A Rational Decision-Making Technique for Transportation Planning

WILLIAM JESSIMAN and DANIEL BRAND, Traffic Research Corporation; and ALFRED TUMMINIA and C. ROGER BRUSSEE, Massachusetts Bay Transportation Authority

Evaluation of transportation improvements by conventional benefit-cost analysis raises the problem of trying to evaluate benefits (or costs) which cannot readily be converted to dollars and cents. Sometimes these benefits are neglected. Sometimes they are converted to dollars no matter how crude the estimate. Most often they are merely qualitatively weighed in the mind to determine whether or not they are sufficient to alter the decision recommended by the economic analysis based on the quantifiable factors.

To help in these situations, a technique or framework is presented which would treat all pertinent factors more rationally and systematically. Examples are presented showing the results of the technique at each intermediate step. An extension of the technique is made to consider a system of possible projects and the optimal allocation of available capital among them. This extension results in a problem which may be solved by integer linear programming techniques. The formulation of this linear program is shown.

•MOST major transportation facility plans today evolve from a procedure wherein various alternatives are generated and evaluated, and the one which appears most favorable is selected. The evaluation process utilized is quite often a benefit-cost ratio technique or something closely related to it. This means that each of the benefits and costs associated with an alternative are itemized and appraised in dollars and cents to avoid the "apples and oranges" comparison dilemma.

Several problems confront the engineer or planner who is trying to evaluate alternatives by this method. He must be sure he has stood far enough away from an alternative to have considered all its effects on the overall system. For many effects which he has delineated there are serious problems of how to convert their impact on the system to dollars and cents. Quite often the solution to the problem of not being able to assess the dollar value of some of the benefits or costs is to ignore this factor on the grounds that its impact cannot be measured accurately enough with the monetary yardstick. There is also the frustration of having singled out a pertinent benefit or cost and converted it to its estimated dollar value, only to realize that the factor is an order of magnitude more important than some more obvious factors which he has painstakingly developed and evaluated. Perhaps he is reluctant to believe this, even though the dollars point it out. Finally, although everyone is in favor of better transportation, there is considerable difference in points of view as to what this means. The transit manager, the city engineer and the local communities may have radically different goals for "better transportation."

It is useful to consider the example of a public transit agency or a highway department evaluating a facility being built in a growing suburban region. Many objectives

Paper sponsored by Committee on Transportation System Evaluation and presented at the 46th Annual Meeting.

or goals, both public and private, must be considered in selecting the optimal length and location of the facility and the level of service to be provided. It should be appreciated that all examples of objectives used here should be viewed liberally since it is the decision technique and not a recommended set of objectives that is the central theme in this paper. The following are some examples of objectives which might be deemed important:

1. The facility should show the best possible revenue-cost picture or tangible return on capital invested. This includes not only the facility being considered, but any other facilities in the system which are also affected, including feeder bus service and private transit companies in the case of transit.
2. The highway or transit facility should serve as many users as possible.
3. The facility should remove as much congestion as possible from neighboring facilities.
4. Priority should be given to an area which has long been without sufficient service, or one which has a critical transportation need.
5. In the case of transit, an improved quality of service should be provided to enhance the public's image of transit and to halt the general trend of diversion from transit facilities to automobiles. The type of improvements in service quality may vary from area to area depending on marketing recommendations.
6. The alternative selected should further the economic development of the communities it is affecting. In addition to the level of economic impact on the community, this objective involves both the timeliness of making this impact now, and the direction of the communities' own plans for development or redevelopment. The generation of potential tax revenue by new residential or industrial development along the new route is included here.
7. The agency must satisfy certain political requirements and constraints.
8. The facility should have the most flexibility to meet anticipated future growth or a variety of assumptions on anticipated growth.

This very general list of objectives would need to be refined before being applied to a particular facility study. Still, all the above factors merit inclusion as legitimate objectives of a transportation agency. Collectively they present an appealing description of what an agency is setting out to accomplish. However, when it comes time to apply these objectives to the evaluation of alternatives, some difficulty is usually encountered.

A good deal of time and effort is spent analyzing the first objective, maximization of direct return on capital. This is especially true in the example of a transit agency planning a new extension, where the return on capital is in the form of increased net operating revenue. The third objective, removal of congestion from highways, is often evaluated by determining the number of minutes the average automobile commuter on the highway saves and multiplying by some dollar value of time saved and the number of automobiles using the highways. However, in transit cases, this estimate can rarely be as accurate as an operating balance forecast because of the crudeness of present-day dollar values for time. Yet, it is probably the same order of magnitude as the estimated operating balance even if logically it might not seem as important. For instance, a typical rapid transit extension may result in an increased operating balance (increased revenue minus increased operating cost) of $200,000 per year. Yet, if the transit extension results in decreased peak-hour highway congestion such that the 6000 rush-hour commuters still in their automobiles save 5 minutes each way on the average, this can be calculated as a saving of (6000 people) (2 directions) (5 minutes) ($1.50[1] per hour value of time) (250 days per year)/(60 minutes per hour) = $375,000 annually—and this is for the rush-hour alone. Most transit agencies would probably feel that the increase in operating balance really is worth far more than the decrease in automobile congestion in spite of these figures.

