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Foreword

Five papers are included in this Highway Research RECORD which deal with various approaches to evaluation of urban transportation systems. Two were presented at a conference conducted by the Committee on Transportation System Evaluation, covering two basic topics: (a) development of transportation system alternates, and (b) criteria for evaluating alternates. This conference was aimed at defining the full and proper scope of system evaluation, and assessing the current state of knowledge and techniques. George Ferguson's paper is addressed to system development as a design process entailing conception, testing, compromise and retesting. The paper by Neal Irwin discusses the effects that the choice of criteria may have on transportation planning recommendations.

The last three papers approach system evaluation from various points of view. Perazich and Fischman draw together many aspects of costs and benefits—to users, operators, and the whole community. Hay, Morlok and Charnes apply linear programming to optimization of a radial transportation network. The objective is to find the combination of highways and rapid transit which minimized total transportation costs. Marvin Manheim shows why transportation planning, a decision process of complex structure, calls for powerful, flexible problem-solving systems.

Contents

Development of Transportation System Alternatives

GEORGE A. FERGUSON, Study Director, Regional Development Planning and Transportation Planning Program, Pittsburgh, Pa.

•AT ONE time the preparation of an urban transportation plan was approached as an engineering problem that had as its principal goal the development of a workable solution. Today, workability alone may not be enough. True, plans for urban transportation systems must be functional; but plans must also represent an efficient allocation of resources and a step toward the achievement of a better overall urban environment. These more complex demands on the urban transportation plan mean that a meaningful solution can be achieved only after a thorough search for alternative workable transportation systems that have been evaluated in terms of their various attributes.

To identify where the development of alternatives fits into the total picture, the Chicago Area Transportation Study serves as a representative example of a transportation planning process that arrived at the recommended plan after investigating a number of area-wide alternative systems. Because of this, it can show where the development or conceptualization of alternatives fits into the overall transportation planning process. Briefly, the CATS procedure was as follows:

1. Determine the objectives (criteria) that will be used to select the best transportation system.
2. Develop alternative metropolitan-wide transportation networks (these are initially in the form of sketch plans).
3. Subject each alternative to a testing process that measures the alternative in terms of travel time, cost, and other factors.
4. Select the alternative that best meets the stated objectives.
5. Refine the alternative by testing minor changes in the network in order to better meet the objectives.

Only the second step, development of alternative networks, is the subject of this discussion. This means that we are concerned with strategies and techniques for producing transportation plan alternatives which will be subjected to further testing and evaluation in another part of the transportation planning process.

Any design process is one of repetitive stages of conception, testing, compromise, and retesting; therefore, even in the process of developing or creating alternatives, a considerable amount of testing and evaluation may take place. It should also be recognized that development of alternatives and refinement of the selected alternative are closely related. Many techniques may be common to both these stages in the process of arriving at the final plan. Although we may lack a perfect conceptual framework, this should not prevent us from focusing on the need for research into how one goes about reaching out for ideas that can be developed into alternative network proposals.

The process of designing alternative systems for further evaluation has been the subject of little research. Last year each member of the Transportation Systems Evaluation Committee was asked to submit the five references that, in his opinion, represented the best published work dealing with the development of transportation

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Paper sponsored by Committee on Transportation System Evaluation and presented at the 45th Annual Meeting.

system alternatives. Out of a number of references, only three appeared on more than one list:

1. Chicago Area Transportation Study, Vol. III: Transportation Plan (1962),
2. Pittsburgh Area Transportation Study, Vol. 2: Forecasts and Plans (1963),
3. Creighton, R. L., Hoch, I., Schneider, M., and Joseph, H., "Estimating Efficient Spacing for Arterials and Expressways," HRB Bulletin 253, pp. 1-43, 1960.

Even though only three references were duplicated on one or more other lists, it is significant that each reference represents a technique or strategy designed to systematize the art of conceiving transportation systems. The need for systematic and replicable methods of system conceptualization should not require debate. The very absence of a consensus on how alternatives should be developed underscores the desirability for further investigation in this area.

In most urban areas much of the job of developing alternative systems is already done. The existing system is in place, and something called the committed system is usually taken as a given factor. Also, there are often proposed projects of merit which have been put forth by individuals or agencies and which have not been implemented over the years.

The process by which plans are first conceived is well known. It usually involves plotting existing facilities and proposals on a map, followed by attempts to weave the best of these into alternatives that will have system continuity. Sometimes this process will result in a wide range of alternative designs; but often the existing and committed system, along with topographical or other constraints, will appear to limit the alternatives to be tested to a single theme with a few minor variations.

At this point, a few questions may arise. Are we sure that the best alternative has been included within those we are proposing? Can another transportation planner come along in a few years and, by widening the accounts, propose a system that is better but that was not included within our set? Can we explain or demonstrate to others that, in developing the plan, we have given full consideration to all reasonable alternative means of moving people and goods? In short, have we followed some methodology which assures us that the best possible transportation system has at least been proposed?

To begin to develop some sort of systematic process for conceptualizing alternatives, we must first know the criteria that define what we mean by "best." Such criteria may be simple cost criteria or complex criteria related to regional goals and policies; but, regardless of what they may be, they need to be known. A knowledge of the criteria by which systems will be evaluated is essential to the development of any systematic method of generating alternatives.

The "efficient spacing formula" (one of our recurring references) represents an example of a technique used in developing an alternative that is directly related to a criterion. The criterion or objective is to determine the spacing which will minimize the sum of all transportation costs. This formula relates the spacing of expressways to trip end density, the cost per mile of expressways, the cost of travel on expressways and arterials, and the proportion of all trips that will use expressways. The formula makes a number of simplifying assumptions, but it "does much to eliminate wild guessing and inefficient testing of plans. It allows the planner to define more narrowly the territory within which an optimal plan can be found."[1]

Since this formula determines spacing and, also, since it does not explicitly consider the existing expressway system when determining efficient expressway spacing, it is most useful for indicating what kind of ideal or schematic system configuration would provide least cost transportation for a given pattern of trip ends. This ideal form—ideal if one accepts the criterion—can be compared visually to the existing system so that the existing system can be added to in such a way that, hopefully, the plan resembles the ideal form as much as possible.

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[1] Chicago Area Transportation Study, Volume III: Transportation Plan, p. 44 (1962).

Techniques similar to the efficient spacing formula can help to assure that system alternatives are near the optimum in terms of some broad, single objective. In this way such techniques can aid in answering such questions as, "Are we sure that the best plan has at least been proposed?" The efficient spacing formula is used here as one of the few examples of a technique specifically designed to aid in the conceptualization of alternatives. It cannot do the whole job. There are still potential alternatives that might involve other transportation modes or new kinds of transportation hardware. But, it is a start.

Up to now this discussion has viewed the development of alternatives as though the alternatives themselves were entire area-wide systems. It is assumed that these area-wide alternatives then will be subjected to some process of testing or measurement which will permit the selection of the alternative that best meets some criterion. In a sense, then, this entire process is a search for the ideal plan or end state.

If one is inclined toward a deductive strategy of plan development that moves from the general to the particular, such a process may have appeal. There is, however, no reason to assume that it is necessary for plans to be made in this way. Perhaps some process which incrementally adds facilities to the existing system in some optimal fashion would be better.

The question of whether the planning process should have as its objective the production of a plan representing an end state or whether it should have as its objective the development of a mechanism for incrementally programming optimal improvements is one that should receive some attention from transportation planners. Other planners are becoming concerned with this question.[2]

Suppose that, instead of being concerned with an ideal end state, a planning strategy is used which first programs in the improvement most needed by the existing system. Then, with this as a base, the next most needed improvement is added. On the assumption that we would have some way to allow for changes in transportation demand caused by urban growth, where would this kind of process take us?

One of the problems with this approach is that when each project is added it may divert traffic or patronage, thereby absorbing some of the benefit of prior projects; so theoretically, at least, negative system benefits could result even though a particular project had seemed to be warranted. Thus, the specific rules for determining which project is best and should be added become very important. Furthermore, they are reflected in a chain of decisions that may or may not result in a good plan. As long as some of these problems are considered, it may be possible to develop incremental programming techniques that will, for all practical purposes, yield a solution as valid as the conventional and state approach. In addition, there are some obvious side benefits of incremental programming that make it attractive.

This discussion presents no brief for either approach, nor does it attempt to advocate any particular technique. Rather, its purpose has been to underscore some of the work and thinking that has been done to develop transportation system alternatives. Conceivably, there could be many ways to approach the problem. Certainly, there is no book solution. Hopefully, future research in this area will lead to replicable methods that will aid in the development of effective transportation systems.

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[2] See Webber, Melvin M., The Policy Sciences and the Role of Information in Urban Systems Planning, pp. 1-21, and specifically pp. 10-16, of Urban Information and Policy Decisions, a publication derived from the Conference on Urban Planning Information Systems and Programs and published by The Institute of Local Government, University of Pittsburgh (1964), Editor, Clark D. Rogers.

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Discussion

JOHN HAMBURG, New York State Department of Public Works—First of all, an activity system refers to that collection of land, enterprise, and people (otherwise called "the city") which exists at some point in time as a function of history and utilized technology.

A transportation system (a) serves as the connector to all the spatially separated activities in an area and (b) to an unknown degree shapes the emerging activity system.

The notion of alternative transportation systems has a double meaning: (a) as alternative transportation systems for a given activity system, or (b) alternative transportation systems for alternative activity systems. For us, the alternative activity systems are hypothetical . . . being the alternative future activity systems which are to be considered.

If we consider the problem of transportation system alternatives for a given activity system, our quest is to find a transportation system that is better than any other that we consider; in other words, the optimum system.

Now in order to arrive at alternative transportation systems from which to select the best one, we must somehow generate a series of systems. Choice, after all, implies the existence of at least one other system. Usually, highway and transit elements will be necessary subsystems in these alternatives.

A time honored technique is to get out the grease pencils and the aerial photo mosaic and begin drawing routes and systems.

An autocratic way is to have the boss do this over a weekend when everyone else is out mowing their lawns or playing golf. Another way is to have the multi-discipline, mission oriented research team prepare alternative systems. As an aside, over and above any useful ideas that may evolve from this process, it represents a gaming technique which management can use in personnel evaluation. The contrast between system sketches prepared by mathematicians, design engineers, planners, and sociologists is a lesson in itself.

Still another technique, one which is used extensively in Upstate New York, is to have local agency planners and the district engineer submit their system ideas for the study through the planning committee.

All of these system development techniques work in the sense that they generate an abundance of plans to consider. But how do we choose the best one? Also, how can we avoid the lingering doubt that the best transportation system may not have been among the alternatives and therefore had no chance of being selected.

At the present time, we attempt to make our selection based on a least cost notion. That is, we select that network which has the least total cost considering both the cost of the network (the cost of building and maintaining) and the cost of traveling on that network. It seems clear that if we believe we can evaluate alternative transportation systems and choose one which is the optimum, we really should be using the criteria by which we choose between systems to develop the best system in the first place. After all, the choice criteria must exist in order to choose; we may as well use it at the outset instead of waiting to use it at the end of this part of the planning process. Why flail around subjectively and not only take a chance of missing the best one, but also spend time dreaming up plans which have no chance of being selected? The moral: design the best system using the criteria required in the evaluation process; or, the very criteria used in evaluation should be used to design.

As Mort Schneider would say, "This is a trivial problem conceptually." However, the mechanics of the solution are a great deal tougher. For example, the optimum spacing notion was one attempt to use the criteria-design idea. The assumptions of a rectilinear transportation system coupled with constant density of vehicular destinations, failed to provide a unique and continuous transportation system. It provides the planner with a useful rule of thumb with regard to spacings of routes, but not a complete system.

The choice problem is further aggravated by the fact that there is typically a fairly large plant of existing transportation facilities which may or may not conform to or be easily reconciled to a transportation system which is an optimum system for a given region ignoring the existing facilities.

Because these existing facilities represent a very substantial investment, they must be integrated into any final system plan. It is not clear, however, whether a continuation of the system configuration implicit (if any) in the present network would be a superior strategy to one of attempting to warp the present network into the ideal network.

For this reason, and in order to objectively demonstrate the inadequacies of inferior systems, which may be someone else's pet, it is clear that we will have a continuing need for an evaluation technique. It seems equally clear, that we must continue to attempt to derive an optimum transportation system for a particular activity system from the very criteria which we use to evaluate the transportation system.

Properly, the planning process should not stop with the design of a transportation system; it should extend itself to include alternative city forms. While this is a much more difficult task than "just" arriving at the optimum transportation system, the approach should be the same. That is, (a) establish the criteria, (b) unify these into a frame by which to evaluate proposals, then (c) design the optimum form (activity system) using the established criteria. It is not certain whether we can do an adequate bookkeeping job on the problem, quantify the criteria, or select the least-cost activity system. However, for each of the activity systems considered, we should include the transportation system which is optimal to it . . . and presumably the transportation system's cost will include a substantial part of the combined activity-transportation system structure.

WALTER G. HANSEN, Alan M. Voorhees and Associates, Inc., Washington, D.C. It does not seem proper to separate, even at the high conceptual level suggested by Mr. Hamburg, the effect of the transportation system on the activities system from its reverse, the effect of activities upon transportation. Alternative transportation systems that are developed by techniques based on this separation will have certain advantages. They will have in common some easily calculable criteria. Their pros and cons will be, thus, easily stated, and final determination of an "optimum" system will be clear-cut. This will come about because of the predefined nature of the factors being considered and, unfortunately, because the procedure fails to consider the real problem.

What is being missed, then, is the consideration that must be given to the "goals" of the area, in terms of both transportation and activities systems, before any alternatives can be established. The minimization of transportation cost may, or may not, be one of these goals. The reverse, the maximization of opportunities, may be one. Most likely, the regional goals will reflect some balance between the two. In any case, it is important to know in what general direction the community wants planning to go.

How to use something so imprecise to determine alternatives? The diversity of the goals of most areas would seem effectively to rule out any direct measurement of the "optimum-ness" of a system, at least in the sense of being able to calculate numbers in a systematic and regular fashion. The development of alternatives should, rather, be the function of a group of people representing as many as possible of the interest groups, political organizations, and technical disciplines present in the area. The consensus of this group would, then, determine those alternatives which approach optimization of the diverse criteria present and are, therefore, worthy of complete analysis.

There is another problem which must be faced in the development of alternatives, that of the constraint placed upon such development by the existing network and worsened by the presence of a "committed network." These two will probably constitute well over 90 percent of whatever future network is to be proposed. Although there is probably little that can be done with the existing system, it is important that those who are developing alternative systems minimize the restraint caused by the committed projects. They may, after all, be "committed" only because the highway department has commissioned the design of a bridge or an interchange. Tearing-up or altering these plans would certainly be cheaper in the long run than building the "wrong" system. The keynote of the development of alternatives must be flexibility; too often, those developing these alternatives use the existence of large "committed" networks as an artificial limit on what they may propose. They should, rather, try to minimize the constraints upon the alternatives developed.

It should be stated that, at this stage in the normal procedure, a traffic forecast has been made and the 90-odd percent of the system that exists has been inventoried. This means, in fact, that it is not a question of designing a system, but, rather, one of selecting additions to an existing system. This process, therefore, should approach the problem in the second manner, as outlined by Mr. Ferguson, that of making optimum additions to that which already exists.

Criteria for Evaluating Alternative Transportation Systems

NEAL A. IRWIN, Vice President, Traffic Research Corporation

•A CRITERION, according to Webster's Dictionary, is "a standard of judging; a rule or test by which anything is tried in forming a correct judgment respecting it." Our discussion focuses, then, on defining a set of rules or standards for evaluating proposed transportation systems, such that the "best" system will be chosen for implementation.

There is, of course, no unique set of such criteria, just as there is no undisputedly correct method of applying the various criteria to evaluate transportation systems. In a paper such as this, we can only hope to list what appear to be the most important criteria, classify them in various ways which may be useful, and discuss briefly the effects that the choice of criteria may have on transportation planning recommendations. It may then be possible to reach a few tentative conclusions as food for thought and subsequent discussion.

People seek opportunities, and in doing so they must transport themselves and their goods from place to place. A discussion of transportation planning rules and standards has far-reaching implications which stretch broadly across such fields as philosophy, economics, politics, sociology, engineering, and aesthetics. To place some bounds on this enormous topic, the following assumptions are made:

1. We are dealing with a single urbanized area, which has functionally realistic boundaries, a known political, economic and social structure, defined regional development goals, and an existing transportation system.
2. We are confronted with a set of proposed new transportation system alternatives for the area and we are reasonably sure that this set covers all reasonable alternatives, includes all modes of transportation and types of ownership, and contains the "best" system.
3. We also have at our disposal an effective method for weighing and comparing the various criteria to evaluate the proposed transportation systems.

In other words, we assume that other members of the Committee on Urban Transportation System Evaluation have successfully defined methods and criteria for developing such systems and also methods for evaluating them. Our problem then, is solely to define criteria on which the evaluating process is to be based.

BASIC QUESTIONS

Before attempting to classify and discuss the criteria in question, it is useful to list some of the more obvious questions to be asked in evaluating an array of proposed transportation systems.

1. Which system would serve most people, both in peak hours and during the entire day and week?
2. Which system would be most convenient to most people in terms of travel time, reliability, walking, waiting, transferring, and comfort?
3. Which system will have the smallest out-of-pocket costs for its users?
4. Which system is safest?

Paper sponsored by Committee on Transportation System Evaluation and presented at the 45th Annual Meeting.

5. Which system will be least expensive in terms of capital cost, operating cost, land requirements, and effects on the amenity of adjacent areas?
6. Which system will foster the most desirable social and economic development of the area?
7. Which system will produce the greatest direct revenue from taxes, tolls and/or fares?
8. Which system will have the greatest versatility for other uses, such as transportation of goods?
9. Which system will have the greatest flexibility to deal with sharp travel demand peaks, and to adapt to changing land uses, technology and travel habits?

Many other questions could be asked, and the picture is complicated by the need to consider the various factors in combination, to produce an optimum benefit-cost solution, a least-cost solution. or some other best solution.

One point that emerges in considering these questions is that an attempt must be made to reconcile the requirements of the individual (for example, the first four factors) with the needs of society (as illustrated by the last five factors). It is understood, of course, that "society" in this context comprises many diverse elements including those who operate the system, those who are affected (for better or worse) directly by the system, and those who are affected only indirectly by it.

Decision makers must try to determine what proportion of the city's total resources, in terms of money, land, employment force, and pleasant surroundings, should be allocated to transportation facilities. Should an attempt be made to allow everyone a door-to-door, high speed vehicular travel means always available for instant use, or must this level of service be reserved for those to whom it is essential or those who can afford to pay a sufficiently high price for it? Can and should we design transportation systems with sufficient capacity to allow high speed, uncrowded travel during peak travel periods, or must we allow pricing and/or crowding and congestion to discourage unnecessary travel during peak periods?

Perhaps a closer look at some of the criteria implicit in these questions will provide a useful framework for studying possible answers.

CLASSES OF CRITERIA

In reviewing some of the questions, it is apparent that criteria for evaluating alternative transportation systems can be classified in a number of ways.

Urban Budget Allocation Criteria

Criteria in this class would provide rules and standards for determining what proportion of a city's budget should be expended on transportation improvements, as opposed to the many competing demands for urban budget expenditures in the areas of education, urban renewal, crime control, welfare, etc. Unfortunately in this area, where the range of choice is perhaps widest, usable criteria appear to be scarcest.

In theory, it is possible for an urban government to accept the existing transportation system as adequate, spending nothing on system improvements, or, at the other extreme, to spend the lion's share of their available funds on improved transportation at the expense of other urban requirements. Criteria are urgently required which will allow benefits from improved transportation to be measured against benefits from other types of expenditures, so that benefit thresholds and/or marginal returns on various proposed expenditures can be compared. Such criteria would imply methods of equating per capita gains from transportation improvements with those from, say, improved education, presumably in terms of common units of value such as dollars. They would include also standards for comparing communications improvements, such as videophone, with transportation improvements as a means of increasing opportunities for interaction.

The pitfalls of estimating dollar values of what are often rather intangible benefits to persons living and as yet unborn place criteria of this type very much in the yet-to-be-developed category. Until they exist, decision-makers will be forced to rely on the traditional method of estimating "minimum" requirements in each area of need and allocating the budget accordingly, with due regard for political pressures, matching funds in some areas from outside budget sources, special interests, etc.

Transportation Budget Allocation Criteria

Criteria in this class provide a basis for deciding how best to improve existing transportation facilities, given a specified amount or range of budget moneys and/or other resources available for this purpose. It is criteria of this nature which are usually applied, implicitly or explicitly, in urban transportation planning studies. They include all the value judgments implied in current controversies over "balanced transportation," the needs of one segment of society or sector of a city versus those of other segments or sectors, the need for a reasonable choice of travel mode alternatives, the questions previously raised, and the comments and complaints of all who move from place to place in cities.

Among broad standards to be applied in this area are the effectiveness of proposed systems in dealing with peak-hour journey-to-work travel problems, weekend recreational travel problems, downtown conflicts between pedestrians, automobiles, buses, and trucks, downtown vehicle storage problems, and problems of downtown freight collection and delivery.

Criteria Classification According to Subject Area

Some classifications of this type are as follows:

1. Social: such as air pollution levels, possible disruption of neighborhoods, and increased well being due to greater opportunities for interaction.
2. Economic: such as effects on regional employment, development patterns, distribution costs, property values, and real estate taxes.
3. Physical: such as capacity for moving people and goods, convenience to users, flexibility to meet peak loads and adapt to changing urban development patterns, reliability, and safety.
4. Fiscal: such as capital costs, operating costs, and revenues.
5. Aesthetic: such as noise levels, effects on the urban landscape, and effects on parks and open spaces.

Absolute and Relative Criteria

An example of an absolute criterion would be all trips, whether made during peak or off-peak conditions, are to be possible at a door-to-door average speed of at least 35 mph. An example of a relative criterion would be that transportation system improvement will be selected which produces the greatest increase in average travel speed per dollar spent.

Other means of classifying and expressing various criteria will undoubtedly suggest themselves. The entire question of criteria to be used and the manner in which they are expressed is, of course, intimately connected with the method of applying them to evaluate transportation systems, and those methods are not within the scope of this paper. Accepting this limitation, it is still useful to postulate what may be the most useful types of criteria.

SUGGESTED TYPES OF CRITERIA

As a general dictum, it is suggested that absolute criteria be applied primarily to insure that given sectors of an urban area and segments of its population are supplied with at least minimum levels of service. Absolute criteria could also be applied to meet minimum standards in certain social, physical and aesthetic areas to which dollar values may not be readily applied. Finally, having weeded out any proposed transportation systems which do not meet these minimum levels, relative criteria could be applied in the economic, physical and fiscal areas, to provide a basis for selecting the system which produces the most benefits per unit cost.

