineering resources and the costs of information. Discarding that band of interest is in fact an optimum strategy. This view of suboptimization has wide ramifications for the structure of engineering processes in general.

SEARCH TECHNIQUES

In our discussion of decision theory, we assumed that all the alternatives were given, and that we knew for each the utility associated with that alternative and a particular state (Table 1). Several questions arise: How did we know what utility was associated with each action-state combination? How did we get the alternatives in the first place? We will return to answer the first question later; here our discussion is focused on the problem of search or how to get the alternatives in the first place.

We define search as the process through which one or more alternatives are produced. [Ferguson (13) discusses the issues at the network planning level.] The process of search may be highly formal, as when mathematical models are used, or highly intuitive, as when an engineer or planner sits down and sketches a possible regional transportation system; or it may be some combination of these. The spectrum of search techniques ranges from mathematical models to intuitive design procedures. The most powerful search techniques now available are those of mathematical optimization, such as linear programming. These techniques do have limitations. First of all, there is the computational difficulty, i.e., the time required for computing solutions. Second, there is the very real limitation of having to force complex sets of goals into the format of a linear objective function and set of constraints. Third, there is the problem of forcing our understanding of a very complex set of phenomena into the linear or partially linear forms required by linear programming and other mathematical programming techniques. Often, however, these limitations are not so grievous, and the returns more than justify the limitations. Thus, we can find many useful mathematical programming formulations that can be used to generate possible alternative solutions to a transportation problem (14, 15, 16).

Less restrictive as an approach is direct search. Direct search techniques include "hill-climbing" approaches, which operate as follows: Arbitrarily or randomly select an initial possible solution to the problem as a base point, explore various small changes to this solution and compare, determine the best of the small changes, and shift the base point to that best solution. Repeat the cycle but explore small changes from the new base point. Continue the process until finally small changes do not produce any improvement. More complex simulation models can be used for testing the solution with direct search techniques than with mathematical programming. For example, instead of the optimal flow formulation, the descriptive approach of traffic assignment can be used. Direct search techniques, unlike mathematical programming, do not guarantee that an optimum solution will be found; but they should prove useful in finding at least local optima if not global optima (17).

One can go further in loosening up the structure of the problem and formulate a variety of heuristic search techniques. By heuristic, we mean simply that these techniques are likely to produce good solutions, but there is no guarantee that they will produce an optimum solution, or even produce good solutions all of the time. For transportation planning, heuristic techniques may be derived by asking questions such as this: If an engineer were looking at a network, how would he try to develop small changes that might be potential improvements to that network? We can propose a number of approaches of this form, program them for the computer, and then use them to try to get better transportation networks via heuristic procedures. This will probably be the most fruitful area for practical search techniques in the near future (18, 19, 20, 21, 22, 23). For example, at present the use of a mathematical programming formulation requires an approach to predicting flows in networks different from the more behavioral approach of traffic assignment (24, 25). Instead of trying to force the network analysis problem into linear programming form, we could use traffic assignment procedures (and thus have a more realistic analysis of the network alternatives) and design heuristics based on the kind of procedures an intelligent engineer might use to modify the network to get a better network. Thus, the heuristic procedures, programmed as a set of computer routines, together with a traffic assignment model might be a reasonably efficient way of searching out alternative transportation networks.

As a fourth major class of techniques, we should mention procedures for guiding the engineer's intuition about the nature of desirable alternatives. One extremely insightful model for guiding intuition was developed by Alexander (26) in the context of architectural design problems, but it is applicable to many different kinds of problems, including transportation planning. This technique is particularly insightful because it does not replace the transportation planner's crucial role in inventing and creating new solutions; it just tries to guide him in the essential issues.

The basic approach is this. First, list all the objectives and constraints that the particular solution has to meet. Second, examine this list of requirements; and for every possible pair of requirements, identify whether that pair is particularly difficult to resolve. For example, if we are dealing with the design of highway interchanges, we may find that the requirement for sufficient vertical clearance for underpasses really conflicts quite strongly with the requirements for minimum earthwork costs (27). On the other hand, requirements for vertical clearance may not conflict at all with lateral clearance requirements; however, lateral clearance does conflict heavily with lane widths or median widths.

Based on this simple analysis of the requirements that the solution must meet, a model of the problem can be built. Each of the requirements corresponds to a node of a linear graph. Where there is a significant conflict or interaction between 2 requirements, we establish a link between the corresponding nodes in the linear graph; where there is no significant conflict, we do not put a link between the 2 requirements. Thus, the structure of a design problem, which may have hundreds of requirements, can be mapped in this way. Then, this structure can be analyzed, using certain procedures. The result of this analysis is the specification of a sequence in which the designer should try to address the requirements; this sequence results from the systematic decomposition of the overall problem into subproblems, using the information in the linear graph. The designer searches for a solution to the problem, juggling these requirements and their interactions. The value of the approach is that the sequencing of the requirements makes the designer's approach more effective. This approach has been applied in an experimental way to search in 2 transportation problems, highway interchange design and route location (28). McHarg (29) in work done later used a similar technique of overlaying diagrams in order to search out a route location. However, there was no systematic analysis of problem structure in McHarg's approach; his technique seems wholly arbitrary.