In practice, this might work out in the following manner. First, define acceptable criteria levels such as the following: (a) accidents per million passenger miles; (b) on-time performance (travel time reliability) as measured by allowable variance from average speeds or travel times per mile; (c) maximum allowable noise levels (different for residential, commercial and industrial areas) due to transportation facilities; (d) maximum allowable air pollution contribution rates from transportation facilities; (e) maximum allowable encroachment on existing or planned parks and open spaces; (f) minimum allowable levels of public transportation seats per hour per square mile as a function of population density and employment density; (g) minimum allowable levels of capacity for passengers and goods in heavily traveled corridors expressed as a percentage of estimated design year peak period flows; and (h) minimum allowable levels of off-street parking facilities per square mile as a function of population density.

For all proposed transportation systems meeting defined "entrance requirements" of this nature, calculate total costs and total benefits, reduced to present day dollar values, including the effects of such criteria as capital costs, operating costs, user costs, operating revenues, property values, taxes, goods distribution costs, and time saved by users with suitable weighting for walking, waiting and transferring times. Methods to be proposed by other members of the Committee would be applied to select the best system based on costs and benefits of this nature.

Unfortunately, the above suggested framework does not explicitly incorporate such criteria as disruption of neighborhoods, effects on regional employment and development patterns, flexibility to meet peak loads and adapt to changing development patterns, and effects on the urban landscape. Although some criteria of this nature may be incorporated either in the minimum requirements procedure or the benefit-cost measures, it is more probable that they will continue to be included, if at all, as qualitative value judgments applied as an addendum to the benefit-cost appraisal procedure.

The examples given in this section are not intended to be definitive or exhaustive, but rather to indicate an approach which would introduce into the evaluation process criteria which at our present level of knowledge cannot be easily expressed in monetary terms.

EFFECTS OF CRITERIA SELECTION ON DECISIONS REACHED

As indicated by the previous discussion, there are many problems and uncertainties in the choice and definition of transportation system evaluation criteria. In view of this, it is extremely important that decision-makers should be aware of probable effects on their decisions of the omission or inclusion of various criteria as well as the methods by which the criteria are applied in the evaluation process.

For example, elimination of some of the social, physical and/or aesthetic criteria might perhaps result in selection of a system with optimum monetary benefit-cost characteristics when an alternate system with very nearly as good benefit-cost characteristics would have met the non-monetary criteria much more satisfactorily. Similarly, different assumptions concerning such items as the monetary cost of time may result in quite different recommendations concerning the best system.

SUMMARY

In summary, two points seem to emerge from this discussion. First, the choice, definition, and application of criteria for evaluating transportation systems are fraught with uncertainty. Second, more knowledge is urgently needed concerning the effects of these uncertainties on transportation planning decisions which must be made and are being made based on whatever facts and recommendations can be put together.

It is therefore strongly recommended that research projects be set up as soon as possible to carry out systematic sensitivity studies using real city data to test the effects of alternate criteria and methods on transportation planning recommendations. Such a program, it is felt, would be one of the most direct means of developing truly effective methods for evaluating transportation systems.

Discussion

THOMAS B. DEEN, Alan M. Voorhees and Associates—Neal Irwin's paper goes a long way toward bringing order to an enormously complex subject. His classification of various criteria serves to point out the wide range of urban activities which are touched upon by transportation proposals.

Fundamentally, a transportation system, like other public improvements, should exist for the purpose of serving people, that is, individuals. To get at the relative worth of a particular transportation system proposal, it might be worthwhile to ask Mr. Citizen how he would evaluate the proposal for himself. Doubtless he would ask at least some of these questions:

Will it serve me? My family? For which trips? How much time will it save me and mine? Will it allow me a greater range of places to live while still holding the same job? Allow me to take another job without moving my home? How convenient will it be? How safe? How comfortable? How much will it cost me to use it or not to use it? How will it affect my property visually, olfactorily, audibly, physically, and socially, both now and in the future? From similar standpoints, what about the effect on my neighborhood and my city?

Each individual and each family will weigh these points in different ways, and their ordering of the questions will be in accordance with the hierarchy of their own personal value systems. In fact, the basis of individual criteria for the evaluation of anything must be these personal goals or values. All individuals have goals, whether stated or otherwise. A complete list would be long and extremely diverse, but some common ones are personal security, freedom to choose values and pursue goals, physical and mental development, accumulation of knowledge, physical comfort, serenity, physical pleasure, meaningful relationships, acquisition of material goods, and sense of worth.

The existence of society provides both opportunities for the fulfillment of, and necessary constraints on, personal aspirations. An ideal society would provide an environment encouraging the maximum fulfillment of personal goals, and the public agencies of such a society would establish collective goals which tended to maximize that fulfillment. These goals might be aggregated at various levels, starting with the individual and moving to neighborhood, subregional, regional, state, and national goals. Since, at each larger scale, the amount of diversity to be accommodated would increase, the common elements would decrease and the items included would change according to the scale of the function at each level. Thus, collective goals at any level are a reflection of personal goals; and they are essentially arrays on hierarchies of values, only a part of which can be measured in objective or numerical terms. Monetary or economic items constitute only a part of the total list. Criteria for the evaluation of any public improvement, then, can only be established by reference to the goals of the level of society undertaking that improvement.

Unfortunately, as we all know, society is not so ideal. Collective goals are difficult to establish at any level with any degree of consensus. There is no arm of society which has the authority or competence to establish collective goals; and thus, there normally exist no community goals within which to establish criteria for urban transportation systems evaluation. Nevertheless, such criteria must either explicitly or implicitly be developed by reference to what are thought to be community goals.

As technicians, we long for the simplicity and objectivity of a procedure which would combine all the diverse elements that must be considered in evaluating a set of transportation systems into a single weighted index and thus provide the answer as to which is the best system. There is danger perhaps that we go so far in this direction, that we overemphasize those elements which are measurable and which do fit into the equations, or that we substitute our own subjective ideas as to how society weights its values. The result is that our recommendations and their underlying rationales are sometimes dismissed as technical exercises. It is apparent that, of the list of personal goals mentioned, only a few can be labeled as monetary or economic goals. In the future, as the debate over where to channel our affluence increases, the problem of attempting to reduce our criteria to strictly economic or monetary terms is likely to become even more troublesome. In the past, when man's primary concern was with the acquisition of food, shelter, and clothing (all terms easily reducible to monetary terms), it was much easier to find the consensus that economic considerations should prevail. Today, we are seeing society show an increasing interest in, and responsiveness to, such non-economic values as the arts, environmental aesthetics, recreational facilities, and getting to the moon.

The relevance of our economic criteria is not enhanced by present fiscal policies. Funds for various system components come from such varying sources as state and federal gasoline taxes, local fare box revenues, local real estate taxes, state sales taxes, and federal income taxes. It is apparent that two otherwise equally desirable systems might look quite different from the standpoint of local costs, since one system may well have a higher portion of its costs eligible for external (i. e., non-local) financing. As long as this situation prevails, it is unlikely that local officials will be as much impressed by the most economic system as they would be by that which can be obtained with the least local financing. The search for relevant criteria requires recognition of this situation. The need for more rational criteria requires more control of transportation fiscal policy at the local level.

Choices among alternative transportation systems often involve trade-offs between conflicting goals. It is difficult for an individual, as for a community, to know which group of his personal goals are the most important when decisions among a limited number of alternatives require that he sacrifice some goals for others. For example, the construction of an urban highway immediately raises the goals of reduced travel time and increased travel opportunities, and in opposition, those concepts of a better urban environment that consider noise, visual aesthetics, and air pollution. Perhaps only when faced with a specific decision, where the consequences of each alternative are drawn in explicit terms, can one make such a trade-off. Criteria for evaluation must, then, be flexible and may sometimes be "weighted" only at the time of decision.

Such considerations maximize the need to measure all those elements which are subject to quantification, to improve techniques for describing, picturing, and projecting those elements which involve more subjective considerations, and to present the entire array of considerations to political decision-makers and to the public.

Final decisions should be made at the political level and must of necessity involve some debate, since the decision involves trade-offs between conflicting values of each individual, as well as between individuals and between groups. Our job is to see that the facts (that is, the consequences of alternative decisions) are available and are so understandable as to greatly enhance the possibilities of informed constructive debate.

JOSEPH McC. LEIPER, Director of Transportation Planning, New York City Planning Commission—Neal Irwin's paper does a good job of identifying the issues involved in evaluating alternative transportation systems and the lack of knowledge available with which to make these evaluations.

My remarks stem primarily from 15 years of experience in the New York area—years which have afforded little opportunity to step back and take a really reflective look at our decision-making tools and mechanisms. New York is, no doubt, unique in the intensity and complexity of its on-going action. On the one hand, we have a mature city with highly developed activities, facilities, and institutions—all resistant to change. But New York's role as the nation's business headquarters and other forces are bringing about profound changes within the social, economic, and physical structure of the city.

The problem of planning for transportation, or any other function, is one of adapting the existing urban structure over a period of time to changes that cannot be precisely measured. These forces of change include the distribution of population and economic activity, income and education levels, availability of fiscal resources, technology, and institutional evolution.

The standard procedure of transportation studies, faced with the responsibility for system planning, has typically been to extrapolate trends of urban development 20 years into the future and design a balanced system of modern rail rapid transit and free-flowing expressways.

While we have learned a great deal in following these best available procedures, our methods have left us with great uncertainties:

1. We really do not know how the city of the future will develop—to what extent, for example, will the exodus of blue collar jobs from the urban cores continue or accelerate?
2. We cannot yet measure the impact that transportation access, or the lack of it, will have on urban development and redevelopment.
3. We cannot even be sure, at least in some of our major cities, that the systems we are planning will be the best transportation solution for the 40 or more years of their existence. Perhaps a technological breakthrough is possible, if not imperative, to combine the flexibility of auto transportation with the space efficiency of mass transit.
4. We have difficulty in finding convincing ways of persuading people, businesses, and politicians that they should allow urban activities to be relocated in order to build new transportation facilities.

Because of these limitations of knowledge, I would tend to accept Neal's thesis of using minimum explicit criteria for evaluation of transportation systems. This, however, should not be interpreted as inhibiting the range of planning and evaluations—far from it. We should go ahead and project into the future and lay out a maximum range of possible courses of action. But we should not be afraid to keep our thinking flexible and use judgment freely to evaluate alternatives and set priorities when more explicit criteria are lacking.

I would point up four general criteria that I think are particularly significant in the evaluations which we are considering here today:

1. Efficiency of investment and conservation of resources must be a prime consideration in planning major urban areas. While national economic productivity is expanding at a rapid rate, needs and expectations are also growing in all areas of human activity, and barring a revolutionary reallocation of resources, older cities will continue to be financially strapped for the foreseeable future.
2. Quality transportation is essential. Rising incomes will inevitably generate demands for improved transportation, and while investment may be limited, it should be put into facilities that will have maximum utility in changing times. Older cities, however, must not lose sight of special transportation needs for lower income residents.
3. Flexibility is the key to a sound transportation development strategy. While transportation system decisions inherently tend to commit major expenditures in facilities that will be fixed over a long period of years, it should be possible to stage transportation programs so that a change in policy as to facilities and services may be effectuated at some time in the future as new conditions may dictate. Otherwise, we may become committed to massive transportation programs that will be obsolete by the time they are completed.
4. Feasibility must be uppermost in setting urban transport development priorities. While broad planning and promotion can stimulate public acceptance of new ideas, effective transportation programming must concentrate on policies and projects which can be effectuated in the relatively near future. These programs, however, can and should be consistent with longer range thinking that is being evolved over a period of time.

These criteria may sound conservative and myopic. In the long run, however, I think they may prove dynamic and realistic in making maximum progress toward improved access in some of our larger metropolitan areas.

S. M. BREUNING, Massachusetts Institute of Technology—It must be recognized at the outset that this discussion is intended to provoke thoughts and deliberation on an issue about which much current concern exists without adequate methodology or data to handle its problems. After recognizing that Mr. Irwin's paper points up crisply the major ideas and capabilities which we have today to deal with the problem, I should like to stress the limitation in his approach and the resulting problem to which we must address our research for the future. He is presenting an adequate and well-outlined case for a practical approach to today's problems, but does not provide the broad basis needed to plan research to deal with future problems.

The Academic Point of View

Some other participants in the discussion deal with similar questions of breadth of basis for the decision process. Therefore, I shall not belabor the basic question but rather will discuss the reason why I, as an academician, must concern myself with this breadth, even if it involves vague statements and Utopian suggestions. We academicians teach students, and if we do our job right, we will teach them about those things with which they will have to cope early in their professional careers. In other words, we have to teach them about the questions that will face them five or ten years from the time that we speak to them in the classroom. This is the time that will have elapsed before they attain positions in their professions in which they will be concerned with questions of sufficient depth and significance that they fully require the background of their educational framework and policies. Before this time, these engineers are in relatively subordinate positions where their contributions are not on the policy level. In the longer range, we can expect that the experience in their professional careers will gradually build upon and supplant the background they have obtained at the university. Thus, we must look at the problems for the student in a futuristic framework and must ask ourselves what questions will they have to resolve ten years from today.

The Parts of the Problem

Analyzing the title of our topic, we find essentially three items of information: criteria, evaluation, and transportation systems. Criteria here have been well defined by Mr. Irwin. We may circumscribe them differently as the scales by which we measure certain phenomena. The combination of such scales provides a total measurement for the transportation system under examination. By comparison, evaluation could be defined in terms of the gradations on the scales or criteria. Value is a quality determination of a measurement, and in comparison with criteria, it defines how much better or worse one measure is than another. While the definition of value is confusing enough in itself, it becomes still more so when applied to value of a transportation system. Thus, value and criteria are problematic points of discussion, with which we will have to grapple more and more as time goes on if we are to resolve such questions as those posed in our discussion. In comparison to the previous two factors, the transportation system is a rather simple one to define and discuss. It is defined as all physical facilities and their operating characteristics working together to provide transportation for an area.

The Problem

In consequence of the foregoing, it becomes our immediate problem to deal with the question of evaluation. One could perhaps argue that criteria are as important as evaluation, but from the practical point of view evaluation is the key to the answer. Let us look at two examples of the problem of evaluation.

Example 1. It is readily apparent to anyone that there is increased dissatisfaction with today's highway transportation system compared with that of ten years ago. We can nevertheless show that at least some value facets are better today than they were at that time. Time by automobile for the same distance traveled is less today in almost all cases than it was ten years ago, be it for inter-urban or intra-urban trips. Furthermore, the quality of highways is considerably better today. Why, then, are people more dissatisfied today than they were ten years ago? Obviously travel time and the quality of roads cannot be the sole measures for this dissatisfaction. Thus, if our value measure, which shows greater dissatisfaction today than ten years ago, includes time and physical highway facilities which are now better, then some other value facets which enter into the value measurement must be considerably worse today in order to offset these two positive developments.

We could next assume that this dissatisfaction is not based on individual physical factors of the system but rather on people's belief that the highway transportation system of today could be considerably better than it actually is. This assumption, which has considerable merit and support, leads to another disturbing factor gleaned from this short discussion, namely that value as a single measure is a time-dependent factor which changes not only in its composition of supporting facts such as time and comfort, but also changes as a function of human expectation.

Example 2. Next, let us compare transit and the automobile in their attractiveness to the user. In most cases, out-of-pocket costs of transit are considerably less than those for the automobile for comparable trips. But the automobile almost invariably is preferred by the users. Obviously, then, the automobile provides the user with added "values" for which he is willing to pay an additional amount. Again, this points to the basic question: What is this value of transportation for which people pay differing amounts of money? The individual user prefers the automobile even considering the basic inadequacies of and dissatisfactions with today's highway transportation system. To the public official, i. e., from the point of view of the city government or other governing bodies, the transit system is preferable because of its surmised high capacity and low real estate and operating costs. Some of these public values of transit have been extolled as of late in numerous more or less factual professional and news articles. Nevertheless, transit patronage is not increasing. This again demonstrates that value is a highly controversial and changing item for each individual user. It adds the further complication that value differs from the point of view of the individual user on the one hand and from that of the society as a whole on the other, assuming that the civic governing bodies represent society as a whole.

Mr. Irwin deals with current possibilities for criteria and values. He shows possible approaches, but to any serious reader he shows that our present value scales and criteria are woefully inadequate to represent the problem. But unfortunately we have nothing better to suggest at this time. Therefore our needs are primarily in developing research to solve these problems.

Research Needs. It becomes fairly evident that essentially three steps are needed in the research program to provide answers to our problem, we must:

1. Define value of transportation despite its ambiguity, including its many and varying facets and its changes with time.
2. Establish practicable measurements of the value or its measurable facets.
3. Integrate these measurements in some way that makes possible the comparison of different transportation systems or services.

Discussion. So far, the discussion has been rather esoteric and it can easily be argued that the ideas may be all right but their implementation would be impossible. There are, however, some suggestions as to how one may go about doing the research as suggested.

A transportation user makes some rather definite decisions when he decides to buy transportation services. Appropriate analysis of this decision makes it possible to obtain some quantitative measures of values. Unfortunately, the aggregation of factors is such that a specific measurement of individual value facets is not easy. But this is exactly where good research intellect and modern technology are needed and can provide possible approaches. Society's value of transportation is somewhat more easy to determine when one considers that 20 percent of the gross national product is spent on transportation (not counting secondary inputs in transportation). In contrast to this known quantity, it might be interesting to study the amount of effort individual people spend daily on transportation. Such a study might be expanded to determine what criteria people use in their transportation choices and decisions.

The above problems are mentioned by Irwin briefly, but since he, no more than anyone else, knows of no appropriate answers nor an easy way to handle them, he moves on to other criteria to serve as substitutes for these basic items. This is appropriate when we are trying to solve today's problems. But research must be originated now to lay the groundwork for better solutions to the problems of tomorrow.

Research in these areas is practically nonexistent or, at best, confused. It is therefore necessary to under take both a conceptual development of the many interacting factors involved as well as a research design for obtaining very specific and quantitative data for all parts of this problem. Much of the problem is in the human factors area and needs sound research approaches which take human factors principles and methodologies into account. Some of the needed information might be adapted from existing concepts, models, or data worked out for different applications.

Recommendations. In conclusion, I should like to point out again that my arguments are aimed at developing more research to provide better answers in a field involving tremendous human investment and sparse understanding of the problem. I therefore recommend the following:

1. We must recognize transportation planning as a process which can be made orderly through the application of rational methods of analysis.
2. We should initiate and support research in those areas required for the implementation and for the working of the planning process. The real need is not only to do more research, but also to aim much of it at the basic human questions of transportation demand, generation, and distribution, for the individual as well as for society.
3. In order to provide workable measures for evaluation, such procedures as Irwin's "budget allocation criteria" might be developed as a first step. Such a method can be improved step by step as research makes available better basic data and evaluation criteria for the decision process.

Utilizing an evolution process with a heavy research backup, we should be able to develop an efficient framework which exists today only in outline form. Discussions might do as much to focus attention and establish needs as they contribute to the solution of the specific problem.

NEAL A. IRWIN, Closure—The viewpoints expressed in this discussion represent, in microcosm, the type of problems and discourses observed today in many urban areas confronted with transportation planning decisions.

Speaking from planning agency and consulting experience in a number of cities, Mr. Deen emphasizes the value judgments and criteria used by individuals in evaluating a transportation system. He points up the diversity of such value judgments and the resultant difficulty of distilling from them a meaningful consensus by which planners and decision-makers can be guided. He stresses the need for planners to include nonmonetary values in the plan evaluating process and their responsibility to make known the facts concerning all relevant alternative plans so that the political process of plan selection can be carried out in a sufficiently wide context.

As a transportation planner with fifteen years' experience on the New York City Planning Commission, Mr. Leiper highlights some of the practical problems experienced in the field, including difficulties in forecasting urban development, attaining transportation system flexibility, and obtaining community approval for new transportation facilities which may require some relocation of businesses or residences. As criteria for judging new plans he suggests efficiency of resource allocation, provision of a mix of both high quality and low cost transportation, system flexibility, and system feasibility.

Speaking as an academician, Dr. Breuning stresses the present lack of criteria which will be effective for long-term as well as short-term planning, and the need for research to develop such criteria and related evaluation methods. Among suggested avenues of research are analysis of decisions made by individual travelers, studies of the amount of time and resources committed to transportation by various individuals, and development of usable "budget allocation criteria" of the type outlined in the subject paper.

In summary, it is apparent that the criteria we seek are elusive. In working toward them we must follow a middle path between oversimplification on the one hand (the "single all-inclusive measure of excellence") and a know-nothing attitude, born of despair in the face of great complexity, on the other. Stated in other terms, we would be ill-advised to attempt avoiding the political decision-making process by reducing plan evaluation to a purely numerical exercise; however we, as technicians, must assemble and explore all ramifications of the most feasible alternatives so that the community and its leaders may have the best possible basis for decision.

A number of worthwhile ideas for research into plan evaluation criteria have been suggested in the discussion. Let us proceed along these lines and all others that look promising. We are starting from a rather small base.

Toward Optimal Planning of a Two-Mode Urban Transportation System: A Linear Programming Formulation

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The purpose of this study was to develop an analytical methodology or model for finding the optimal combination of two modes in providing transportation service. The specific case treated was that of providing automobile transport facilities and possibly some rapid transit facilities in a radial, downtown-oriented corridor. The objective was to find that combination of facilities which minimized transport costs—including both capital and operating costs of transit and auto transport—during the design or horizon year.

Since transportation is a service to its environment, the services provided were required to have certain attributes. The capacity of the two modes had to be capable of accommodating the peak period flows. Furthermore, the system had to be designed so that the peak period and non-peak period interzonal travel times did not exceed their respective maximum acceptable values. Because a two-mode system was dealt with, the modal choice behavior of travelers had to be incorporated into the model.

In order to insure the usefulness of the model, it was developed with reference to a specific real world situation in the Chicago area. The nature of the cost functions for the two modes and the constraints related to capacity, travel times, and modal choice was such that the prolem could be characterized within the framework of linear programming. This very efficient optimization technique was used to find the solution, which appeared to be quite reasonable.

•THE URBAN transportation planning process has been advanced to a high level of sophistication. It is now possible to predict future demand for transportation and to evaluate any transportation plan against that demand in terms of many different measures of performance. From any given set of alternative plans it is usually not difficult to select that one plan which is best according to some specified criterion, such as minimization of total annual cost subject to service constraints.

Despite the tremendous strides made in planning methodology, at least one serious weakness remains: the time and expense involved in developing and then evaluating an alternative plan precludes the consideration of the large number of plans which are quite different from one another yet are all reasonable alternatives and merit serious

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[1] Now with the Technical Analysis Division of the National Bureau of Standards.

consideration. In only a few studies, such as the Chicago Area Transportation Study (4), have a large number of highway alternatives been considered and evaluated. Even when this is done, highway planning and evaluation often proceed independently of that for public transportation. Under these circumstances it is very difficult to believe that near optimal network configurations and combinations of expressways, arterials, and mass transit facilities are found.

In this paper a mathematical model of urban transportation facilities in a radial corridor is presented. The purpose of the model is to circumvent some of the objections to conventional techniques. The essential attributes of various combinations of arterial streets, expressways and rapid transit, and the predicted demand for transportation are characterized within the framework of linear programming. This efficient computational technique is then used to find the optimum plan.

THE MODEL

This model considers the travel along a single corridor in an urban area. The objective function to be minimized is the total annual cost of transportation, during one design year:

$$\min \quad \left\{\begin{matrix}\text{annual road}\\ \text{capital cost}\end{matrix}\right\} + \left\{\begin{matrix}\text{vehicle operating}\\ \text{cost}\end{matrix}\right\} + \left\{\begin{matrix}\text{annual transit}\\ \text{capital cost}\end{matrix}\right\}$$

$$+ \left\{\begin{matrix}\text{annual transit}\\ \text{operating cost}\end{matrix}\right\} + \left\{\begin{matrix}\text{annual parking}\\ \text{facilities cost}\end{matrix}\right\}$$

The specific form of these cost functions is discussed in a later section, since these are based on empirical data. Assumed costs of the time of travelers, while used in several other transportation studies, is not included here. The authors feel that the value of time is so dependent on the amount under consideration and the time of day, as well as the individual, that the concept of an average value is probably not particularly useful. The constraint set includes various types of travel time constraints which we feel are more meaningful than some hypothetical value of time.

With the above formulation, transportation costs would be minimized by producing no transportation. However, since transportation is a service to its environment, this service must have certain attributes in order to meet the needs of the environment satisfactorily. These requirements are reflected in the constraints of the problem.

All transportation systems are characterized by a capacity limitation, and in this case, it is required that design capacity meet or exceed the predicted demand. It should be borne in mind that it is a choice of transportation decision-makers whether to provide sufficient capacity to meet demands—often at considerable expense—or to limit capacity and thereby force a displacement of some trips in time and space.

Another set of constraints refers to the maximum travel time which will be permitted for trips between the various possible origin-destination combinations. These constraints can be precisely the interzonal travel times assumed in trip distribution; thus, this concept of travel time constraints is useful in fitting this model into the existing urban transportation planning methodology.

These constraints also point out a public policy question regarding the level of service and accessibility which are to be given to each region. Within the technological constraints on speed there is nevertheless a wide range of choice as to level of service and accessibility, and these must be dealt with directly. Of course, public expectation as to reasonable travel times and the willingness to pay the price of speed and capacity significantly influence decisions here. In this program lower bounds on speed are specified along with the upper bounds imposed by technology, permitting the program to choose any speed within this range.

Since the program deals with both road transport and rapid transit, the behavior of people regarding modal choice must be taken into account. This is also done in a constraint set, which attempts to duplicate one of the more sophisticated modal choice models currently used in planning studies. The choice is based on such factors as door-to-door travel time, transit waiting time, out-of-pocket costs, trip purpose, and socio-economic status of the traveler.

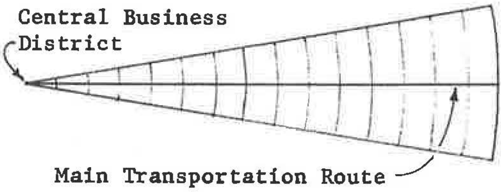

Figure 1. The region.

In order to demonstrate the usefulness of this model, it was implemented using cost and demand data from the Chicago area (1, 4, 6, 11, 14) and a modal choice model developed for the Washington area (8). The sole reason for these choices was the availability of data. It should be remembered that we are not solving for the actual optimum solution to Chicago's problem, because we are treating the problem assuming no rapid transit or expressways exist, and we are treating a hypothetical average Chicago area corridor, not a real one. These conditions were imposed by the difficulty of obtaining more complete and detailed data in the short time available. It is also emphasized that in any real world application it is necessary to obtain detailed cost and demand predictions for the region in question before this model can be expected to yield valid results.

Only the problem of transportation improvements in a radial corridor is considered. Because generally neither corridor travel demand nor costs follow any simple mathematical relationship with distance from the central business district, the 30-mi long corridor was divided into 2-mi long zones (Fig. 1). This permits approximations of any demand and cost distributions and greater accuracy, if desired, can be achieved by reducing zone length. Demands and travel times are treated on an interzonal basis, while cost parameters are uniform in each zone. In this particular application only travel to and from the central business district is considered, in order to simplify the computations, but the model can be used for all interzonal travel in the corridor.

Before discussing the model in detail, mention should be made of the relationship of this paper to the existing literature in the area. In this paper the concern is with the addition of capacity and improvement in the level of service in an existing network, where these additions can be in the form of incremental changes in existing streets or in the form of entirely new expressways or freeway-type facilities with the associated high threshold costs. The studies by Garrison and Marble (9), Carter and Stowers (3), and Quandt (12), however, are solely concerned with essentially continuous additions of capacity to existing facilities, while the work of Roberts and Funk (13) is concerned only with new investments of a very lumpy sort. Also, in our study the level of service to be provided is treated explicitly as a choice variable, subject to explicit constraints, whereas none of the other studies deal with this directly.

Beckmann (2) presents a very general and sophisticated model for freight flows, but this model is implemented by use of the calculus of variations. Unfortunately, algorithms for solving such problems have yet to be developed, so that his model is effectively not operational.

Creighton et al (7) treat investment in a two-mode system, but make some very questionable assumptions regarding the transport network configuration and the nature of cost characteristics. Moreover, it does not appear that systemic effects even on a link—much less a network—can be taken into account. We have attempted to develop the model so that it follows known cost functions and demand interrelationships closely.

This model also differs from the others mentioned in that it deals with only one corridor, not a complete network. Therefore, certain systemic effects cannot be dealt with. Nevertheless, it is felt that this model is useful, because in certain corridors—particularly radial corridors in larger cities—the flows are much larger than in the intersecting corridors.

THE OBJECTIVE FUNCTION

The cost functions for road transport, rapid transit, and parking are considered separately. The specific purpose of these functions is to relate the cost of producing transportation to measures of the amount and quality of the transportation produced. In each case some theoretical considerations are discussed first, and then the models are developed from data on actual systems.

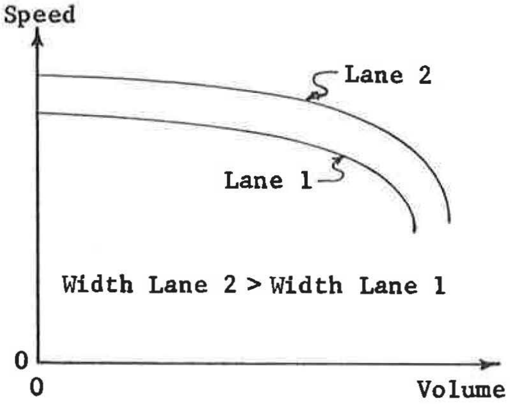

Figure 2. Lane capacity.

Road Capital Costs

The capital cost of highway facilities is related to the capacity of the road (the maximum vehicular flow rate it can accommodate) and the average speed at which this traffic moves. For one lane of any given road without signals or stop signs the speed and flow are related (Fig. 2). Thus an increase in speed with no change in capacity can be obtained by an increase in the number of lanes or, up to a point, in the width of lanes, both at an increase in cost. Similarly, increases in capacity with constant speed are associated with the expense of wider lanes or more lanes.

Because of these characteristics of flow, the capital cost function for a given length of road resembles the surface in Figure 3. This surface is drawn without discontinuities to represent changes in the number of lanes, because it is felt that changes in road width will provide for the specified changes in speed and capacity. In Figure 3 it is assumed that some sort of road already exists, for non-zero speeds and capacities can be obtained at zero cost. This is generally the case in urban areas, but the alternative can also be considered within the framework.

In the case where different road technologies are available the best for any given combination of speed and capacity can be determined rather easily. For graphical simplicity, consider one speed, with varying capacity. The cost curves might resemble those in Figure 4, with the choice of road type being that which yields lowest cost.

The above considerations lead to the linear road capital cost model for a road spanning zone i

$$C_i c_i + M_i \left(1 - \frac{m_i}{\bar{M}_i}\right) + S_i (m_i - s_i)$$

$$m_i \geq \underline{M}_i$$

$$m_i \leq \bar{M}_i,$$

$$s_i \leq m_i, \text{ and}$$

$$s_i \geq \underline{M}_i$$

where

C_i = annual unit capacity cost, \$ per vph;

c_i = capacity, vph;

M_i = annual unit peak period speed cost, \$;

m_i = peak period slowness, min/mi;

$\bar{M}_i$ = maximum (technological) slowness, min/mi;

$\underline{M}_i$ = minimum (technological) slowness, min/mi;

S_i = annual unit cost of additional non-peak period speed, \$ per min/mi; and

s_i = non-peak period slowness, min/mi.

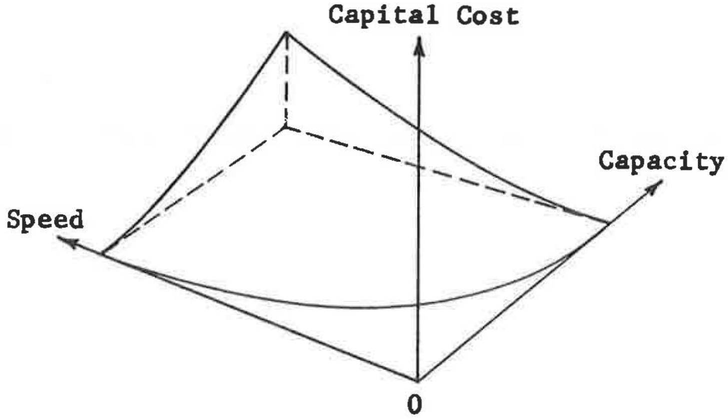

Figure 3. Road capital cost function.

Two factors require additional explanation: the use of minutes per mile or slowness rather than miles per hour or speed, and the inclusion of non-peak period speed. "Min/mi" was used so that the travel time between zone pairs would be a linear combination of the choice variables. Non-peak period slowness was included because it might be desirable to let a road operate at 30 mph, for example, during the peak period to keep capital cost low, but to design it so that non-peak drivers could safely drive at 50 mph during uncongested periods. Clearly there is an additional expense due to such features as longer acceleration and deceleration lanes on expressways and more adequate signing and signaling on arterial streets.

The parameters in this cost expression were estimated using data on some existing and proposed facilities in the Chicago area. Because of data limitations, no general validity is claimed for these estimates. As mentioned earlier, the purpose here is to demonstrate that this model is operational, not necessarily to solve a specific real world problem.

Costs for two different types of urban roads located near the central business district are plotted in Figure 5. The lower curve is for an arterial street with through-lane overpasses at major intersections, on which traffic can flow at about 2 min/mi. The upper curve is for a freeway type facility, designed for flow at about 1.2 min/mi. The other curves are based upon extrapolation with the linear model.

Costs for the arterials are taken directly from Haikalis (10), with an adjustment for the location. It was assumed that the ratio of downtown arterial to Haikalis' outlying arterial costs is the same as that ratio for freeways, \$15,500,000/\$12,000,000 = 1.29. This yielded an arterial cost of \$3,400,000 for a road with a 2,000 vph capacity at 2 min/mi. This total capital cost is converted to an annual cost with the assumption of a 30 yr life and an interest rate of 6 percent per annum, for an annual cost of about \$250,000 per mile of road.

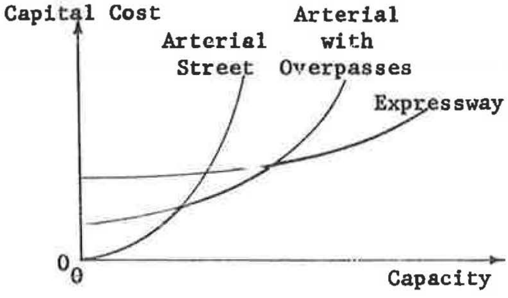

Figure 4. Choice of technology.

The freeway costs are based on the work of Aitken (1) and Satterly (14). Aitken reports that 6.4 mi of an 8-lane freeway entering the downtown area cost in average of \$15,500,000 per mi, or \$1,130,000 annually. According to Satterly the construction (but not right-of-way) cost of a

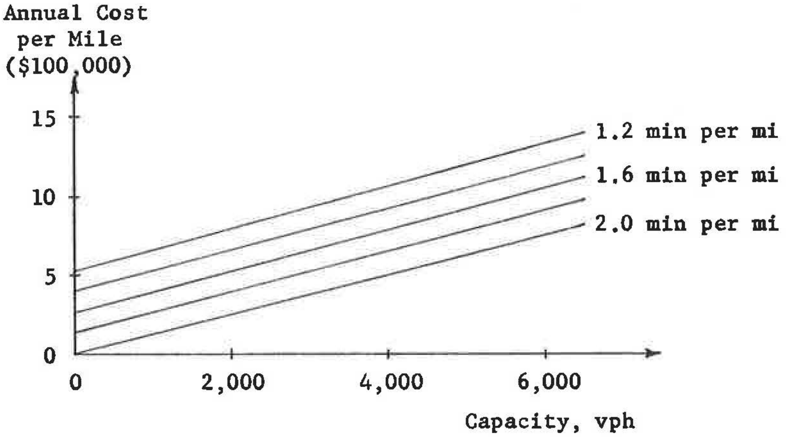

Figure 5. Cost surface for road near the CBD.

10-lane freeway with grade separations every one-half mile and interchanges every mile is $690,000 per lane-mi. Taking the marginal cost of a lane-mile to be Satterly's average construction cost plus one-half of Aitken's freeway right-of-way cost for one lane, the annual marginal lane-mile cost becomes $75,000. Each lane of a freeway can accommodate about 1100 vph at 1.2 min/mi. The resulting cost curve is as shown in Figure 5.

If the cost-slowness relationship is linear in the range of speeds under consideration (Fig. 6) the parameters can be evaluated readily. Unfortunately no data were available on high capacity urban roads built for travel times within the range of 1.2-2.0 min/mi, probably because none have been constructed recently, so that this assumption could not be tested.

The resulting parameter values for a two-mile roadway are as follows:

C = $250 per vph,

$\bar{M}$ = 2.0 mi/mi,

$\underline{M}$ = 1.0 min/mi,

M = $3,000,000, and

S = $600,000 per min/mi.

Since no information was available on the costs associated with S, this value was established from the educated guess that it would cost about $4,000,000 to improve the roadway design so as to permit an increase in speed, at a very low traffic volume, from 30 mph to 60 mph.

All autos entering the central business direct must be stored, and therefore parking costs must be included. The cost of constructing ramp garages in the Chicago Loop during 1954 and 1955 varied from $2,260 to $2,830 per space (6), so an approximation of $2,500 per space is used here. Assuming that demand patterns dictate that three spaces be provided for each one required during the peak hour, the annual cost coefficient becomes $550 per peak hour space. This can be added directly to the road cost coefficient for zone 1 to yield the capacity cost coefficient for that zone.

The cost coefficients for all other zones were developed in a similar manner, with the omission of parking costs. These gave a reasonably accurate representation of the rather scanty historical costs available. All of the coefficients are given in Table 1.

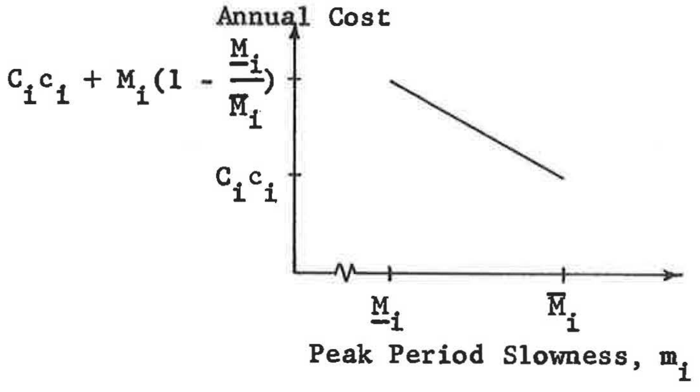

Figure 6. Cost as a function of m_i, with $m_i = s_i$.

TABLE 1

OBJECTIVE FUNCTION COEFFICIENTS

Zone	Coefficients				
i	C_i (\$/vph)	M_i (\$)	S_i (\$/min/mi)	P_i (2/pass./hr)	V_i (\$/veh-mi)
1	800	3,000,000	600,000	253	16.80
2	200	2,500,000	500,000	253	16.80
3	170	2,000,000	400,000	253	16.80
4	120	1,600,000	300,000	253	16.80
5	70	1,200,000	200,000	253	16.80
6-15	40	800,000	100,000	313	16.80

Vehicle Operating Costs

Vehicle operating costs are based on information given in Smith (15). We assume that one-half of the drivers using transit would get rid of the car which would otherwise be used for the trip, and therefore one-half of the auto users should be charged the marginal operating costs of driving, whereas the other half should be charged with the full costs.

Total operating costs, exclusive of garaging, parking, and tolls	\$0.0751 per veh-mi
Marginal operating costs	0.0368
	\$0.1119 per veh-mi

Average operating costs = 11.19/2 = \$0.0560 per veh-mi. Converting this figure to an annual basis, using 300 equivalent days per year, V = \$16.80 per daily veh-mi.

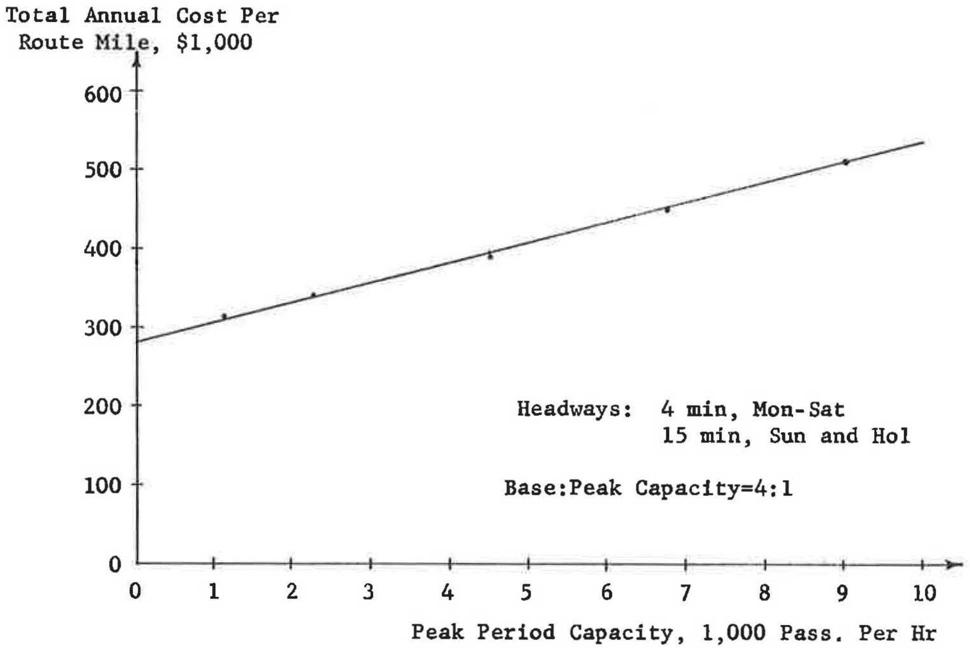

Figure 7. Annual rapid transit cost and capacity.

Rapid Transit Costs

The rapid transit costs used in this study are based entirely on a separate model of rail transit costs developed previously by Morlok. This model relies heavily on the data found in Lang and Soberman (11), and is similar to their model. It does, however, distinguish more completely between fixed and marginal costs than their model.

Although it would be inappropriate to discuss this model in detail here, the essential characteristics are as follows. The model represents a conventional rail transit line operating on a two-track elevated structure of modern design, which costs about $3.5 million per mi. Only high-speed, air-conditioned cars are used, but no automation of train operation or fare collection is assumed. Trains are operated for 16 hours of every day, and all passengers are provided with seats during the entire operating period.

In this model total annual costs can be predicted from capacity and headway during weekday peak periods, weekday non-peak periods, Saturdays and Sundays and holidays. Headways are fixed at 4 min during weekdays and Saturdays, and at 15 min on Sundays and holidays. Saturday, Sunday, and holiday capacity was set at one-eighth of that during weekday peak periods, and weekday non-peak period capacity was set at one-fourth peak capacity. These specifications leave peak period capacity as the only choice variable, yielding a cost function of the form

$$C_{rt} + \sum_{i=1}^{n} P_i p_i$$

where

C_{rt} = annual capital cost of rapid transit, $;

P_i = annual cost per unit of peak capacity, $ per pass./hr;

p_i = peak period transit demand from zone i, pass./hr.

Cost estimates based upon Morlok's model are given in Figure 7. The cost coefficients for a 10-mi long route—the length of the transit line to be considered in this example problem—are fixed cost, \$2,870,000, are variable cost, \$253 per pass./hr. (The use of an externally specified transit line length will be explained in the final section. Suffice it to say here that for each run of the program, costs will be minimized for a given transit route length, which is arbitrarily chosen at 10 mi for this example. The program is run for each of the possible transit line lengths, of which there are generally only a few reasonable alternatives.)

In addition to train expenses, parking costs vary directly with the capacity of the system. The unit parking cost used was that of constructing the lot at the outer terminal of Chicago's Skokie Swift line in 1964, approximately \$275 per space (5). Again assuming a total of three spaces must be provided for each space required during the one peak hour, and that these facilities are paid for in 30 years at 6 percent interest, we have an annual parking cost of \$60 per peak pass./hr.

Including the parking costs, the final cost coefficients for a 10-mi long transit line are as follows:

C_{rt} = \$2,870,000,
P_i = \$253 per pass./hr, $i = 1, 2, \ldots, 5$, and
P_i = \$313 per pass./hr, $i = 6, 7, \ldots, 15$.

THE CONSTRAINTS

This section examines the set of constraints which characterize our problem. The equations related to capacity, modal choice, level of service, and the calculation of vehicle-miles are considered separately.

Linearity

Our constraints as well as our objective function are, of course, in linear form. The real world is obviously not that neat. We do not feel, however, that any unjustifiable liberties were taken in achieving linearity. For one thing, all the relations did, in fact, closely approximate linearity, at least in the range which was relevant for the problem. Furthermore, no sharp discontinuities are apparent, suggesting that a linear approximation will not give vastly unrepresentative results. Finally, and most important, nonlinearity has not proved destructive of linear programming in the past due to the existence of techniques such as piecewise linear approximation. Though the problem would no doubt become substantially more complicated, there is no reason to believe that such techniques could not be used here. It is left to critics to show that even a complicated problem is not superior to the next best technique available for the solution of such an urban transportation problem.

Capacity

The capacity constraints are of the form

$$Ec_j + \sum_{i=j}^{n} p_i \geq \sum_{i=j}^{n} D_i \qquad j = 1, \ldots, k$$

$$Ec_j \geq \sum_{i=j}^{n} D_i \qquad j = k + 1, \ldots, n$$

where

c_j = capacity of the road in zone j, vph;
E = 1.5 persons per vehicle, average automobile occupancy;

p_i = peak hour transit passengers originating in zone i, pass./hr;

D_i = total number peak hour passenger trips generated in zone i, persons/hr; and

k = the last zone served by transit.