The problem of search is in the development of good alternatives. Approaches available range from the completely intuitive design to mathematical models. Each type of search technique has its assets and its limitations. We can look forward to the proliferation of a wide variety of search procedures, each of which is best for certain circumstances, but none of which is best for all problems in transportation planning.

EVALUATION AND CHOICE

Let us now turn to the first question we asked: How do we get the utility associated with each combination of an alternative and state? To get the measure of the worth of a certain action, we must first predict its consequences and evaluate those consequences. This evaluation can look at the alternative by itself as well as compare the alternatives with others. In standard transportation planning and highway location studies, the basis for the evaluation of alternatives is nominally that of economic analysis, the standard benefit-cost analysis, or variations on this theme. However, these economic analysis techniques have extremely severe limitations.

The essential issue is this: Any change in the transportation system impacts differentially on different groups. Some groups benefit, some groups lose. If we build a highway through a city to serve automobile-owning suburban commuters, we displace homes and jobs, and reduce transit ridership, thus causing increased fares and lower service for nonautomobile-owning transit users. It is particularly important not to hide these differential impacts, but to trace them out explicitly. If we try to place a dollar value on all the benefits and costs and to compute some aggregate total, such as net benefits or costs, or benefit-cost ratio, we ignore how each of these different groups will be affected. The real issue is not how much total net benefit is increased or decreased, but how each particular group is affected. Any politician recognizes this fact of life: no system can be implemented in reality unless no group is disrupted. For, if some group is negatively affected, then we can expect politically effective reactions. Thus, in the systematic analysis of transportation alternatives, we must explicitly trace out the incidence of these differential impacts.

Techniques are under development to assist in differential impact analysis (30, 31). These include the concept of a goal-fabric as well as the development of computer software systems.

CONCLUSIONS

This has been a very brief survey of a wide variety of relatively subtle issues. We started out with the statistical decision theory approach to treating uncertainty. We extended the simple model to that of sequential decision processes and pointed out its relevance to the problem of hierarchical structure. Then, we discussed search, the generation of alternatives, and finally, very briefly, the subtleties of evaluation and choice among alternatives. Our main objective has been not to present a text on these techniques but simply to point to some of the directions of current work in decision theories that may be useful in transportation (4, 32).

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Discussion

Wilson Campbell

What you are talking about is a procedure that is not done in a few minutes, or hours, or even years; it is a continuing and comprehensive process. I do not see that it is greatly different from the techniques being used today.

Marvin Manheim

True. But let us honestly recognize (a) that we never actually solve the urban transportation problem, (b) that actually the way things get done is as a series of sequential decisions, (c) that we deal with a multiplicity of objectives in a fairly complex way and do not act as though they are all dollar-valued in the market, and (d) that we do not really deal with the problem as a single-level problem but we develop some preliminary alternatives and some final alternatives. Let us recognize this continuous planning process for what it really is.

Dan Haney

Even though we would desire to keep the various objectives and goals separate so that the impact on the different alternatives of each may be measured, we have to know the overall objective function if we are to make major decisions on a systematic basis. This objective function must be used by many people in an organization for designing and evaluating plans; it must cover not only user consequences but nonuser consequences as well. Let us derive it as best we can, and then use the techniques of sensitivity analysis to evaluate what would have been the choice if, for example, the weighting of reduction in unemployment were different in relationship to user costs.

Marvin Manheim

We have to develop a much more flexible, much more subtle approach; sensitivity analysis is one very important tool. The idea is that we should not define some objectives, then find some alternatives and pick the best alternatives in line with the objectives. Rather it is to use widely different statements of objectives as ways of clarifying the issues and finding the alternatives that abide by these objectives, and then to go back into the political process to get the choices made. One very simple experiment I would like to try is to provide an on-line network analysis capability including a visual display, and let the neighborhood groups who are concerned with the highway location vary the line to see what happens in terms of impacts on other groups in the community. Thus, the neighborhood groups would see what it is that either they or the people in the other town are going to pay and to whom and in what form. The essential issue is not analysis by taking a clear-cut statement of objective and solving the problem; rather it is analysis by interacting in the political process to clarify alternatives and objectives, which will lead to decisions in the political process.

Wilson Campbell

Granted goals are likely to change, but we need some target or direction to aim for at a higher level. The target will change and that is why these planning studies are continuing. There are changes in the social and economic attitudes, and presumably these studies are flexible enough to change their goals accordingly.

Marvin Manheim

I believe that you should not come out with reports that say "these are the alternative systems, and this is the recommended system to be completed by 1985 or 1990." Rather the reports should indicate that A is the best alternative to be carried out over the next 5 years, and, if this is done, then probably we will do B over the following 5 years and so on. We would like to have more explicitly addressed the continuing nature of the transportation plan with a statement as to the conditions under which we will choose the alternatives at the next stage.