The D_i are generated from the estimated 1980 population figures in each radial ring as estimated by CATS (4). The ratio of trips to population for 1956 is given as 0.163. This figure is retained for 1980. Since we are dealing with a corridor representing one-seventh of the population, the D_i are given by applying a coefficient of 0.0023 = (1/7) (0.163) (0.1) to the CATS figures. The 0.1 is to convert daily into peak hour passengers given that approximately one-tenth of daily trips are made during the peak hour. The specific D_i are presented in Table 2.

TABLE 2

PEAK PERIOD TRIP GENERATION

Zone i	Trips D_i (persons/hr)	Zone i	Trips D_i (persons/hr)
1	356	9	1040
2	1281	10	1076
3	2139	11	1006
4	1976	12	1027
5	1868	13	1093
6	1391	14	584
7	1325	15	720
8	951		

This set of constraints stipulates that the total transportation capacity of the zone must at least equal the number of passengers who will pass through that zone during the peak hour. Obviously, if the capacity of the system is sufficient to meet peak hour demand, it will, because of the definition of peak hour, be able to meet all remaining demand as well. We have taken the peak hour demand to represent 10 percent of the daily total, and have estimated that 40 percent of total daily demand will occur under peak hour conditions, i.e., there are four "equivalent" peak hours. This latter consideration is important in estimating the modal split since the split will, in general, be different during the peak and off-peak periods. While c_i represents a true capacity (since it will not, in general, be reached except during peak periods), p_i is both the demand and the capacity for rail transit. Thus we assume that the rapid transit line is operated with no excess seating capacity at the location of maximum loading during the peak hours. This set of constraints, then, because of this identity, can be seen as stipulating the road capacity in each zone.

Modal Choice

The modal choice constraints are of the form

$$p_j = A_j \sum_{i=1}^{h} m_i + B_j \qquad h = j \text{ if } j \leq k \text{ and } h = k \text{ if } j > k$$

where

A_j, B_j = empirical constants related to modal choice characteristics and D_j.

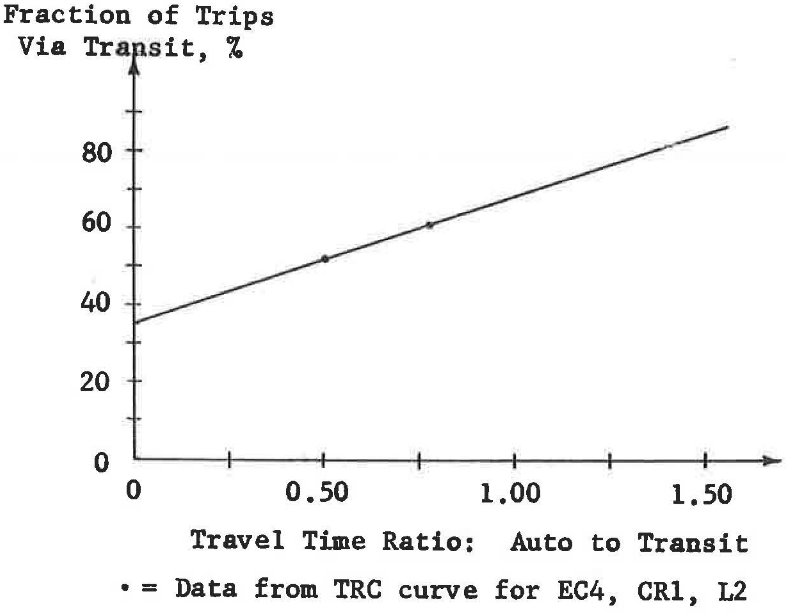

Figure 8. Example modal choice curve.

As previously explained m_i denotes the slowness of the road system in zone i, during peak hour conditions. The basis for these equations is the Deen, Mertz and Irwin report (8), in which the percentage of passengers going by transit is formulated as a function of the ratio of travel times of the two modes with certain cost and service characteristics entering as parameters, along with the income class of the group. Their curves, which express transit travel as a function of travel time by transit to that via automobile, were not, in general, of linear shape. However, we found that by plotting

TABLE 3

MODAL CHOICE EQUATIONS

Income Range ($/family/yr)	Zones i	Equation
3100 or less	2	$\frac{P_i}{D_i} = 0.65 + 0.125\ (TTR)^a$
3100-4700	3	$\frac{P_i}{D_i} = 0.60 + 0.100\ (TTR)$
4700-6200	4	$\frac{P_i}{D_i} = 0.35 + 0.350\ (TTR)$
6200-7500	1, 5, 6	$\frac{P_i}{D_i} = 0.35 + 0.333\ (TTR)$
7500 or more	7-15	$\frac{P_i}{D_i} = 0.17 + 0.500\ (TTR)$

[a] TTR = Travel time ratio, auto to transit

the percentage of rail passengers against the inverse of their travel time ratio, we achieved a very nearly linear relation. An example curve is shown in Figure 8, and the equations are given in Table 3.

Deen, Mertz and Irwin (8) further divide their split estimates into work and non-work groups, but the data from which they derived the non-work estimates were so sparse that we ignored the minor differences between them and used their work trip relationships for all trips. There are still two modal split equations for each zone, however, since the peak hour travel time ratio and demand will, in general, be different from the non-peak ratio. Only the peak hour mode choice equations will affect the capacity constraints because of the definition of road capacity.

Three points should be made concerning the modal split equations. First, the relative income status of each zone was assigned on an intuitive basis aided by the author's experience in the Chicago area. A more rigorous method of assignment is, of course, desirable, but, unfortunately, not readily available on a zone-by-zone basis. Secondly, the Deen, Mertz and Irwin equations were derived primarily from data for Washington, D. C. It is assumed that these relations are valid for Chicago, partly because such features as income status are separated out of the equations as parameters. The ultimate reason for the assumption is, as always, the lack of such data for Chicago. Finally, it should be noted that as the equations stand there is nothing in the mathematics which would prevent the percentage of passengers going by rail from exceeding 100. Ideally one would like to be able to formulate the equations so as to prevent this possibility without putting restrictions on the travel time ratio. Unfortunately there seems to be no easy way of doing this without substantially cluttering up the model or resorting to nonlinear equations. However, the use of upper and lower bounds on slowness for both technological and service reasons not only serves these primary purposes but these constraints should also in general act to retain the percentage going by rail well within the 0-100 range. An additional check is present in the constraints which limit total travel time.

The travel time ratio for zone j which appears in the modal split equations of Table 3 is of the following form

$$\frac{\sum_{i=1}^{h} L_i m_i + H_h}{\sum_{i=1}^{h} L_i R + W_j} \qquad \begin{array}{l} h = j \text{ if } j \le k \\[1em] h = k \text{ if } j > k \end{array}$$

where

L_i = length of zone i (two miles for all zones);

H_h = average time required for the traveler to go from his home to the main corridor highway plus the time required to travel from the highway in the CBD to his destination when h = j (i. e, j ≤ k) or simply the average time from the highway to his downtown destination when h = k (i. e., j > k) since the travler in this instance is already on the highway and is considering the benefits of transferring to rail at zone k—thus, in our modal choice equation, only the time still left to be spent traveling is relevant;

R = uniform average slowness of transit, min/mi; and

W_j = average walking and waiting time to and from the transit station when zone j is served by transit (both ends of the trip), or the average transfer and waiting time for transit when zone j is not served by transit, plus the walking time at the downtown end.

When numbers are chosen for the H_h and W_j and the value of R is entered, the modal choice equations take the form shown in the constraints. For our example we use H_h = 15 min for j ≤ k, H_h = 8 min for j > k, W = 5 for all zones, and R is a uniform 1. 89 min per mi.

The third set of constraints in this group is of the form

$$d_j = X_j \sum_{i=1}^{h} m_i + Y_j \sum_{i=1}^{h} s_i + Z_j \qquad h = j \text{ if } j \le k \text{ and } h = k \text{ if } j > k$$

where

d_j = daily travelers from zone j traveling via transit, pass./day; and

X_j, Y_j, Z_j = empirical constants related to modal choice characteristics and D_j.

Thus the sum of peak and off-peak demand, d_j, is obtained from a set of equations identical in form to those appearing in the previous set of constraints with the exception that s_i, slowness in the off-peak periods, is used in addition to m_i. This set of constraints is, as seen, composed of equalities which are used in the next set to determine total vehicle-miles for the purpose of deriving operating costs of automobile travel.

Vehicle-Miles

The constraints which determine total daily vehicle movement are

$$v_j = \frac{2}{E}\left(\sum_{i=1}^{j} L_i + F_j + G\right)(10D_j - d_j) \qquad j \le k$$

$$v_j = \frac{2}{E}\left(\sum_{i=1}^{k} L_i + G\right)(10D_j - d_j) + \frac{2}{E}\left(\sum_{i=k+1}^{j} L_i + F_j\right)(10 \cdot D_j) \qquad j > k$$

where

v_j = total daily automobile movement due to trips generated in zone j, veh-mi;

F_j - average distance from the home to the main corridor road, mi; and

G = average distance from the main corridor road to the downtown parking location, mi.

In this problem we took F_j as 3 mi for all zones and G as 2 mi.

These last two constraint sets, giving daily transit travel and vehicle-miles of automobile movement, could have been collapsed into one set. The reason for this is that daily transit travel does not enter directly into the criterion function and there is a unique relationship between daily transit travel and vehicle-miles of travel for each zone. But these were left separate so that the solution would include the important statistic of total daily transit travel for each zone.

Level of Service

The constraints on level of service imposed by current highway technology, reflected in the upper and lower bounds on slowness in this program, have already been discussed. In addition, a set of overall travel time constraints is included:

$$\sum_{i=1}^{j} L_i m_i \le T_j \qquad j = 1, 2, \ldots, n$$

and

$$\sum_{i=1}^{j} L_i s_i \le T'_j \qquad j = 1, 2, \ldots, n$$

where

T_j = maximum peak period travel time from zone j to the downtown, min; and

T'_j = maximum non-peak period travel time from zone j to the downtown, min ($T'_j \leq T_j$).

These specify that the total travel time from any particular zone to the CBD be not greater than an externally defined number. In general any model which attempts to specify facilities to meet a target demand should first be able to satisfy the total travel times assumed, since that factor is an important element in determining future demand. However, in other models of this type, it is often found that the travel time which is generated by the facilities which are planned is different from that which was specified in order to predict demand. It is then necessary to start the problem again with a different total travel time, correspondingly different demands and facilities, etc. It is hoped that this procedure will lead eventually to a solution which is consistent with the assumptions. It is clear that this problem is avoided in our model. The total travel time and therefore the demand can be specified with certainty and entered as a constraint.

In our problem we chose to include only three sets of travel time constraints, feeling that 30 mph travel was satisfactory for zones within 18 mi of downtown. These constraining travel times are given in Table 4.

RESULTS

The Matrix

At this point, we can present the complete matrix of the linear programming problem:

$$\min \sum_{i=1}^{n} \left(C_i c_i + M_i \left(1 - \frac{m_i}{M_i}\right) + S_i (m_i - s_i) + V_i v_i + P_i p_i + 0 \cdot d_i\right) + C_{rt}$$

Subject to

$$Ec_i + \sum_{j=i}^{n} p_j \geq \sum_{j=i}^{n} D_j \qquad i = 1, 2, \ldots, k$$

$$Ec_i \geq \sum_{j=i}^{n} D_j \qquad i = k+1, k+2, \ldots, n$$

$$p_i = A_i \sum_{j=1}^{i} m_j + B_i \qquad i = 1, 2, \ldots, k$$

$$p_i = A_i \sum_{j=1}^{k} m_j + B_i \qquad i = k+1, k+2, \ldots, n$$

$$d_i = X_i \sum_{j=1}^{i} m_j + Y_i \sum_{j=1}^{i} s_j + Z_i \qquad i = 1, 2, \ldots, k$$

$$d_i = X_i \sum_{j=1}^{k} m_j + Y_i \sum_{j=1}^{k} s_j + Z_i \qquad i = k+1, k+2, \ldots, n$$

$$v_i = \frac{2}{E}\left(\sum_{j=1}^{i} L_j + F_i + G\right)(10 \cdot D_i - d_i) \qquad i = 1, 2, \ldots, k$$

$$v_i = \frac{2}{E}\left(\sum_{j=1}^{k} L_j + G\right)(10 \cdot D_i - d_i) + \frac{2}{E}\left(\sum_{j=k+1}^{j} L_j + F_i\right)(10 \cdot D_i)$$

$$j = k + 1, k + 2, \ldots, n$$

$$\sum_{j=1}^{i} L_j m_j \le T_i, \qquad i = 1, 2, \ldots, n$$

$$\sum_{j=1}^{i} L_j s_j \le T'_i, \qquad i = 1, 2, \ldots, n$$

$$m_i \ge \underline{M}_i, \qquad i = 1, 2, \ldots, n$$

$$m_i \le \bar{M}_i, \qquad i = 1, 2, \ldots, n$$

$$s_i \le m_i, \qquad i = 1, 2, \ldots, n$$

$$s_i \ge \underline{M}_i, \qquad i = 1, 2, \ldots, n$$

The tableau is shown in Figure 9.

TABLE 4

MAXIMUM TRAVEL TIMES

Zone i	Maximum Travel Time to Inner End of Zone 1: Peak Period T_i (min)	Non-Peak Period T'_i (min)
10	35	30
13	41	36
15	45	40

TABLE 5

FRACTION OF FLOW VIA TRANSIT IN ZONES 1 TO 5

Zone i	Fraction of Flow via Transit: Peak Period (%)	Daily (%)
1	78.2	78.2
2	77.8	77.8
3	77.2	77.2
4	77.8	77.8
5	76.8	76.8

TABLE 6

FRACTION OF TRIPS VIA TRANSIT

Zone i	Fraction of Trips Via Transit: Peak Period (%)	Daily (%)
1	99.0	99.0
2	85.2	85.2
3	74.1	74.1
4	79.1	79.1
5-6	75.5	75.5
7-15	78.0	78.0

TABLE 7

ROAD DESIGN SPEEDS

Zone i	Design Speed: Peak Period (mph)	Non-Peak Period (mph)
1-5	30	30
6-7	30	60
8	40	60
9-15	60	60

$c_1..c_i..c_n$	$m_1..m_i..m_n$	$s_1..s_i..s_n$	$v_1..v_i..v_n$	$p_1..p_i..p_n$	$d_1..d_i..d_n$	Variables
$C_1..C_i..C_n$	$...S_i-\frac{M_i}{\overline{M}_i}..$	$-S_1.-S_i.-S_n$	$V_1..V_i..V_n$	$P_1..P_i..P_n$	0...0...0	Costs
$E_1.$ $.$ $E_i.$ $.E_n$				1...1...1 .. 1.1...1	$\geq\sum_{j=i}^{n} D_i$	Capacity
$A_1.$ $:\ .$ $A_i.A_i$ $A_n.A_n$				1. .. 1 .. 1	$=B_1$ $=B_i$ $=B_n$	Peak Mode Choice
$X_1.$ $.\ .$ $X_i.:X_i$ $X_n.X_n$	$Y_1.$ $.\ .$ $Y_i.:Y_i$ $Y_n.Y_n$				1 $=Z_1$ .. 1 $=Z_i$ .. 1 $=Z_n$	Daily Mode Choice
		1 .. 1 .. 1			$U_1.$ $=W_1$ $U_i.:U_i$ $=W_i$ $U_n.U_n$ $=W_n$	Vehicle-Miles
$L_1.$ $.\ .$ $L_1..L_i.$ $L_1..L_i..L_n$					$\leq T_1$ $\leq T_i$ $\leq T_n$	Peak Travel Time
	$L_1.$ $.\ .$ $L_1..L_i.$ $L_1..L_i..L_n$				$\leq T'_1$ $\leq T'_i$ $\leq T'_n$	Non-Peak Travel Time
1 .. 1 .. 1					$\leq\overline{M}_1$ $\leq\overline{M}_i$ $\leq\overline{M}_n$	Upper Bound, Peak Slowness
1 .. 1 .. 1					$\geq\underline{M}_1$ $\geq\underline{M}_i$ $\geq\underline{M}_n$	Lower Bound, Peak Slowness
1 .. 1 .. 1	-1 .. -1 .. -1				≥ 0 ≥ 0 ≥ 0	Upper Bound, Non-Peak Slowness
	1 .. 1 .. 1				$\geq\underline{M}_1$ $\geq\underline{M}_i$ $\geq\underline{M}_n$	Lower Bound, Non-Peak Slowness
c_i, v_i, p_i, $d_i \geq 0$, $i=1,2,...,15$						

Figure 9. The tableau.

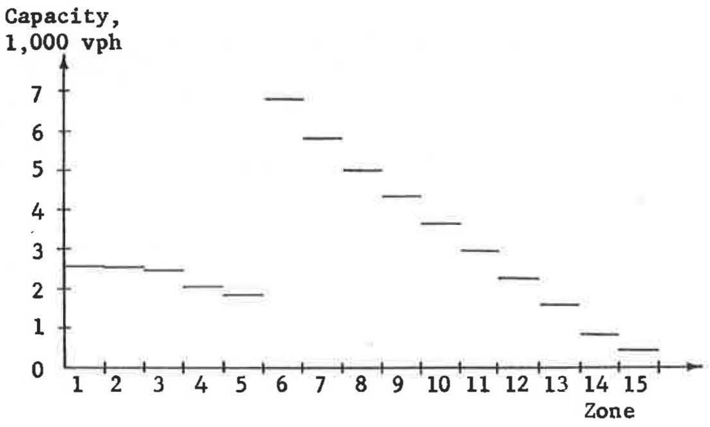

Figure 10. Road capacity at peak period speeds.

Solution and Interpretation

The main results of the computer program are presented in Tables 5 to 7 and Figure 10 which indicate, respectively, the percentage of traffic handled by rail in zones 1 to 5, the percentage of passengers from each zone who go by rail (within the last 10 miles), the peak and non-peak speeds, and the prescribed road capacity for each zone. Of course, the program is designed to yield normative rather than descriptive results, but one is comforted when the prescribed results are in the same vicinity as observations of current conditions. This seems to be the case with our particular example. For instance, the values in Table 5 coincide well with the empirical observation that 87 percent of Chicago's current peak hour downtown oriented traffic goes by transit.

The optimal choice is to build the more expensive high speed facilities in the outer zones, provided the travel time constraints can be met. This is in contrast to the planning in many areas where full freeways are called for even in the heart of downtown areas. However, if in our problem lower travel times in the zones near the downtown areas are desired, higher type facilities would have to be constructed in those areas also.

The dual to the road plus transit capacity constraints appears to be amenable to interpretation. As expected, the constraints are satisified with equality and hence the duals exist and are positive. They range from $5300 in zone 1 to $.027 in zones 7 to 15. This we interpret representing the maximum amount one could profitably bribe a passenger in a given zone to do his traveling through that zone during an off-peak hour.

From Minimum to Minimum Minimorium

At this point we attempt to explain the meaning to the solution we have found. We have set the length of the transit system at 10 miles (extending through zone 5) and have set up the program to select those values of the choice variables which minimize the total annual cost of building and operating the multi-mode system subject to the constraints, given that k = 5. The value of the objective function at the optimum is approximately $52.3 million to which must be added the capital cost of the given transit system (since this is constant for a given length transit) to arrive at the total annual cost of the given program—$55.2 million. This, of course, is only a minimum. To find the overall solution we must select that value of k, the length of the transit line, which yields the minimum minimorium; in other words, that complete system for which total annual cost (including capital costs) is minimized. The complete problem, then, requires additional runs of the program in which some (but not all) of the coefficients will change.

We feel that we are justified in restricting k to a few values because of the real world observation that transit stations and the corresponding parking lots are feasible at only certain points. Further, if the curve relating total costs to transit length represents any kind of a smooth function we can be reasonably confident that allowing k to take on continuous values will not have any significant effect on the solution.

Extensions

The model oversimplifies the real world in two important respects which we feel should be the main targets for additional research and refinement. First, the model deals with a single corridor, one of seven rays emanating from the CBD. The ideal program should treat the entire network, including the radial and circumferential facilities. Second, the notion of planning for a target year, although frequently employed, is patently unrealistic. The program should be dynamized to find that sequence of construction of new facilities and extension of existing ones which would optimize some cost criterion while providing transportation for a population which is expanding year by year rather than in discrete jumps of twenty years. However, although the solution we have presented does not fully represent the needs of the real world, we feel that it provides a good point from which to begin.

SUMMARY

This paper presents a linear programming model of an urban transportation problem, viz, the design of a two-mode transportation system in an urban corridor for a target year. The specific example used to test the feasibility and efficiency of the model employed data for the city of Chicago for a target year of 1980. The model differs from other methods of solution in that it selects that system which is optimal among all possible systems of a given type rather than merely examining a small number of alternatives.

The objective function to be minimized represents the total annual cost of the entire system. The standards of service are specified in the constraints. The primary choice variables are the transit capacity, the highway capacity, and the peak and off-peak highway speeds. The length of the transit route enters parametrically but by a finite number of runs of the program this also becomes a choice variable.

The model does not force any persons to a particular mode of transportation against their will, except insofar as the transit line extends only a certain length into the corridor. Rather, each individual makes his choice on the basis of several parameters, the most significant of which is the relative travel time of the two modes. It is these travel times which are the primary operational variables of the planners.

The model proved computationally feasible and appeared to yield reasonable results. Certain caution is urged, however, in the use of the model without the proper data. Furthermore, the model represents only a first (but important) step in the approximation of reality; the usual trade-off between model validity and operational ease still remains.

We hasten to assert that much of the application of linear programming to real world problems represents a learning process. One starts with a basic model and tests for validity and feasibility. This is what we have done. Moreover, one gains insights into what must be added to the model and how it might be changed by examination of the results of the simple problem. The theoretical work is not yet completed. But perhaps the most vital area of work which remains is the empirical. The model, as a tool for practical policy, is a function of its coefficients. Without the proper coefficients or at least reasonable approximations the model remains an abstraction.

ACKNOWLEDGMENTS

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Discussion

EDWARD F. SULLIVAN, Tri-State Transportation Committee—Mr. Morlok and Mr. Hay under Dr. Charnes' direction have made an interesting attempt at applying the power of linear programming to development of urban transportation plans. As the authors are quick to point out, their work is just a beginning. But they have pointed the way towards development of mathematical programming methods which might provide assistance to transportation planners and decision-makers. Although the complexities of transportation system capacities and demands defy simple formulation, mathematical programming (linear, dynamic, etc.) holds sufficient promise to warrant encouragement of further development of such methods for transportation planning.

What may we expect of mathematical programming? It is not simply another set of formulas. Rather, it is a conceptual approach in which an entire system is described in a comprehensive (even though simplified) way, from the viewpoint of how to allocate resources most effectively for a whole enterprise—in our case, the transportation system.

An integrated transportation system offers a wide choice of alternatives. Different costs are associated with different operational and investment alternatives. Resources are allocated to the component parts of this integrated enterprise. In a business the ultimate objective is to allocate resources to maximize overall profitability. This objective applies equally well to a public enterprise (such as transportation) if instead of "profit" we say "difference between gains (benefits) and costs."

In linear programming an objective (cost) function describes an economic objective in terms of which the system is described. Operational variables describe the interdependence of various activities of the system corresponding to physical conditions. Investment variables establish the physical configuration of the system and introduce the effect of additional capacity on operations. The value taken by the cost function depends on the values assigned to all of the operational and investment variables. Determining the best plan of action or the "optimum solution" for a transportation system consists of finding a set of values for all the variables so as to maximize (or minimize) the cost function while, at the same time, satisfying all the relationships which describe the physical operation of the system. This set of interrelationships includes not only equations describing interdependency, but also inequalities which describe limitations imposed on the system.

Sets of optimum solutions can readily be generated corresponding to various levels of demand and facility investment. Likewise, the results of different policies can be tested by restatement of the objective function. For example, we might examine optimal solutions based on minimizing total transportation costs, minimizing public costs, or maximizing benefits minus costs. Useful by-products are generated with each solution which make it possible to study the sensitivity of each variable, and costs imposed by each constraint. Coefficients can be checked to see how far their values might be changed before changing the strategy indicated by the solution.

Thus, mathematical programming is a potentially powerful tool for transportation system development and evaluation. It deals efficiently with large amounts of information and can explore systematically a great number of alternatives and restrictions characterizing the functioning of a complex transportation system.

The paper under discussion meets some of these expectations, but falls short of others.

In the model, transportation costs (both capital and operating) are minimized. Limits to be satisfied include demand volumes, minimum speeds and maximum times. Cost formulas reflect capital and operating costs corresponding to facility demand levels. Another formula determines mode choice as a function of auto vs transit travel time.

A noteworthy feature inherent in this approach is that the formulas describe all feasible possibilities within a broad range. Within this range of feasible solutions, the most economical combination is found by systematically converging calculations. The authors have set out to provide a means for assuring that alternatives considered in the transportation planning process are within the optimal range, taking into account the cost and performance characteristics of the various elements of the highway and transit systems.

The general applicability of the method as presented is severely limited by the simplified assumptions, such as dealing only with CBD trips through one corridor. Recognizing that in this first effort such assumptions were necessary to keep the problem manageable, the question remains whether a more comprehensive description of the system might be achieved.

The only operational variable is highway speed. Within the model the percent using transit varies only with the travel time ratio (auto/transit). Person trip demands are held fixed, and only CBD trips within a single corridor are considered. Thus, there is no provision for changes in magnitude or orientation of demand with changes in capital investment. Whereas the model does reflect changes in mode usage in response to system investment, it does not reflect changes in trip orientation, which may be of equal significance. Therefore, the optimal linear programming solution would have to be checked by more explicit system-wide trip distribution and assignment.

Likewise, the only investment variable relates highway capital cost to highway speed. Here, the formulation seems needlessly oblique, expressing the increments in cost incurred to provide sufficient capacity to maintain levels of service. The off-peak term seems an unnecessary and unlikely provision, since it is difficult to conceive of saving significant costs by reducing geometric and traffic design standards. The other investment variable, transit capital cost, is actually introduced as a constant.

The fixed set of person trips implies the same average length of trip, regardless of mode. Recent evidence seems to point to longer CBD trips by transit than by auto. This greater length is a counterbalance to the small increment of transit trip cost with distance (Fig. 7).

Only one set of highway capital costs is employed (Fig. 5). It appears that existing facilities can be handled by the present model simply through appropriate cost coefficients. Further development of the model might well incorporate highway cost as a function of area characteristics such as development density.

The assumption of one radial road competing with a transit line in each corridor is troublesome, leading to gross assumptions, such as an average of 3 miles from home to the radial road and 2 miles from the road to downtown parking. Such a constant assumption may well dictate the solution more than the variables. It also neglects to reflect alternatives within the highway system, such as sharing the traffic load between arterial streets and freeways. In other words, the description of the system is not explict enough to describe its operation properly.

The model does not consider whether the optimum solution is fiscally feasible. Calculations of highway and transit revenues, however, could readily be made from the outputs, along with the assumptions regarding fares and tax revenues. If the optimum solution were too costly, re-orientation of demand might be indicated, or constraints would have to be relaxed, such as lowering minimum speeds. Conversely, the cost of providing better service could be assessed by tightening the constraint limits.

In summary, these remarks are intended to encourage further explorations into applying mathematical programming to transportation system planning.

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KENNETH J. SCHLAGER, Southeastern Wisconsin Regional Planning Commission—It is important to comment that the relative lack of previous interest in design models as opposed to forecasting models is indicated by the fact that only one paper presented herein deals with a design model. The other models are related to forecasting and policy formulation problems. The lack of plan design models, or at least conceptual plan design frameworks, has severely limited the determination of requirements for data collection and analysis in urban transportation studies. The largest costs in urban transportation planning relate to the collection and analysis of data. The great majority of these data are used for describing the current state of the system and for forecasting probable future development. Very little data are collected that allow for the consideration of alternative plan designs. Since most studies do not provide for such data, much less a model framework for evaluating plan designs, the degree to which real alternatives are considered in a final plan is open to questions. Transportation planning seems to be in the same situation as defense planning was in this country before the planning-programming-budgeting approach to planning that for the first time allowed for the consideration of alternatives to meet stated objectives.

In the area of model formulation, one question that might be directed at the paper is the treatment of a transportation plan design without regard to land use. It has become an accepted concept in urban planning that transportation and land use interact. At the very least, transportation models should be constrained by land-use requirements because one of the possible solutions to a transportation model so constrained is that no new transportation facilities will be needed at all. Difficulties exist sometimes in quantifying certain land-use constraints in a transportation model, but an imperfect quantification of such constraints is usually better than ignoring such constraints altogether.

Many of the practical problems raised by such a model relate to the estimation of costs used in the model. Previous estimations of transportation costs have not usually been in a form suitable for use in design models. Much work remains to be done on the estimation of capital costs and costs relating to the operation of the transportation system. It is also important that such costs be developed so as to allow the consideration of real transportation alternatives. Transportation should be treated as a system with technological alternatives and not as a commodity to serve an aggregate travel demand.

The use of linear programming has some limitations as a framework for a transportation design model in that some of the constraints are discrete rather than linear in nature, and it is difficult to express these in a linear programming algorithm. Integer programming models have not proved practical for transportation networks of any size. Linearity also presents problems in the statement of cost relationships, but these linear limitations are probably still small compared to the errors in the cost parameters themselves. At the present state of the art of design model development, much may still be gained through the use of linear programming with all its limitations.

The principal suggestion that this commentary would make for the improvement of the subject model would be a model modification that would allow for joint consideration of the existing as well as the proposed two-mode transportation system. The revised model would consider a transportation system using a primal linear programming model to represent the loading of the present network and would study the benefits and cost of alternatives to this basic network through parametric analysis of the model of the existing system. Such an application would allow for long-run changes in the light of the optimal short-run use of the existing system. In this way, a better relationship between the alternatives of improving the existing system versus the construction of new facilities may be weighed. Such a model may indicate that funds could be better spent for the development of command and control systems to improve the efficiency of the existing system rather than the construction of new facilities.

An interesting result of the model application is the correspondence between the model output and the existing modal split between highway and transit in the city of Chicago. Such a correspondence indicates that the transportation market is performing admirably well, and it makes one wonder if the market is working so effectively, whether at our present level of understanding of the activities we are modeling that we should not leave the market alone.

DANIEL BRAND, Senior Project Engineer, Traffic Research Corporation—This paper proposes a linear programming solution to an important transportation planning problem. The problem is that of providing a minimum cost combination of two modes of transportation service from a corridor to a downtown area. The solution includes demand for the transportation service as well as the cost of supplying the service. Hence, the method gives a solution which is both optimal from the standpoint of supplying and which is capable of being achieved in practice, i.e., being utilized to the extent planned for.

The major points where the paper needs discussion are (a) the lack of mutual independence of several variables in the cost function, (b) the inability to calculate properly vehicle operating costs in the cost function, and (c) the assumption of fixed total demand for transportation service.

Critique

Interdependence of Terms in the Linear Road Capital Cost Model. —In formulating the first three terms of the objective function (the linear road capital cost model for a road spanning zone i) the assumption is made that money may be spent to add peak period road capacity, peak period speed, and additional off-peak period speed, independently of each other. This is contrary to the fact that design measures to increase peak period capacity (additional lanes, grade separations, etc.) are highly correlated with measures to increase peak period speeds, as the traditional speed-capacity curves would indicate. The same independence is also largely true for increasing off-peak speeds. Examples are given in the paper only for design measures to increase off-peak period speeds independently of the other two variables. Of the examples given, the longer acceleration and deceleration lanes normally increase ramp capacities as well as off-peak speeds by reducing relative speeds of merging vehicles and increasing gap acceptances. Another measure given, more adequate signals, is perhaps the only independent design measure, since signals are not fixed in their effect on different traffic flow patterns. They can be made to vary in their response to traffic at various times of day. Thus, additional money may be spent to add off-peak progressive timing or detailed traffic responsive control to increase speeds of off-peak period traffic. However, this additional money will be small compared to the cost of building new physical facilities.

Contrasted to this, an assumption that additional money may be spent for lower off-peak transit travel times (lower waiting times) may be appropriate, since the costs of running additional trains to shorten headways are the primary moneys involved. Studies of transit operating costs in the Boston area show these additional costs to be quite important.

An inability to provide an optimal mix of capacity and speeds eliminates the ability to calculate optimal speeds, and hence to predict transit trips, remaining auto trips, and vehicle miles of auto travel. This is a blow to the model as presently formulated.

Calculation of Vehicle Operating Costs. —In the calculation of vehicle operating costs, the assumption is made that one-half of the drivers using transit would get rid of the car which would otherwise be used for the trip and, therefore, one-half of the auto users should be charged the marginal operating costs of driving while the other half should be charged with the full costs.

The model uses the same fraction of one-half in two calculations, even though the fraction is computed with different bases, i.e., transit riders in the first instance, and auto users in the second. In addition, there is no provision to use the proportion of trips using transit, predicted by the model, to calculate the fractions of auto trips to charge full and marginal costs to.

Other difficulties in calculating vehicle operating costs are that these should be calculated using average interzonal car occupancy rates, which rates may vary from 1.1 to 2.0 or more, depending on the origin and destination of the trip, the trip purpose, the time of day, etc. Also, the assumption that one-half the drivers using transit would sell their car is a very difficult assumption to make. This number would vary with the location of the trip origin because of varying compositions of transit trip purposes and income of trip makers at the different origins.

Assumption of Fixed Total Demand for Transport Service. —The authors state: ". . . in other models of this type (the type treated in the paper), it is often found that the travel time which is generated by the facilities which are planned is different from that which was specified in order to predict demand. It is clear that this problem is avoided in our model. The total travel time and therefore the demand can be specified with certainty and entered as a constraint."

The contention that their model avoids the stated problem may be contended. Only the range in which travel times are generated by the model is limited. Demand is fixed but peak period trunk line travel time is allowed to vary on individual links (in their example) from 30 mph to 60 mph. (In the example, the model does in fact additionally restrict travel speeds over and above the 30 mph to 60 mph range by limiting overall travel time to a certain maximum from the six zones farthest out; about 30 percent of the trips are made from these six zones.) This is not an abnormal speed range to find in traffic models (gravity models with capacity restrained assignments) which vary travel demand by iterating over demand prediction and travel time calculation. It would appear, therefore, that total demand cannot be specified beforehand in this model with much more accuracy than in other models. Hence, it is not clear that the problem has been avoided.

To carry the discussion one step further, a reduction in the allowable range of speeds would enable the fixing of total demand in this model with more certainty. However, this would narrow the range of alternatives which could be tested by the model. It also may be possible that the model application yielded "reasonable" modal splits, because within the speed ranges given, the modal splits are reasonable. Hence, the setting of allowable speed ranges has important meanings for the model as presently formulated.

Model Application

Solutions Tending Toward Boundary Values of Variables. —Are the authors disturbed that many of the variables solved for, yielded values on the boundaries of the region of possible values of the variables? For example, the optimal results for peak and off-peak speeds (m_i and s_i) are either 30 or 60 mph for 29 out of the 30 solutions. In particular, the question may be asked, does the propensity of linear programming methods to yield values on the boundaries of possible solution space affect the ability of this model to yield reasonable results?

Consistency of Results for Modal Splits and Speeds. —The similarity of the peak and daily fraction of trips via transit yielded by the model (Table 6) does not appear consistent with the solution for peak and off-peak speeds (Table 7). The latter vary between the two periods of the day. It is the varying speeds which are used in the determination of the similar peak and daily fractions of trips via transit.

A Possible Extension of the Model

The application of the model in the paper yields optimal values of 30 mph for both peak and off-peak speeds in downtown and neighboring zones. The authors' comment: "This is in contrast to the planning in many areas where full freeways are called for even in the heart of downtown areas."

It must be noted that only trips to the single downtown destination zone are being considered. Through trips and trips to intermediate destinations are not being considered.

An extension of the model to be origin-destination specific rather than origin specific is needed if real planning problems are to be solved. This would complicate certain aspects of input data preparation, in particular the modal choice constraints and their associated parameter values. Also the notion of how to interpret capacity between many origin-destination pairs is of interest.

A discussion by the authors of whether such an origin-destination formulation of their model could be solved would be useful.

Conclusion

Despite the criticisms in this discussion, I feel this is a very important paper. The present linear programming solution may fall short of being meaningful to the problem-oriented planner; however, with additional work and reformulation, linear programming may be capable of providing efficient low-cost solutions to meaningful transportation planning problems.

EDWARD K. MORLOK, Jr., and GEORGE A. HAY, Closure—The discussions can be divided into two broad categories: (a) comments about applications of mathematical programming in general and (b) comments about the specific application in our paper. We shall concentrate on those comments specifically about our paper, since we are in agreement with virtually all of the comments in the other category. However, we would like to add two general but relevant observations about modeling and decision-making to the general comments of the discussants.

There seems to have been considerable misunderstanding of the road capital cost function. Mr. Brand makes the comment "the assumption is made that money may be spent to add peak period road capacity, peak period speed, and additional off-peak period speed, independently of each other." We have not made this assumption nor even intended it, at least with respect to peak period values. We fully recognize the interdependence of these variables. In fact, we are considering a single class of improvements, whose benefit may be taken in additional speed, increased capacity, or some combination of the two. The interdependence, and therefore, the combinations which are achievable are defined by the speed capacity tradeoff diagram (Fig. 2). Additional expenditure need not be directed specifically toward speed or specifically toward capacity, but can be thought of as yielding an outward shift in the whole speed capacity frontier. This frontier is defined by the functional relationship $f(m, c) = k$ where k is the expenditure, and it is this frontier which is represented in Figure 2. In deriving our capital cost function $\left[C_i c_i + M_i \cdot \left(1 - \frac{m_i}{\overline{M}_i}\right)\right]$ we have simply given a specific form to this functional relationship, a linear one. There may be objections to this form of the relationship, but they are not those to which Brand has referred.

Among the possible objections are the following: (a) we have approximated a set of non-linear curves with a set of linear ones; (b) we have assumed that the relationship $f(m, c) = k$ is homogeneous of degree one. This, together with the linearity, implies not only constant returns to scale but also that the marginal costs of increasing one variable (e.g., speed), is independent of the level of the other variable, capacity. The first implication is probably acceptable within the range of acceptable alternatives. The second should be accepted or rejected on technological rather than theoretical grounds.

Both Mr. Brand and Mr. Sullivan mentioned that the additional cost of increasing off-peak period speed over that for the peak period probably would be small in comparison to the cost of building a new facilities. We were unable to find any definitive evidence on this. We decided to include the third term in the cost function, because we felt that this cost could be significant in some situations.

Turning to another aspect of road costs, Sullivan states that the only investment variable relates highway capital cost to highway speed and that this formulation seems oblique. Highway costs are related to capacity, peak period speed, and non-peak period speed (where capacity is defined as that volume at which the specified speed is achieved). We related cost to measures of output capability (capacity and speed) rather than to the physical road itself and then to output capability because the former is more efficient. The physical road its speed-volume characteristics are referred to in developing the cost function, but once this is developed there is no reason to return to the road itself. Mr. Sullivan also states that only one set of highway capital costs are used and suggests that in future applications these costs might be a function of development density. Actually this was done in the application given in the paper. The road capital cost coefficients used decrease with increasing distance from the CBD (Table 1).

In addition, Sullivan says that the other investment variable, transit capital cost, is actually introduced as a constant. This, of course, is not true. While introduced as a constant in the first run of the sample program (the only run presented in the paper) it must be remembered that this run is one of several which must be performed (in each run the transit system is extended one zone further with transit capital costs increasing correspondingly) according to the minimum minimorium technique outlined in the paper. The run which yields the lowest total cost of all those considered will be the true optimum solution.

Brand's points concerning the difficulty of accepting our assumptions about average automobile occupancy rates and the fraction of drivers who would sell their autos if they used transit are well taken. The reason for our assumption was the absence of more detailed data for the region we considered.

It is important to note that both of these parameters can depend on the residential zone of the travelers in question simply by approximately subscripting the relevant parameters. In the case of auto ocupancy, the capacity constraints become

$$c_j \geq \sum_{i=j}^{n} \frac{D_i}{E_i} - \sum_{i=j}^{n} \frac{P_i}{E_i} \qquad j = 1, \ldots, k$$

$$c_j \geq \sum_{i=j}^{n} \frac{D_i}{E_i} \qquad j = k+1, \ldots, n$$

Since each vehicle-mile constraint calculates the total daily vehicle-miles generated by trips from a single zone, the occupancy rate E and the cost parameter V only need be subscripted in the present formulation to take care of zonal differences.

Also, a further distinction between peak and non-peak periods can be made very simply. Since the capacity constraints refer to only the peak periods, they present no problem. In order to distinguish between peak and non-peak values of E_i, V_i, and v_i, we might add a second subscript, p for peak period and n for non-peak period. The constraints which determine vehicle-miles of travel then become

$$v_{jp} = \frac{2}{E_{jp}} \left(\sum_{i=1}^{j} L_i + F_j + G \right) \cdot (2D_j - 2p_j) \qquad j \leq k$$

$$v_{jp} = \frac{2}{E_{jp}} \left(\sum_{k=1}^{k} L_i + G \right) \cdot (2D_j - 2p_j)$$

$$+ \frac{2}{E_{jp}} \left(\sum_{i=k+1}^{j} L_i + F_j \right) \cdot (2D_j) \qquad j > k$$

$$v_{jn} = \frac{2}{E_{jn}} \left(\sum_{i=1}^{j} L_i + F_j + G \right) \cdot (8D_j - d_j + 2p_j) \qquad j \leq k$$

$$v_{jn} = \frac{2}{E_{jn}} \left(\sum_{i=1}^{j} L_i + G \right) \cdot (8D_j - d_j + 2p_j)$$

$$+ \frac{2}{E_{jn}} \left(\sum_{i=k+1}^{j} L_i + F_j \right) \cdot (8D_j) \qquad j > k$$

Brand's conclusion that in this model one cannot specify interzonal travel times at the outset with much certainty of achievement appears to be based on a limited examination of the example application rather than the general form of the model. While in the example we used only three peak and three non-peak period time constraints, the model as given contains two for each zone—one for the peak period and one for the non-peak period. These constraints are upper bounds on travel time.

Because extra speed costs money, minimum cost solutions will generally call for travel times very close to or equal to the maximum allowed. This was verified by experimentation with the model, and is exhibited in the example given. Thus we feel justified in our statement that interzonal travel time expectations will be met (or nearly so), so that interzonal demands can reasonably be taken as fixed.

The reason for no travel time constraints for zones 1 through 9 in the example was that we felt that 30 mph average main road speeds were adequate for travel to points up to about 18 miles from the downtown area. Since this speed is already embodied in other constraints (zonal speeds), there was no reason to add redundant travel time constraints. It was felt that the constraints for zones 10, 13 and 15 sufficiently narrowed the range of travel time choices for zones 11, 12 and 14 that no explicit constraints for these were included. This suspicion was confirmed by the outcome.

If any difficulties with travel times were to arise, it would be possible to add a second set of constraints. A second constraint for each one would place a lower limit on travel time. Thus the travel time from any zone could be constrained to a range as small as desirable.

Brand's doubts concerning the consistency of our modal split results are easily cleared up. The set of equations which yields the number of passengers who take transit daily is as follows:

$$P_j = A_j \sum_{i=1}^{h} m_i + B_j \qquad h = j \text{ if } j \leq k \text{ and } h = k \text{ if } j > k$$

Note that when j > k, the zone in which transit ends, the modal split depends only on the speeds in the first k zones. In our example k = 5 and the peak and off-peak speeds are determined to be the same for those zones. The peak vs off-peak discrepancies in zones 6-8 do not, therefore, affect the modal split.

Both Mr. Brand and Mr. Sullivan emphasize the importance of extending the model so as to include consideration of trips which neither originate nor terminate in the CBD. We could not agree more fully.

The consideration of trips made solely along the axis of the corridor would not be too difficult: the capacity constraints must be changed so that the combined road and transit capacity in any zone is at least as great as the total flow through that zone. The equations for calculating vehicle operating costs would become much more complex, but these present no problem from the programming point of view. In principle, an equation for modal choice should be included for each origin-destination zone pair which is served (at least for part of the trip) by transit. This is possible, but would tend to make the program unwieldy, and we would suggest consideration of the assumption that trips to some zones served by transit would not be made by transit. This assumption could be defended for zones in which only a small fraction of the zone's total business activity occurs near the transit stations.

As to the extension of the model to consideration of trips with one or more ends outside of the corridor, we feel that this would be much more difficult than the previous extension. While we are certain that the extension to inclusion of all trips solely within the corridor could be made, success in making this further extension without some major (and possibly unacceptable) assumptions is not certain. One such possibility is to fix the point at which trips enter and leave the corridor. This reduces the problem to one very similar to the extension covered in the preceding paragraph.

Sullivan brings up the additional point that there is no provision for changes in the magnitude or orientation of trips with changes in capital investment. To the extent that changes in capital investment correspond to changes in travel time, cost, etc., these changes will cause some changes in trip volumes and orientation. However, in the model we constrain road travel times to a narrow range, and, of course, transit running times are fixed. Pricing is also assumed fixed for each run of the model. Therefore, we feel justified in the assumption of a fixed total demand. Major changes in travel times and pricing are accommodated only with additional runs of the model, in which the total demand and modal choice parameters have been revised to reflect these changes.

In a broader sense, however, we must agree with Sullivan's comment. Over a long period of time the nature of the transportation facilities and services provided in a region undoubtedly strongly influences the pattern of development of the region. An example within the context of our model might be: the provision of rapid transit in the corridor could attract a concentration of dwelling units and business establishments along its route, which would be more widely dispersed throughout the entire region if the rapid transit line were not constructed. Presumably this increase in development in the corridor would result in more travel within the corridor. Thus, if one takes into account the differences in developmental consequences of alternative transportation services, then there certainly is an effect of alternative transport choices upon travel patterns and land use. The question is: How strong are these influences?

The question posed has not been answered, to our knowledge. The urban studies which we have seen do not appear to have actually taken the developmental influences of alternative systems into account in their models. Much more research directed at identifying and quantifying the appropriate relationships is necessary before we would have any justification for inclusion of such relationships in our model. We do earnestly hope that this research will be carried out.

Closely related to Sullivan's remarks, but of a more general nature, is Mr. Schlager's comment that the model should take greater account of the interaction of transportation and land use. To the extent that this interaction is reflected in traveler movements in the corridor, our discussion in the preceding three paragraphs is relevant. Schlager undoubtedly is also referring to environmental constraints on such items as the location of new facilities and the extent to which additional land can be taken for improvements to existing travel arteries.

As to routing, the model in its present form presumes that the routes of new roads and transit lines are specified outside of the model. It assumes that the cost and other coefficients are applicable to routes which are feasible, both from the economic and social standpoint. There is, however, no provision to limit the land area occupied by the new or improved facilities. Similarly there is no means for restricting other design features, such as elevation, which might affect the environment. The inclusion of these types of restrictions might be quite difficult given the present form of the model, although the subject must be investigated in detail before a statement as to the feasibility of adding such restraints could be made.

Sullivan also discusses the problem of fiscal feasibility, which is not explicitly handled by our model. His suggestion that demand and travel time constraints be varied so that estimates can be made of the additional cost of accommodating more travelers or increasing speeds has great merit. In this way one could compare the benefits and cost of improvements to the transportation system.

An alternative, which we do not consider as useful as that described above, is to include a budget constraint in the model. This would limit the capital expenditure to a predetermined amount.

In his discussion of the assumption of demands fixed in magnitude and orientation, Sullivan suggests that if strong assumptions are made in the mathematical programming formulation the solution should be checked by the more complex network and demand simulation models. We doubt that any mathematical programming models could ever rival computer simulation models in their ability to accommodate all the details of a phenomenon. However, they do have the distinct advantage of efficiently finding the optimum of a very wide range of alternatives, while the searching for optimum solutions with computer simulation models usually is extremely expensive. Therefore, we feel that these two types of models can be complementary, with the optimization models being used to narrow the choice to a few distinct alternatives. The simulation models then would be used to explore these alternatives in more detail.

Schlager's suggestion that the model be revised to consider the loading of the present system as the primal programming problem is very interesting. The constraints in this formulation presumably would reflect the characteristics of the existing network. The dual variables then would indicate the value of various marginal changes in the existing network, as these would be reflected as changes in the constraints.

The results of such a program would be very different from the results of the present program. The revised program would yield the most beneficial marginal improvements, whereas the present program yields specifications for a system which is optimal at some future date. Of course, the question as to whether the problem could be formulated in the suggested manner still remains. However, we feel the suggestion has considerable merit and intend to examine the feasibility of a revised formulation before developing our model further.

There are two additional ideas relevant to models and decision-making of the sort considered in this paper which we feel are important but which have not been mentioned.

The first is that a model of some real world phenomenon is necessarily a simplification of that phenomenon. Those who evaluate a model must decide—on partly subjective and partly objective grounds—whether the model includes all of the important or relevant relationships and factors and ignores all others. It is not clear to us, for example, that the most fruitful direction for further development of our model is toward considering an entire region, or toward considering the staging of improvements, or toward considering the developmental consequences of alternative transport decisions.

Moreover, if all of these were included, the model might become so complex and costly to run that it would be of little value to the problem-oriented planner. The complexity might defy comprehension, so that understanding the various solutions is difficult. Costliness would tend to limit the number of alternatives considered, defeating the purpose of the model. Under these conditions, transport decision-making would not be improved by the extensions. We do not claim that these conditions would result from major extensions, just that they could.

The other major idea we wish to transmit is not our own and has been stated often (especially in the writings of William Garrison and Tillo Kuhn), but seems to be heeded rarely. If one is dealing with a transport decision of such magnitude that it will influence travel patterns and the pattern of development of a region, simple economic criteria related to transport phenomena are wholly inadequate. At the least, the criteria used should reflect the broad spectrum of society's benefits and costs (both monetary and non-monetary) resulting from alternative decisions.

We feel that it will be extremely difficult to quantify and transform into the same units (such as dollars) this spectrum of benefits and costs. This is especially difficult in situations where the benefits and costs are non-uniformly distributed over the population and the region. If this cannot be done, it will not be possible to utilize the optimum-seeking capabilities of mathematical programming, for the optimum is not defined. It may not be that broad choices as to transport development are inherently social choices, best left to the citizens and the political process (17). For these broad questions, the value of programming formulations is probably in identifying alternatives—not specifying solutions.

Reference

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Transportation, Problem-Solving and The Effective Use of Computers

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The argument of this paper rides on the conjunction of three themes: (a) the scope and complexity of transportation planning problems, (b) the structure of transportation planning as a problem-solving process, and (c) the development of highly flexible, multi-user, remote-access "interactive" computing systems. Analysis of the scope and complexity of transportation planning and of the problem-solving process leads to the conclusion that transportation planners need highly flexible systems with a variety of transportation planning tools. Analysis of the new computer systems shows how they will provide an environment for this required flexibility. Thus, our task is clear—to design and implement a flexible problem-solving system for transportation planning.

Brief examples are given to show specific system design implications of the argument presented.

•THREE streams of development have come together to create tremendous opportunities for fundamental changes in the process of transportation planning. This paper summarizes these three themes and explores their implications.

The first theme is the scope and complexity of transportation planning. It is developed through summarizing the policy options available, the wide range of their impacts, and the variety of models required for predicting the impacts of a given plan.

The second theme is the structure of transportation planning as a problem-solving process. Analysis of this structure indicates that the transportation planner must have available a variety of compatible models and procedures, and that he must have great flexibility in his use of these procedures in tackling problems of the complexity of transportation planning.

The third theme is the flexibility of the new computer systems, particularly the interactive, remote-access, multi-user ("time-sharing") systems. We conclude that this new technology will enable far more thorough analysis of problems as complex as transportation planning than has ever been achieved before, because these systems will allow the planner great flexibility in the conduct of his analyses.

Our task is to design and implement such highly flexible, problem-solving systems for transportation planning. This task can be accomplished successfully only through developing our understanding in each of these three areas—the scope and complexity of transportation planning problems, the structure of the problem-solving process, and the characteristics of the new computer systems.

In order to present clearly the main thrust of this argument, we must skim lightly over a number of highly complex and subtle issues. We consider this to be only an introductory statement—one which will be revised and expanded greatly as we gain knowledge and experience in the design of transportation planning systems.

Paper sponsored by Committee on Transportation System Evaluation and presented at the 45th Annual Meeting.

- FIXED FACILITIES (ALL MODES)
  - Networks--Configurations
  - Links--Locations
    - Capacities
    - Other operating characteristics
  - Nodes--Interchanges for single mode
    - Terminals for interchange between modes
    - Storage, parking, etc.
- VEHICLES (ALL MODES)
  - Quantities
  - Operating characteristics--Propulsion systems
    - Guidance and control systems
    - Relation between vehicles and supporting medium
    - Cargo- and passenger-carrying characteristics
- OPERATING POLICIES--Routing
  - Scheduling
  - Pricing (tariffs and tolls)
  - Segregation of traffic
  - Ownership
  - Regulation
- INFLUENCES ON DEMAND--Land-use controls
  - Advertising and merchandizing
  - Socio-economic development policies
  - Education
  - Enforcement

Figure 1. Transportation planning options.

SCOPE OF TRANSPORTATION PLANNING[1]

The scope of transportation planning can best be understood by enumerating (a) the types of policy options open to the planning agency, (b) the types of impacts of a plan which will affect the selection of a plan for implementation, and (c) the basic component models necessary for predicting plan performance.

The major policy options are summarized in Figure 1. The scope of this list is influenced strongly by the experience and insights gained by the highway engineering profession during the evolution of urban transportation planning over the last decade. In area after area, highway engineers have come to realize that highways cannot be planned separately from mass transportation facilities and parking; that pricing policies, such as tolls and parking charges, are potentially useful controls on demand; and that land-use controls and transportation policies must be carefully interrelated in order that land-use and travel patterns evolve in complement rather than in conflict.

Figure 2 summarizes the major kinds of impacts of transportation plans. Not all are equally important, nor even significant in every context; however, they are potentially relevant in every transportation planning analysis, and should be carefully evaluated before being classed as irrelevant in each specific context. Again, it is the history of urban transportation planning which stimulates the scope of this list, for we have long since learned that the first cost of the facility is only one of many possible impacts.

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[1] The discussion presented here draws strongly upon unpublished conclusions of the Boulder Conference on Transport Systems Analysis sponsored by the National Bureau of Standards in August 1964, under the direction of S. M. Breuning.

- DOLLAR COSTS
  - First Costs--Construction
    - Land Acquisition
  - Continuing Costs--Maintenance
    - Administration and policing
    - Vehicle wear and tear
- DOLLAR REVENUES--Tolls and other charges
  - Special taxes
- NON-DOLLAR COSTS
  - Quantifiable--Travel time
    - Land takings--Recreation
      - Parking, etc.
    - Displacements--Population
      - Employment
      - Retail sales
    - Changes in growth patterns--Employment
      - Population
      - Land use
  - Non-Quantifiable--Changes in social structure
    - Political power structure
    - Community structure
    - Disruption for individuals
    - Aesthetics--Driving experience
      - Perception of urban form

Figure 2. Impacts of transportation.

The relationships between the list of options and the list of impacts is shown in Figure 3. A transportation plan is defined in terms of the options; from this statement we wish to obtain a prediction of the impacts of the plan. To do this, we use one or more models—for example, traffic flow models and traffic assignment techniques to predict travel times and link volumes; land-use change models to predict the effect of travel time and other factors on land use; other models to predict construction quantities, land takings, and other data necessary for determining first costs.

A major part of transportation modeling is the prediction of the behavior of the transportation market. This behavior results from the interaction of supply and demand within the channels of the transportation network.

The physical facilities, consisting of networks, terminal facilities, and vehicles, "produce" transportation. The product—transportation—can be described potentially in terms of a number of variables (Fig. 4). We call these "level of service," or LOS, variables. The economists' notion of a "supply" function represents the production potential of a given set of transport facilities, as defined in terms of these LOS variables. For example, the supply function for a given highway link may indicate the dependence of travel time and/or travel cost on the volume of traffic using that road.

Similarly, a demand function can be defined. Such a function gives the volume of traffic desiring to use a given transportation facility as a function of the LOS variables; for example, traffic volume as a function of travel time and/or cost, as represented by the use of the gravity model with appropriate definition of the "distance friction" terms.

These considerations of the interaction of supply and demand in the transportation market (Fig. 3) lead to identification of a major type of model required for transportation analysis, the model for predicting the equilibrium between supply and demand in

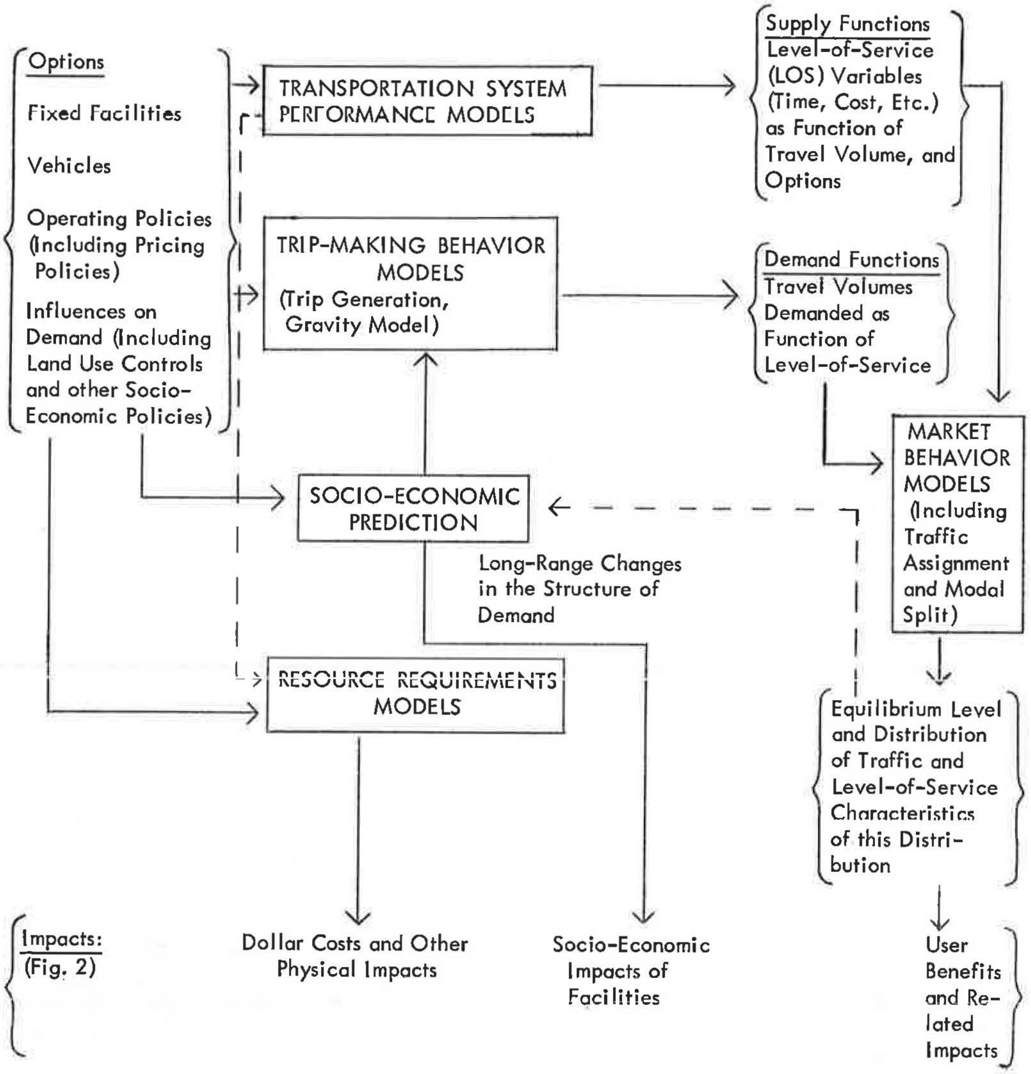

Figure 3. Major types of transportation models.

this peculiar market. This is the area in which urban transportation planning has focused much of its attention; e.g., assignment and distribution models. It is also a difficult area, as evidenced by the fact that there has not yet been developed a single, well-behaved, easily computed model for predicting this equilibrium.

The wide spectrum of transportation planning options, the wide spectrum of impacts to be considered, the large number of models required, and the difficulty of finding the equilibrium of the market all indicate the complexity of the transportation planning problem. This complexity is epitomized by the fact that we do not have a single, comprehensive procedure for determining the ideal transportation plan, but must go through a large number of steps with many, many recyclings. Thus, transportation planning is a complex problem-solving process, and must be studied as such.

- TIME
  - Total trip time
  - Reliability--frequency distribution of trip times

- COST (to user)
  - Out-of-pocket (marginal) costs
  - Continuing costs (e.g., auto ownership)

- SAFETY
  - Probability of fatality
  - Probability distribution of accident types

- COMFORT AND CONVENIENCE
  - Physical comfort
  - Psychological comfort
  - Privacy

- AESTHETIC SENSATIONS
  - Sequence of visual impressions

Figure 4. Level-of-service variables.

STRUCTURE OF PROBLEM-SOLVING

The principles we will now discuss are not taken from profound psychological studies, nor are they derived from advanced mathematical specialties. Rather, they present an intuitive approach to establishing a fundamental understanding of the problem-solving process of engineering and planning, and are applicable as well to business decision-making and many other areas.

Problem-solving involves generating possible alternatives and selecting one for implementation. In the previous section we described the scope of transportation planning; alternative transportation plans are described in terms of the variables identified in Figure 1. We call these decision variables—the object of planning is to make decisions about the "values" to be taken by these variables. Alternative transportation plans will be examined in terms of their projected impacts (Fig. 2).

Alternatives and Search

The scope of transportation planning alternatives has been identified by listing the "decision variables." Each of these decision variables can take many different values; a transportation plan is described by identifying the corresponding value of each decision variable. The set of all possible combinations of values of the decision variables is the set of all possible transportation plans.

Some transportation decision variables are easily described, as continuous mathematical variables; however, most are not, for example, the configuration of a transportation network or the location of a particular highway. Most transportation decision variables are difficult to describe in any compact, neat way, so that the set of all possible transportation plans is also difficult to describe compactly.

The first phase of problem-solving is generating alternatives for consideration. We call the process of alternative generation "search" (Fig. 5). If the decision variables in transportation were continuous variables, generating alternatives might be significantly easier. But the decision variables are so complex, and the set of possible transportation plans in a given context so large, that search is difficult and takes measurable effort.

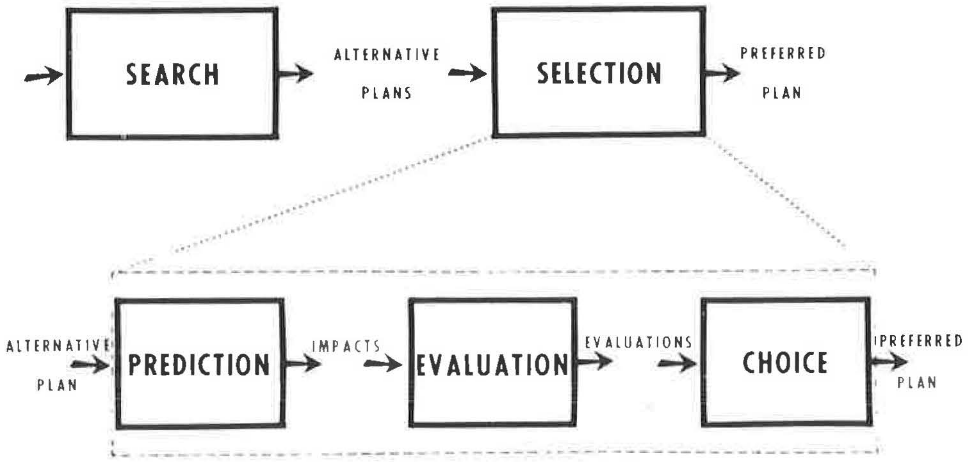

Figure 5. Basic problem-solving modules.

Goals, Impacts, and Selection

Transportation plans are implemented to achieve goals (we ignore here the questions of whose goals, or which goals). The basis for choosing one plan over another is the judgment as to which plan will most likely achieve the goals.

We call the process of examining plans in terms of their achievement of the goals "selection." We identify three major phases in selection. "Prediction," the first phase, operates on the description of a plan in terms of the decision variables to predict the plan's impact. These included physical and socio-economic impacts (Fig. 2). Note that costs and value judgments are not attached yet; prediction is concerned with purely real-world questions. The second phase, "evaluation," involves placing values (dollars and others) on the impacts through costing and other techniques. For example, determination of the effect of a plan on travel time is prediction; the changed time is an impact. Placing a value on travel time and then computing the total dollar value of the changed travel time is evaluation.

The third and final phase of selection is "choice." In this phase, the values of the impacts of alternative plans are compared, and a choice made. In those plan analyses where all values are in a single common unit, such as dollars, choice is not difficult. However, in most situations dollars must be weighed against such factors as loss of recreation land, loss of tax base, destruction of neighborhood social structure, and others; in such cases, choice is indeed difficult. Clearly, trying to reduce everything to dollar values will not answer the difficulty.

Implications of Search and Selection

Examining the discussion of the scope of transportation with which we began, we reach several conclusions:

1. The models identified in Figure 3 address only the prediction problem in selection. In addition to these prediction models, we need techniques and models for assisting the transportation planner in evaluation and in choice.
2. Evaluation models would consist primarily of cost models, but will often require heavy planner judgments as inputs, especially for evaluation of non-dollar-valued impacts.
3. Choice requires balancing dollar-valued costs and benefits against evaluations of non-dollar-valued impacts; for example, dollars of construction cost against removal of a popular park. Therefore, except when the difficulty of choice is assumed away through use of dollars or another denominator, choice procedures will require heavy planner interaction.

4. Besides selection models, the planner could use methods to aid in his search, or generation of alternative transportation plans. Such techniques might be optimizing algorithms, or just rule-of-thumb heuristics. Linear programming would be an example of the former when used to select link sizes (number of lanes and capacity) for a given network configuration. An example of a heuristic would be a procedure which, given a network proposed by a planner and already evaluated, would generate other networks by making small changes in the original one. A third kind of approach, guiding the planner's creativity in an organized way, is represented by the method of Alexander (1).

5. The full range of decision variables and of impact types is very large; even the crude decomposition of the plan analysis process shown in Figure 3 results in several basic models. In actuality, the planner must use a very large number of detailed models—trip generation, modal split, traffic assignment, earthwork computation, bridge cost estimation, vehicle simulation, land-use prediction, population prediction, and many others—to span from the full set of decision variables to the full set of impact types. Transportation planners cannot expect to develop a single comprehensive model which can be "solved" to determine the "optimal" plan.

6. The planner does not yet have tools for determining analytically the equilibrium in the transportation market between the supply and demand functions, for many reasons—the large number of significant level-of-service variables, the geographical distribution of demand, the different demand functions of different socio-economic groups, the different supply functions of different transport modes, the feedback relationship of pricing policy options, and, most important of all, the interaction of supply and demand in the constrained channels of the transportation network. Therefore, determining the equilibrium distribution of traffic in a network requires a series of interacting computational approximations (use of trip generation, trip distribution, modal split, and assignment models). Of course, taking into account such long-range shifts in the demand functions as correspond to land-use changes is even more difficult.

The implications we derive from this discussion are that there are many different tools needed by the planner for resolving transportation planning problems—a variety of search procedures, a variety of models for prediction of impacts, and a variety of procedures for guiding him in evaluation and choice. Further, it is not likely that the particular bundle of tools applicable to a problem will stay constant, nor that the sequence of their application will be fixed and known a priori. Therefore, the planner requires that all these tools be available to him, within the same computer system, with great flexibility provided for him to use his tools whenever and in whatever sequence he desires; the planner's decision as to what to do next, and with which tool, must depend on the results of his preceding analyses.

Further Implications

Space prevents us from going into a discussion of many other aspects of the problem-solving structure of transportation planning. We summarize some of the more significant:

1. Sensitivity analysis—the planner is often uncertain about the true value of many elements entering into his analysis (for example, predicted increase in income or in auto ownership). The planner needs tools for explicit analyses of the sensitivity of his choices to variations in the assumed values of key data.

2. Uncertainty analysis—having determined the sensitivity of his decisions to key factors, the planner may wish to use choice procedures which incorporate uncertainty explicitly—either probabilistically (perhaps with Monte Carlo techniques) or through decision rules (3, Chapter 13).

3. Analysis of data base—for example, parameters of travel behavior models (generation rates, mode choice functions) are inferred statistically from large volumes of collected data. The planner needs statistical analysis tools to enable him to go back occasionally to the raw data for refinement or revision of earlier estimates, or for analysis from an alternative approach.

4. Hierarchical structure—the planner naturally deals not only with detailed alternatives (transportation plans as defined in Fig. 1), but also with broad, aggregated alternatives, such as radial versus grid systems. The planner needs procedures for deciding when he should be operating at detailed levels and when at broad levels (see Manheim, 6).

5. In such large and complex problems as transportation planning, the planner's view of the problem will change as the process evolves. The goals will change, and other emphases will evolve. The planner will need tools for reevaluating earlier choices, for revising his models to reflect goal changes, etc.

6. Often the planner will need to construct new types of models and validate them against the data base (so long as still within the range of behavior incorporated in the data).

NEW COMPUTER SYSTEMS

Third-generation computer systems will be highly flexible. This will be most typified by the time-sharing models which will provide a large number of users remote access to substantial computer power on an as-needed basis.

From the point of view of the user, time-sharing means that he can have access to the computer through his own console, which may be as simple as an electric typewriter and may be remote from the computer, in the user's own office. From this console the user can enter data, run programs, receive output, and modify, compile, and debug his programs. He has the computing speed and memory capacity of a large portion of the computer available to him, but because he is sharing these facilities with other remote users, the cost is significantly less than the full cost of the computer. Time-sharing systems make available immense computing power for use in small or large chunks as the planner needs it, delivered wherever it is most convenient to him.

Third-generation computers will have another major source of flexibility in the software capabilities available. These capabilities are illustrated by those incorporated in ICES (Integrated Civil Engineering System), a prototype operational system now being developed by the Civil Engineering Systems Laboratory at the Massachusetts Institute of Technology (6, 7).

One of the most important characteristics of ICES is its capability for providing problem-oriented, command-structured languages for various application areas such as structural design, surveying, transportation planning, and highway design. With these languages, the engineer is able to express his processing requirements through sequences of commands. These sequences are highly variable; the engineer can vary not only which specific computational steps he uses in analyzing his problem, but also the order in which they are executed. Other capabilities in ICES, such as dynamic memory allocation, data-base management procedures, and list-processing features, add to the flexibility of the system.

IMPLICATIONS

Through provision of highly interactive processing access via time-sharing and with flexible software, the third-generation computer systems will provide great flexibility to the planner. They will allow him frequent and continuous interaction with his programmed procedures and his data base; he will have freedom to choose the tools to use and the sequence in which they are used.

The planner can consider his models and procedures as a collection of problem-solving modules; he executes one module, observes the results, and selects a module to execute next. This process is repeated until a preferred plan is achieved.

Some modules will be search procedures, others prediction models, still others will assist him in choice. Some modules will deal with traffic, others with land use, social structure, or construction estimates. No single module is itself sufficiently powerful to be used to solve a transportation planning problem in its entirety; the planner must ultimately use a large number of these modules, though not necessarily all of them.

To summarize, then, we see that the conjunction of these three themes implies definite objectives for system design. Because of the scope and complexity of the transportation planning problem, we must make available a variety of specific predictive models. Furthermore, we must recognize explicitly that transportation planning is a problem-solving process, so that we must provide modules not only for prediction, but also for search, evaluation, and choice, as well as a variety of other support roles (e.g., sensitivity analysis, hierarchical structure, systems analysis). Finally, it is only because of the new hardware-software technologies that we can actually implement a system with such capabilities.

This kind of flexible problem-solving system for transportation planning must be our objective.

EXAMPLES

To illustrate these ideas and stimulate discussion, we show some relatively simple examples. These are presented as pairs of interacting analyses. The planner will move back and forth between each type of analysis, or procedure, in the pair.

Network Generation (Search) ⟷ Network Selection

Assisted by computer procedures, the planner generates a network. Next, he utilizes other procedures to predict and evaluate network impacts, and to compare the network with others previously examined. Then he generates and examines a new network or modification of the old. Thus, he uses search and selection procedures in alternation.

Free Assignment ⟷ Capacity Constraint Assignment

The planner will make "free" or unconstrained assignments to determine major desire patterns. As a guide to network generation, he will then use capacity-constrained assignments to determined the deficiencies in the existing or planned network. The differences between the two assignments will indicate in a general way the effectiveness of the network. Making small changes in the network, he will go back again to free assignment, repeating the cycle.

Network ⟷ Link

Having generated and examined a number of alternative networks, the planner fixes upon the preferred network. With this as a basic plan, he generates and examines alternative locations for one or more specific links in the network. If at some point the most preferred link is significantly different in its effect on the network (on flow pattern, user costs, land-use impacts, etc.) from that assumed in making the network choice, the planner must return to the higher level network problem and revise his selection at that level, perhaps generating new alternatives. (This is a two-level example of hierarchical structure.)

Land Use + Network ⟷ Network

Because of the feedback effect of transportation on land use, in general the planner can evaluate networks adequately only with the aid of land-use prediction models. However, once having analyzed the interaction of a network with land-use changes, the planner may be able to assume that for small changes in the network the land-use evolution is approximately the same. So long as this applies, he need only use network flow models (e.g., assignment), and does not need to do land-use prediction for each new network; but as soon as the networks become significantly different, he must use both land-use and traffic models again.

Regional Product and Income Distribution ⟷ Total Annual Costs

Since transportation exists only to serve the region, evaluation of transportation plans requires prediction of their effects on total regional product and regional income distribution. However, when regional parameters are not sensitive to small differences in plans, total annual costs of the networks (first + user + continuing costs) are adequate as proxies for the regional measures. Thus the planner will sometimes use the regional growth and income models and other times use only direct cost models.

Quantitative (dollar) Criterion ⟷ Choice Mechanism

For many alternative plans, the non-dollar-valued impacts may be sufficiently similar or sufficiently obvious in their implications for choice that use of a single-dollar criterion to measure the desirabilities of alternative plans is acceptable. For others, however, choice may be extremely difficult and require analysis of the relative liabilities and benefits of each scheme. Then the planner will use various models to help him explore his judgments (perhaps scale construction methods, or even procedures for guiding introspection in the development of dollar or other equivalents of non-dollar impacts).

CONCLUSION

At this stage, the general argument of this paper is largely philosophical. Final judgment as to relevance and significance can only be made after its implications have been shown in the design of a specific set of computer-assisted transportation planning tools. Therefore, we ask that this paper be considered an opening statement, a statement of intent. In the future, we hope to show in detail the way this argument has influenced our design of transportation planning systems.

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Methodology for Evaluating Costs and Benefits of Alternative Urban Transportation Systems*

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•INCREASING traffic congestion, growing inadequacy of parking space, and problems of urban blight which can be solved only through wholesale rebuilding are combining in cities all over the world today to focus attention, among other aspects of urban planning, on the role of transportation systems. The physical means of getting people to and from work, school, stores, health, recreational facilities, etc., as well as the means of delivering and dispatching goods to and from factories, warehouses, retail outlets, and final consumers, both individual and commercial, is increasingly coming to be recognized not only as an accessory service somehow to be grafted upon city plans, but as an organic factor in determining the design, character, and rate of a city's growth. More than that, transportation is also being increasingly recognized as one of the factors in urban living that carries with it some of the largest costs, both tangible and intangible as well as correspondingly large potential for economic and social benefit. It is no wonder, therefore, that engineers, economists, and city planners are increasingly being called upon to give systematic consideration to the question of how new transportation systems may be designed—and old ones revamped—to provide the maximum in benefit at the minimum in cost.

ALTERNATIVES, SOLUTIONS, AND GROUPS AT INTEREST

Nature of the Alternatives

The basic alternatives which are provided by present-day technology are not too numerous. Private automobile, bus, and truck traffic moving over city streets and highways is the most widespread type of movement. Rail rapid transit (subway, surface, and elevated) is fairly common in large cities. Limited-stop rail commuter service, either self-propelled or locomotive-drawn, is also to be found in many large metropolitan regions. And in a few places, aerial service (by helicopter or other aircraft) has also appeared.

For most cities, the practical choices are limited. Air service, for example, can make little practical dent on the mass transportation problem. Suburban commuter lines are of possible interest only for areas which have a string of suburbs. And such high-investment facilities as subway and elevated lines may be rejected a priori where there is no potential for very high passenger volumes.

Yet even where the basic choices are limited, there is a large number of alternatives for the analyst to contend with. Take automotive traffic alone, for example. There is the question of balance between public and private vehicles. There is the question of whether the public vehicles should be large (buses), small (jitneys), or available for

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charter hire (taxies). There is the question of which and how many routes should be served and of whether (and where) the public vehicles should sometimes have their own rights-of-way. There is the question of what motive power should be used (electricity, gasoline, or diesel) and of whether the public interest requires the use of anti-pollutant devices. There are questions of fares to be charged, and of frequency and hours of service. There is the question of the street and highway capacity to be provided—how many vehicles it should be designed to move, at what speed, and with what "delay" (e. g., entrance queuing) time. There is the question of whether construction designs should lean toward high-investment, low-maintenance alternatives or toward low investment with high maintenance, of what weight-loads they should be built to carry, and of what adversities of rain, snow, and storm they should be able to withstand.

As if it were not enough to face this multiplicity of subalternatives, there is the fact that within any one city, and frequently within any one traffic "corridor" of any one city, two or more of the principal alternatives, as well as all manner of subalternatives, may be combined in an infinite number of proportions.

Nature of the Solutions

Conceptually it should be possible, for any given city (or for any given "detachable" sector) to work out a "minimax" solution for the total transportation question, i. e., to minimize all things bad ("costs") and to maximize all things good ("benefits"). Despite the problems of finding common denominators for tangibles and intangibles, the problems of dealing with benefits to some that are costs to others, and the problems of allowing suitably different values for current, deferred, and "sunk" costs and benefits, as well as the sheer mathematical problem of combining all relevant elements into a single matrix, we do not doubt that some day the efforts that are being made here and there to arrive at an adequate comprehensive logical solution will bear fruit, and that eventually (with the help of modern computers) the models will be both solvable and sufficiently pragmatic to be believable. Until that day, however, we are forced to fall back on the method of instinct (or experience), practical parameter (political judgment), and trial and error.

What we discuss in this paper has to do with only a limited aspect of this last-described method, the manner of conducting the trial. Boiled down to its essentials, the method involves hypothesizing two or more alternative solutions to any given transportation planning problem. Initially, these solutions will be designed out of the accumulated experience of the planners as to which are the prime purposes to be met and which is the most economical, adequate way to meet them. The solutions will also be so designed and delimited that it may reasonably be assumed that, sooner or later, those who have the power to do so will wish to put them into practical effect. At this point, the cost/benefit analysis described in this paper takes over. Its principal purpose is to set forth, in systematic fashion, the costs and benefits of each given alternative to each of three major elements in the community. By thus detailing who is hurt and who benefited, in what respect and in what amount, by each of the alternatives, it permits at the very least an immediate choice among them, based on whom the choosers would most care to favor. More importantly, however, it gives clues (and the more numerous the alternatives the better it can do this) as to how to hypothesize better alternatives. Conceivably it might also point to the approach which clearly produces the most for all at the least cost to all, but barring a rare homogeneity of community interest, this is really too much to be hoped for.

The Groups at Interest

For the same reason that the sum total of workers, consumers, investors, etc., in a community adds up to far more than 100 percent, so the total of the three major groups with an interest in the solution of urban transportation problems also is more than 100 percent; however, it does not quite reach 300 percent. For the sake of simplicity, we refer to these groups, respectively, as "users," "operators," and the "general public." Defining their deliminations is anything but simple, however, and even more so is defining the character of their interests.

Users. —Who is a transportation user? Clearly, anyone who stirs outside of his abode, even if it is only a public walkway which is his transportation facility. True enough, when we examine the costs and benefits of "Transportation Alternative A" we are concerned primarily with the users of the facility or facilities specifically described therein. But we cannot stop there. If the facility were of a slightly different character, perhaps more people would use it, or less. Or it may produce benefits for users of a different facility, by relieving some of the strain upon it. In short, we cannot define the user group for Transportation Alternative A without expressing that alternative in terms of a transportation purpose to be served, rather than in terms merely of a set of facilities. And we must compare all of the alternatives under examination upon the same basis. For example, if the comparison is between different means, say a road and a rail line, for transporting "x" number of persons from A to B, we must examine each of the alternatives in terms of all of the persons traveling from A to B, whether they use either of the means specifically described, or neither.

Some of the problems of defining the user group for a specific comparison are immediately apparent. One alternative may have wider repercussions than another. If the transportation goal being served is defined too narrowly, conclusions may be vitiated by the user interests omitted. If it is defined too broadly, it may comprehend the interests of users on whom one or more of the alternatives may have no effect.

The circumsciption has to be at once geographical, functional, and seasonal. Here is where instinct and experience first come in. The greatest single transportation need in any large city is that of the daily journey to work. Provide for it, and in nearly every case you have provided more than adequately for all other transportation purposes, even if only by relieving the strain on otherwise-oriented facilities. Ascribe all costs to it, and you have allocated costs where there is the clearest benefit.

Singling out the daily journey to work automatically leads to the choice, for analytical purposes, of the days and the seasons of most "normal" travel. The problem of choosing which journeyers to work still remains. For some purposes, and to some extent for all purposes, the planner will wish to examine the effect of a set of transportation alternatives on the journey to work of all inhabitants of a city or metropolitan area as a whole. But the initial practical approach, in most cases, has to be in terms of a major pathway of movement, as defined by empirically determined volumes of movement and as shown graphically by the thickest lines on a traffic flow map. In the typical city, with its one strip or core of major employment concentration, these lines are like rivers flowing down to a sea, each with its own "watershed." By the thickness of the streams, one may identify the "natural" boundaries between watersheds. Each such watershed, or transportation "corridor," then becomes a basis for comparison among the present and proposed transportation alternatives that are hypothesized to serve it. The erratic streams that cut across "divides" will also have to be considered in due course, but the corridor is almost always the logical starting point.

Operators. —The role of operator is not always a clearly identifiable one. Take a private busline, or a self-supporting public one, and there is no difficulty: the operator is the entity that makes the outlays, collects the revenues, and pockets the difference. Suppose, however, the general public is involved, either marginally (as when a facility such as a rapid transit system is to some extent subsidized) or fully (as in the case of a public highway); who then is the operator?

For our purposes, we need a generic definition. The operator is that entity or conglomeration which pays the money costs attached to any given facility and which pockets any directly allocable revenue. Users of a particular facility may also, in another guise, be operators, and the two kinds of costs they bear must be distinguished one from the other. For example, the user of a city subway will pay a fare, which is his cost qua user; at the same time, part of his taxes may go to make up the current deficit, and this is his cost qua operator.

Special problems attach to the situation, normal in the United States, where the costs for some facilities are shared by a number of jurisdictions and the revenue collections are attached in varying degrees to the individual facilities. Who are the operators of facilities which are financed in whole or in part out of general revenues and/or out of gasoline taxes? In appraising the costs and benefits of a particular community's project, is it legitimate to consider only the costs and benefits to the taxpayers of the community itself, or should one take a geographically broader class of taxpayers into account? Are highway fund dollars allocated to a particular transportation project, a cost thereof, or a benefit?

The Community. —It should be apparent that wherever public expenditures and revenues are involved, there is a large measure of identity between operator interests and the community's interests. Unless taxpayers and community are to be regarded as one and the same, however, the identity is not complete. The community is no less diverse a collection of interests for transportation purposes than it is for any other, and the only real solution for cost/benefit analysis is to describe which community elements are either hurt or benefited, in what manner, and in what degree. It is for policy makers, not analysts, to determine the desirable mixture of pain and profit.

The questions of "who" and "in what degree" are complicated by the fact that much of the impact of transportation alternatives is either difficult or impossible to measure in dollars and cents. For example, while some monetary cost may be ascribed to air pollution, how is one to value permanent lung damage, and is one person's lung damage more costly than another's? How does one take account of the progressively lighter (generally) incidence of air pollution as one moves out from the center and form the major highways? Is a 50-mph broad expressway better or worse than a 30-mph narrow road with trees? How many million dollars of alternative construction costs equate with the nuisance value of a mile of elevated monorail? Difficult as it may be, giving form to intangibles like these is an essential part of cost/benefit analysis.

Even where quantitive values may more readily be attached, the impact on the community must still be defined in terms of specific groups. A new highway or a new subway raises land values along its route, but what does it do to values in areas not so favored? Is it a benefit to those who have to pay higher rents? How does one deal with the differential impact of alternative transportation designs on density of residence and consequently on cost of water and sewerage installations; is this a benefit to water-users (assuming a charge is made) or to the community at large? It is easy, in cost/benefit analysis, to gloss over distinctions like these.

TIME, COSTS, AND OPPORTUNITY

We have discussed the nature of the groups at interest. We have referred to the fact that comparisons of costs and benefits, with respect to any one of these groups, must relate to the identical transportation service for each of the alternatives (e.g., the weekday journey to work) if the comparison is to be valid. We come now to the central questions of the meaning of "cost" and of "benefit."

It is in the decision on what costs and what benefits are relevant, and by what yardstick to measure them that, in the minds of the authors, much cost/benefit analysis goes astray. At the risk of appearing elemental, therefore, this section devotes some attention to fundamental concepts of economic measurement. The sections that follow will go more specifically into the costs and benefits of particular relevance to users, operators, and the community at large.

It is hardly revolutionary to state that the real measure of cost (and frequently of benefit) is "opportunity." A cost is an opportunity foregone; a benefit may be a cost avoided. A benefit may also be measured in terms of income, or contribution to income; that increment of income to which the transportation source is essential is a measure of its opportunity value. Cost, conversely, may be a benefit foregone.

Measures such as these are neither easy to apply nor easy to communicate. However, even if deviation is expedient from time to time, the opportunity concept is the best single guide to sound analysis.

One of the most fundamental guidelines that flows from the opportunity orientation is that all cost/benefit analysis should be incremental analysis. We must start from what exists. The costs and benefits of alternative proposals are not the total operating costs or the total current benefits of those proposals, but what those proposals will add or subtract.

A corollary concept is that of sunk costs. Build a bridge, for example, and its costs go on forever. They are terminated neither by the final amortization of the bond issue that financed it nor by the physical demise of the structure. Only to the extent that there is some final salvage value can it be said that any part of the cost ceases.

What, then, is the proper cost measure for a proposed capital expenditure? Not the interest on the corresponding debt. Not the estimated annual physical depreciation. And certainly not, although one may find numerous examples of such "costing," total debt service and depreciation combined. The cost can be measured, in fact, only by the cost of money to the entity who pays it, and it is a cost which goes on year after year, ad infinitum, unless and until the physical capital can be sold and some part of the cost thereby recovered.

Deferred Costs

Fortunately for getting bridges and highways built, the practical man is quite aware that a dollar spent tomorrow has less value than a dollar spent today, so that even infinity has a practical limit. Aside from their irrevocability, the continuing interest (or imputed-interest) costs on today's expenditures are of a piece with the repair and maintenance and other current operating costs implied by any capital expenditure. The more that any of these costs may be deferred into the future (by postponing the expenditure) the less of a cost it becomes. How much less depends upon the opportunity cost of money in the area and to the operator who makes the expenditure.

Interest rates in a particular area become a doubly important factor, therefore, in decisions on whether to adopt a capital-intensive or a deferred-expenditure solution to any transportation problem. Not only do interest rates determine the continuing level of sunk-cost expense, but they also determine the extent to which far-future costs may be equated with near-future costs. Considering the former effect alone, Lang and Soberman (1) calculated in one example that the difference between a 4 and a 5 percent interest rate raised the unit cost per passenger mile of a rapid transit system by 7 percent. For a system with triple the construction cost, the unit cost increase of 1 percent higher interest was more than 14 percent. When this effect is coupled with the fact that

TABLE 1

COMPARATIVE OUTLAY OVER 20-YEAR PERIOD
(Data in tens of thousands of dollars)

Year	$100,000 Facility						$50,000 Facility					
	Interest on Sunk Costs		Current Maint., Etc.[a]		Total Fixed Cost		Interest on Sunk Costs		Current Maint., Etc.[a]		Total Fixed Cost	
	Current Value	Year "0" Value	Current Value	Year "0" Value	Current Value	Year "0" Value	Current Value	Year "0" Value	Current Value	Year "0" Value	Current Value	Year "0" Value
1	10.0	9.1	1.0	0.9	11.0	10.0	5.0	4.5	5.0	4.5	10.0	9.1
2	10.0	8.3	1.5	1.2	11.5	9.5	5.0	4.1	5.2	4.3	10.2	8.4
3	10.0	7.5	2.0	1.5	12.0	9.0	5.0	3.8	5.4	4.1	10.4	7.8
4	10.0	6.8	2.5	1.7	12.5	8.5	5.0	3.4	5.6	3.8	10.6	7.2
5	10.0	6.2	3.0	1.9	13.0	8.1	5.0	3.1	5.8	3.6	10.8	6.7
6	10.0	5.6	3.5	2.0	13.5	7.6	5.0	2.8	6.0	3.4	11.0	6.2
7	10.0	5.1	4.0	2.1	14.0	7.2	5.0	2.6	6.2	3.2	11.2	5.7
8	10.0	4.7	4.5	2.1	14.5	6.8	5.0	2.3	6.4	3.0	11.4	5.3
9	10.0	4.2	5.0	2.1	15.0	6.4	5.0	2.1	6.6	2.8	11.6	4.9
10	10.0	3.9	5.5	2.1	15.5	6.0	5.0	1.9	6.8	2.6	11.8	4.5
11	10.0	3.5	6.0	2.1	16.0	5.6	5.0	1.8	7.0	2.5	12.0	4.2
12	10.0	3.2	6.5	2.1	16.5	5.3	5.0	1.6	7.5	2.4	12.5	4.0
13	10.0	2.9	7.0	2.0	17.0	4.9	5.0	1.4	8.0	2.3	13.0	3.8
14	10.0	2.6	7.5	2.0	17.5	4.6	5.0	1.3	8.5	2.2	13.5	3.6
15	10.0	2.4	8.0	1.9	18.0	4.3	5.0	1.2	9.0	2.2	14.0	3.4
16	10.0	2.2	8.5	1.8	18.5	4.0	5.0	1.1	9.5	2.1	14.5	3.2
17	10.0	2.0	9.0	1.8	19.0	3.8	5.0	1.0	10.0	2.0	15.0	3.0
18	10.0	1.8	9.5	1.7	19.5	3.5	5.0	0.9	10.5	1.9	15.5	2.8
19	10.0	1.6	10.0	1.6	20.0	3.3	5.0	0.8	11.0	1.8	16.0	2.6
20	10.0	1.5	10.5	1.6	20.5	3.0	5.0	0.7	12.0	1.8	17.0	2.5
Totals	200.0	85.1	115.0	36.2	315.0	121.4	100.0	42.4	152.0	56.5	252.0	98.9

[a] Including additions and improvements.

Note: Minor discrepancies in addition are due to rounding.

maintenance, repair, and improvement costs generally start low and then trend upward over the life of a given facility, the desirability of low-investment solutions in a high-interest country becomes quite apparent.

One hypothetical example may serve to illustrate. Assume that the same transportation purpose will be equally served by a $100, 000 facility with a scale of annual expenditures for maintenance, repairs, and improvement trending upward from $1, 000, and by a $50, 000 facility with annual maintenance, etc., trending, more flatly, upward from $5, 000. Assume also an interest rate of 10 percent. Over 20 years, the comparative outlay would be approximately as given in Table 1.

In Table 1, the 20-yr crude total of the first alternative is 25 percent higher than that of the second alternative; it would appear to take an interest rate of as little as 3 percent to make the first alternative the cheaper. On a discounted cost (present-value) basis, the table shows very little difference overall: the first alternative is, for a 20-yr projection, 23 percent more costly. However, on the latter basis it may be calculated that approximately a 4 percent interest rate is the approximate indifference point. Change the configuration of maintenance and improvement costs to one in which the high-investment alternative gave even greater benefits in deferred maintenance and the low-investment alternative required a more rapid expenditure for improvements (e. g., addition of lanes), and an even higher prevailing interest rate would equate the two.

Table 1 is actually incomplete. For by the same token that the original capital expenditure is a sunk cost which involves a continuing "interest" burden, so is every subsequent cost, including the accrual of interest costs themselves. Each year's cost, in other words, should be compounded. In this particular instance a rough calculation suggests that the refinement would have no significant effect upon the relative costs of the two alternatives. Similarly, although the calculated totals would be different for a period of 30 years, or 40, instead of 20, the outlook again is for no substantial effect upon the relative standing of the two alternatives. Thus, in carrying out cost/benefit comparisons along these lines, the analyst will in each case have to decide—largely by inspection and by trial and error—how much refinement is necessary to a valid comparative conclusion.

As a practical matter, the usual way in which such a table would be set up is by time periods, say, of 5 or 10 years each, for comparison with the basic benefits to be secured (a certain level of a specific kind of transportation service) during each of these periods. Both costs and benefits would be calculated on either an average or an aggregate basis for each such time period.

GOALS AND INSURANCE

We have stated that alternatives should be compared for an identical transportation service, for example, a certain volume of journey-to-work traffic. Establishing this goal is one of the major elements in cost/benefit analysis and crucial to its validity.

Planners are well aware of the fundamental fact that transportation plans are not devised for today's traffic requirements, but for those in the future. It is not infrequent, however, that a single target date is picked as the measure of the requirement, and all design and comparisons based on that. Moreover, that single date may have attached to it but one projection of the potential demand, with no indication of how reliable the estimate and the quantitative range within which it may err. In cost/benefit analysis, this can lead to serious error.

As a practical matter, it is not possible to attach any mathematical probability to projections, for one can know neither the degree of validity of the hypotheses nor the extent of dependence or interdependence of each of the chain of factors leading to the final results. As a substitute, however, one can follow out the implications of several sets of hypotheses, each designed to give a plausible, but different result. It is particularly useful to work with a medium, high, and low. All of these should be well within the range of substantial probability, and the high should be as nearly equal in probability with the low as judgment can make it. The high and the low, compared with the judgment, or medium projection, then become rough indicators of the direction and extent of possible error.

Just as important as having a range is to have projections not just for one specific target date, but for each of a series of successive subperiods which add up to the total period of time—20, 30, 40, etc., years—in respect to which the competing alternatives are to be judged. It is only by thus setting up our analysis that we can begin to evaluate an important aspect of costs and benefits, namely, the "premium" cost of insurance against error and the corresponding benefit in terms of elimination of risk.

Premiums and Risk

Let us suppose that we have accurately added up all of the tangible and intangible costs of putting into effect a given transportation alternative, and that we have also accurately added up all of the benefits over and above meeting the assumed transportation service objective. There is still one important omission—the costs or benefits of having provided for a service objective which is either too high or too low. Since high-investment, long-life facilities have differing degrees of overprovision, period by period, from lower-investment, more flexible alternatives, it is only by taking successive readings that we can ascertain the true costs.

A characteristic of alternative transportation designs that enters into the picture is their differing lead times. The system which has to be built now in terms of a given estimate of demand in 1975 is obviously more costly in this respect than the system which can start adapting to meet it in 1970. Against this must be balanced the contingent cost of adaptation or of shortfall.

When we speak, therefore, of comparing alternative transportation systems against a common standard of transportation service, we do not necessarily mean that each system must provide the identical capacity. Each type of service has its own most economical time-phasing, in terms of its flexibility and cost of upward and downward adjustment. Differing economies of construction scale and of right-of-way acquisition are among the factors to be considered. It is best to examine independently each basic alternative, in terms of its costs of achieving low, medium, and high capacities, in each of several forward time periods, selecting that progression of construction which will differ least from the costs of meeting the projected low while minimizing the contingent costs of having to adapt to the medium or, with appropriate discount, to the high.

COSTS AND BENEFITS TO TRANSPORTATION USERS

At this point we may consider some of the specific kinds of costs and benefits that apply to each of the three groups which were previously defined. The first of these is transportation users.

The principal benefit to transportation users, obviously, is the basic transportation service provided. Usually this may be considered in terms of an extension of capacity. Let us say, for example, that we are considering the addition to a particular transportation corridor of either a new, four-lane highway or a rail rapid transit system. As already suggested, the objective with which either of these has to be matched is the phased net addition of a certain amount of capacity, time period by time period. By definition, either alternative will provide the same basic user benefit. It is thus only in the quality of the service provided by each alternative and in the respective costs to the users that differential user cost/benefits are to be found. And since each kind of addition will have a different effect upon the whole complex of transportation services offered, we must look not only at the specific increment as such, but at the changes it brings about in the qualities and costs of the whole transportation service offered.

The nature of these other qualitative and cost aspects is apparent enough; their quantitative evaluation is something else again. Travel time is a cost, but is it the same cost to all users? Comfort is a benefit, but how much is it worth? For the user who pays a fare, the money cost of transportation is clear, but how about the man who drives an automobile? Should the journey to work be costed marginally or ratably? Or should it bear all of the overhead?

It is not uncommon for economists to postulate the rational man and assume that the scale of costs and benefits to transportation users can be evaluated in this light. A private transportation company would hardly take these kinds of liberties with the customers. Rational or irrational, the scale of values of each transportation user is a personal one and the cost/benefit analyst has a duty to respect it.

Before he can work with such factors, however, the analyst must know what the personal preferences of transportation users really are. Hence, the importance of suitable field surveys.

Such adverse concomitants of public transit as having to stand, bumpiness of ride, waiting, walking to transit (especially in inclement weather), and lack of cleanliness are among the factors which incline some people to use private automobiles, even if they recognize an extra cost. On the other hand, irritations due to traffic congestion and difficulty in finding parking space (which often requires the automobile rider to walk some distance to his place of work) are among factors which recent surveys have shown incline automobile riders to switch to subways or commuter trains where available. There are limits, however; at least one survey turned up 8 percent of automobile riders who would not abandon that form of transportation come what may. And cost differentials will retain some part of the market for public transit customers no matter how bad the service.

The question arises whether, in cost/benefit analysis carried on for public policy purposes, these relative traveler values are a pertinent consideration. It may well be that a minimization of the time consumed in getting to work and that a certain degree of physical comfort are both in the public interest, insofar as they tend to maximize general productivity and morale. The public measurement of the benefit may be far different from the private one, however, especially as it affects different traveling groups.

Yet the preferences of individuals, and especially their indifference points with respect to various costs and amenities, are of paramount importance to the planners of transportation systems. An alternative transportation plan which depends upon a distribution of ridership among modes in a way in which individuals with free choice will not distribute themselves is not a real alternative. Consumer preferences, therefore, really are an element in feasibility analysis. Such analysis, at least in preliminary form, should precede cost/benefit analysis and thus insure that consideration is being given to practical proposals.

One should start with a set of projections of patronage, under different assumptions of user-charge, service level, and aggregate transportation demand, for each of the specific kinds of transportation which form part of a possible transportation alternative. For tentative reasons of community interest, which can then be verified in the course of cost/benefit analysis, one can assume charges which are more or less than actual cost in order to achieve a given patronage level, but otherwise (and especially in the case of private operators) the equating of costs and charges would seem to be a priori the most desirable policy. Howsoever the pricing, the marginal user of each facility will presumably be equating his private costs and benefits. Pricing in accordance with economic cost will minimize the aggregate accrual to others of economic surplus.

One might add that the element of publicly established penalty or subsidy, particularly for automotive transportation, is frequently difficult to identify. License fees and gasoline taxes may or may not equate, jurisdiction by jurisdiction, with the street and highway facilities provided. Public central-city parking (especially street parking) may be priced far below the opportunity cost justified by the particular location. And the public at large may be bearing a cost in air pollution, noise, and aesthetic discomfort toward which the automotive-vehicle user pays nothing.

COSTS AND BENEFITS TO OPERATORS

The considerations here are rather different as between privately operated facilities and those operated by a public authority. The public at large can have only marginal interest, if any, in providing a surplus of benefit to a private operator, and it cannot long impose on him a surplus of cost without having either to forego or to take over the facility.

When the public operates a facility, it can take into consideration costs and benefits external to the facility itself. If one thinks of the operator of a public facility as the community's taxpayers, it is plain that the kind of facility which results in higher tax collections, or lower costs for some other public service, may provide a balance of benefits over costs even if the facility as such does not pay for itself.

There is, however, a common element in all systems, whose separate examination leads to more knowledgeable policy decisions. There is a core—whether one has in mind, say, a transit system or a system of highways—which consists on the one hand of certain expenses and on the other hand of certain directly-allocable user charges. Public or private, such an entity may be separately examined as an economic unit, and its deficit or surplus position determined.

We discussed some of the aspects of costing capital expenditures and maintenance and improvement of facilities. The fundamental criterion for capital items was the interest, or opportunity, cost of capital employed, and we pointed out that this manner of costing logically may be applied as well to annual, as to initial, costs, provided they are big enough to make any material difference. The latter is consistent with normal private accounting practice, which capitalizes alterations and additions, while expensing repairs and maintenance, though the distinction is frequently quite arbitrary. In connection with capital employed, the private operator is likely to be concerned only with the opportunity cost of his own equity capital, and to regard interest on borrowed funds as an expense; but for a public operator, and for general economic analysis, it is the average cost of all capital employed which is pertinent.

We have pointedly omitted reference to capital consumption or depreciation which, for transportation facilities particularly is probably far surpassed by obsolescence. Both of these are taken as a cost in private accounting practice, and are allowed to varying degrees by income tax authorities and by the public utility commissions which enforce a fair rate of return. One must remember, however, that any such depreciation and obsolescence allowance must also be deducted from the current capital base.

Given our indefinitely-continuing sunk cost concept, allowance on top of that for obsolescence or depreciation would be double-counting. If we are to choose the other kind of costing, we must make a deduction year by year for the diminution of capital employed. To deal only with sunk costs and ignore the capital consumption seems preferable, however, and more in line with economic reality. No cash passes hands by reason of the annual capital write-off, and neither the public nor the private operator has any less investment to cover. The amount of write-off has no relationship to the actual annual cost of continuing the investment and the money invested is not recovered just because the write-off is 100 percent. Thus, the indefinitely accruing, but time-discounted, money-cost seems the better measure, with obsolescence being reflected instead in the forward estimates of revenues derived from patronage.

There are, of course, other costs besides capital costs, including all of the fuel, labor, and operating expenses that are familiar in utility accounting. There are also current revenues to be taken into account, and it is quite legitimate to deduct from prospective capital employed any cash surplus that is projected to be available either to private or to public operators for withdrawal from the business.

Highway Costs and Benefits

The allocable costs and benefits of a highway enterprise are ordinarily most difficult to estimate. Except for toll roads, the public authorities which operate streets and highways make their collections from the users indirectly, through gasoline taxes, license fees, and fines, rather than on and for the occasion of a specific use. Moreover, in the United States at least, drivers may be utilizing the roadways of jurisdictions A, B, and C in far different proportions from those in which they are paying taxes to the same jurisdictions. Also in the United States a large part of gasoline tax collections goes to the Federal Government, which then re-transfers them according to various formulas to the states; hence, it is not at all clear what, for any given community, constitutes an allocable user charge. Undoubtedly there are similar situations in other countries.

Under the circumstances, it is more practical simply to attach income, as well as expense, to the existence of the projected facility, rather than regarding the revenues as attributable to specific users.

To do this one must estimate what the particular road or highway increment under consideration is likely to mean in terms of increased vehicle mileage resulting in taxes collectible by the particular jurisdiction, as well as what transfer funds from other jurisdictions may be obtained for and on the basis of the increment's construction. (Or construction grant funds obtained elsewhere may, even more logically, be regarded as a diminution of the capital employed by the community-operator.)

One sort of question that arises is whether the particular increment of facilities pays for itself. The question is especially pertinent to the provision of peak-hour additions to the highway network in comparison with the addition of rail transit to satisfy the same requirement (assuming, for the moment, the feasibility of shifting patronage either way). Since the extra highway facilities would not be needed except for the peak-hour commuters, it is obvious that the entire cost must be charged to this group. Whether this cost is covered by corresponding revenue or whether, as there is some reason to suspect, peak-hour highway commuters are subsidized by other highway users, may be determined from a projection of the additional vehicle-miles which would not be traveled were the extra lanes not available. Since gasoline consumption may be estimated from vehicle-mileage and gasoline tax collections from gasoline consumption, a calculation of the allocable revenues may thus be made.

In assessing highway costs, it is important not to overlook certain peripheral costs that are a necessary adjunct to a highway's utilization. Through-highway capacity is useless, for example, without the local streets which feed into it and take off from it; increased capacity for one may demand an increased capacity for the other. There are also additional costs of policing and traffic control and possibly of general administration. If the community-operator undertakes to provide parking facilities at less than cost, this, too, must be taken into consideration.

Mass transportation systems may also involve some of these peripheral costs (such as policing and administration) which are not met by the operation as such. Moreover, whenever one deals with a bus or street car system, or any other system that makes use of public facilities not directly entering into its accounts, the community as operator of the relevant public facilities finds itself as partner-operator of the particular transportation mode and must enter the differential costs of the relevant public facilities into the operator cost/benefit analysis.

There is still another set of transportation-system costs and benefits to the taxpaying element of a community, that which stems from the impact of systems, or additions to systems, on the community's taxable base.

COSTS AND BENEFITS TO THE COMMUNITY

There is no homogeneity within each of the various groups concerned with transportation system costs and benefits. This is particularly true of the community. In the discussion which follows, when we speak of the impact on the community, we may be glossing over any number of distinctions which are quite critical to actual policy decisions. This is necessary for purposes of general discussion. In any specific situation, the analyst will have to be specific about who is affected, and to what extent, by the kinds of impact set forth.

There are four major ways in which a planned transportation increment may affect the community: (a) in terms of general pattern of community growth; (b) in terms of public revenue and expenditure; (c) in terms of direct income; and (d) in terms of environmental conditions. These aspects are heavily interrelated, but it is convenient to discuss them separately.

Community Growth Pattern

It may be thought that transportation facilitites respond to the demands of community growth, and to a large extent this it true. More importantly, however, they help to determine the pattern of that growth.

A community which provides an extensive system of roads and highways of the type which permit high-speed automobile travel is a community which will grow extensively. One may expect an emphasis on one-family homes, the spread of suburbs, and decentralization of shopping, cultural activities, and much business and industry. The community which discourages automobile travel but provides efficient rapid transit as a substitute is likely to be more closely concentrated, with multiple-family and high-rise residential structures, and a more active central core. The community which provides an adequacy of neither is likely to find its overall growth stunted.

There are numerous variations. For example, both highways and mass transportation facilities may be planned so as to provide clearly detached radial corridors. Development will be extensive, heaviest along the corridors, yet centrally oriented. Provide connecting belts and there will be faster filling in of the space between the radials, plus a greater shift of commercial and business facilities to the suburbs.

A mass transportation facility provided early in the development of a particular area may generate its own traffic in terms of close-by high-density residential construction; one provided later may have forfeited its clientele to low-density development, regardless of whether or not adequate road facilities have also been built.

Quite apart from economics, there are both positive and negative values which may be attached to different kinds of community organization. These values will vary from community to community. Where one community values dispersed living, another will be more interested in easy access to metropolitan-quality theaters and sports arenas. One will prefer growth and differentiation; another exclusivity and uniformity. More importantly, different elements in a community may have different views as to the most desirable urban configuration. It will be up to the analyst in each case to determine to what extent the furtherance or hindrance of any of these values attaches as a benefit or a cost to a particular transportation proposal.

Public Revenue and Expenditures

It is not uncommon, in analyzing the impact of a proposed transportation improvement, to estimate the increases in land values along its path and count the improvement as an addition to the community's taxable real estate base. On this basis, kinds of transportation additions which result in more concentrated development (such as subways) tend to be attributed larger benefits than additions of equivalent capacity which lead to less concentrated development. The practice is dubious, for any influence which simply places the location of development in one area rather than another, or concentrates rather than disperses it, is likely to produce somewhat higher land values in one area only at the expense of somewhat lower values elsewhere. For one system to be attributed more of a contribution to the tax base than another, it has to be shown either that it results in a volume of urban occupancy or activity which is greater in total, or that value of land and structure use per person or per unit of activity is greater in one kind of location/density arrangement than another.

At this point one must also note that what is a benefit to the community in revenue terms may not be a benefit to it in other terms. It is possible, of course, that if a given kind of development results in higher land value per unit of activity or per resident than another, this is exactly balanced by a locational saving. But it is also possible that competitive bidding for some land areas may run up their values to the point of displacing former users who are then forced into less advantageous combinations of cost and location. This is a typical consequence of urban renewal or of the opening up of metropolitan transportation to formerly detached rural settlements. It is also possible, where the effect is to encourage more extensive use of outlying land, that the community may gain increased tax base only at the cost of losing to present development land which is highly valuable for future recreational and other public needs.

Another aspect of competitive transportation systems which affects tax revenue is the relative land consumption of the facilities themselves. Nearly all transportation facilities predominanty or wholly involve public rights-of-way rather than taxable land and thus bring in little or no real estate revenue. By economizing on the use of land, buses compared with private automobiles, and rail transit compared with automotive, should leave that much more land (especially in valuable downtown areas) available for taxation. Except, however, where the total land available to an urban community is limited (by the presence of competing jurisdictions on the boundaries or otherwise), one cannot be certain, as in the case of along-the-route impact, that displaced activities may not occupy equally valuable (though more extensive) parcels of land elsewhere. As a rough guide, however, one can assume that the kinds of transportation development that raise the proportion of land occupied by highways and streets to the total of all occupied land in the municipality do detract from the revenue-expenditure balance in comparison with kinds of developments which keep the proportion lower.

Community Income

One of the ways in which transportation systems act differentially on urban finances is in their differential impact on community income. Here, too, however, what serves to increase tax collections is not necessarily of real income advantage to the community's residents.

The clearest case of advantage is the kind of differential transportation development that attracts to the community more income-producing activity per capita. Growth as such may mean more income in the aggregate and higher tax collections, but unless it is on a par with what already exists it may mean even faster increases in community expenditures.

In monetary terms, increased transportation facilities themselves create more income (and more tax revenue), but in real terms exactly the opposite may be the effect. If the average urban dweller is to ride a half-hour for 50 cents where before he traveled 15 minutes for 25 cents (or walked, at no monetary cost) can it be said that he is any the wealthier for it? He may be, if he has gained some net locational advantage, but more likely is the fact that sheer extensivity of growth has created for the average person a greater real cost. Similarly, comparing two proposed transportation systems, the one designed for longer travel distances at higher cost and the other for shorter distances at lower cost, it does not follow that the higher dollar income producer is the more beneficial.

Other things being equal, it may be said that the transportation alternative which minimizes average travel time is the superior contributor to community real income. Other things may easily not be equal, if one alternative also inhibits more than another the pursuit of some other personal income value. Nonetheless, the productivity of the average person's day is clearly higher if he need spend less of that day in routine travel, and the aggregate productivity is a multiple of the average. Similarly, other things being equal, the system which provides the greater degree of per capita comfort and health is also the most productive system for the community as a whole. Thus, there is an identity between certain user benefits and the general community good, and to this extent, it may be in the community interest not to exact a corresponding user charge.

Another important aspect in which there is an identity between user and community benefit is that of relative freedom from accidents. Judging by insurance costs, systems differ markedly in this respect: typical United States costs per thousand passenger miles are $8. 00 for private automobile travel, $1. 70 for buses, and less than $0. 80 for subways. These costs already suppose an impressively large countervailing expenditure in the form of safety campaigns, policing, road hazard elimination, special driver training, etc. To the extent that there is still an accident incidence, the community is doubly hit, both in the necessity for hospital and other accident-relief expenditures and in the lost productivity of the individuals involved, not to mention the incidental property losses.

Environmental Aspects

Finally, there is a whole series of environmental costs and benefits which directly affect not the individual transportation user, but broader segments of the community. They involve such relatively tangible factors as health and welfare and such quite intangible factors as aesthetics and other forms of psychic income or expense.

Different transportation means are quite different in their contribution to environmental health hazards. The most notable contributor, in urban areas, is the automotive vehicle, and one must take account, in any cost/benefit analysis, of the relative pollutant effect per passenger carried of an automobile as against a bus, of a gasoline engine as against a diesel. The particular regulatory antidotes which are possible will affect the cost/benefit appraisal in any given situation, as will the relative density of vehicular movement and varying climatic conditions.

Different transportation means are also different in their contribution to noise levels, exclusion of sunlight, pedestrian hazards, and other factors bearing upon health of city dwellers and workers.

Air pollution, noise, vibration, etc., can also be hazards to property and result in economic loss directly. Some authorities contend that property damages caused by air pollution in the United States average $65 per capita annually, of which about 80 percent, or $52 per capita, is attributable to automotive exhaust. These damages take the form of accelerated corrosion, and damage by dirt or dust to buildings, furniture, machinery, tools, and other items.

In some ways, aesthetics is the most difficult of all items to evaluate; yet in any given community it is possible to get a feel for what the community values and will come to value. Different transportation alternatives have varying effects on the presence or absence of open spaces, trees, wooded areas, depending on their land requirements and the section of the city through which they go; different communities place different values on these amenities. Street car tracks, surface railroad, open cuts, and elevated lines all present differing degrees of negative value to different groups. Some communities are ready to accept modernistic monorail structures, where an old-fashioned elevated line would be taboo. Some communities take huge automobile parking lots for granted, while other regard them as eyesores. Some communities cherish quiet urban byways or pedestrian walkways, while others "couldn't care less."

Perhaps the most important question in applying these values is to determine who is to be the arbiter. Certainly not majority opinion alone, for a successful community must also satisfy important minorities; on the other hand, not the experts and planners alone, for they may be out of tune with the great bulk of the public, and in matters of aesthetics there is no absolute right; and not the opinion of today alone, for interests and styles change.

About the only real guide the transportation planner can follow is (bearing in mind economics) to make those choices which will offend the fewest and please the most. He will also be most careful with the kinds of choices that leave the longest-term imprint and are the hardest to reverse, for in respect of these particularly, he must be certain that what is a benefit today will continue to be a benefit in the years to come.

REFERENCE

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