[1]$1.50 per hour is typical of a value assigned for this type of estimate, although there is, of course, much discussion about what amount should be used.

The same situation applies to the objective of maximizing the economic welfare of the affected communities. Some crude value estimate is often made for this factor, but usually it only serves to water down the effect on the decision of the more accurately measured costs and benefits. Often the recourse is to abandon any attempt to quantify these factors for benefit-cost analysis purposes and merely use them in an all-or-nothing manner. In effect, this means determining whether or not these factors are sufficient to alter the decision recommended by the economic analysis based on the quantifiable factors.

Other objectives in the above list are almost always considered qualitatively only. Improvement in quality of service, the satisfying of a critical transportation need, and the satisfying of certain political constraints are examples, with the latter managing to demand a large amount of attention historically. Still other objectives are converted dogmatically to dollar units in spite of difficulties or inadequacies.

The problem, therefore, is to find a way to consider explicitly the significant benefits and costs not given to monetary measurement simultaneously with those which can be estimated in dollars and cents.

THE SINGLE PROJECT EXAMPLE

The solution described in this paper to the stated problem is best introduced in the context of planning a single project. Such a project may, as before, be a radial highway or a transit extension to be built in a rapidly growing suburban corridor. The alternatives in the case of the highway vary in terms of the location and lengths of new highways, the design standards to be applied, number of lanes, etc., and, of course, whether or not to build any facility at all. In the case of the transit extension, the alternatives vary in the length and the location of the line, the type of cars, the seating standards, the operating speeds, number of stops, etc., as well as whether to build anything at all.

The technique offered for the evaluation of alternatives is given in five steps. The corridor transit extension is a useful example since it is characterized by both public and private motives.

Itemize the Objectives

Assume that the transit agency feels there are five major objectives which ought to be met by the extension of transit service into a particular corridor. Again, this list of objectives should not be thought of in any way as a recommended set of goals, but rather merely as examples:

1. The immediate direct rate of return on investment, i.e., the increase in operating balance at the end of the first year of operation divided by the annualized capital cost of the extension, should be as large as possible. (Operating balance is passenger revenue less total operating costs.) Reference to changes in net revenues over a longer period of time are left out here to avoid excessive complication.
2. Riding volume on the line after the extension and the system have reached a state of equilibrium should be maximized.
3. The image of the transit agency should be enhanced by offering as much comfort and convenience as possible.
4. The transit agency feels it is desirable for political reasons to extend as far as possible into the corridor to promote development of an area rendered relatively inaccessible by inadequate transportation facilities.
5. As many automobile users as possible should be diverted to transit so as to relieve congestion on the corridor's primary highway.

Next, assume that five feasible and different alternative extensions, varying in location, length, and service characteristics have been proposed. (The no-action alternative is not included for purposes of the illustration.) These will be called alternatives A through E and are to be evaluated according to how well they meet the five objectives.

Define the Best Measure for Each Objective

The transit agency decides that the measureable characteristics of the alternatives which best exemplify the five objectives are as follows:

Objective	Measure of Objective
1.	Increase in annual operating balance divided by annual capital cost of building the extension.
2.	Total daily inbound rider volume.
3.	Average percent seated during the peak hour at the peak load point.
4.	Miles of extension into the corridor.
5.	Auto-users diverted to transit during the peak hour.

Weight the Objectives

The transit agency further decides that the first objective is worth about 40 percent of the total decision. Similarly, weights or fractions of the decision are assigned to the other four objectives so that the objectives are weighted as follows:

Objective	Weight	Alternate Weighting Scheme
1.	0.40	8 points
2.	0.20	4 points
3.	0.15	3 points
4.	0.15	3 points
5.	0.10	2 points
	1.00	20 points

Since the weightings are relative only, fractions which total one do not need to be used; any set of numbers with the appropriate relative values may be used, as indicated by the alternate weighting scheme. For purposes of this presentation, the alternate weights will be used.

One point to note regarding the selection and weighting of objectives is that it is easy to choose objectives which are not mutually independent. For instance, hauling the most people possible and diverting the most automobiles from the highway are very much related to each other as objectives for a transit line. It is not wrong to use non-independent objectives as long as judgment is used in the weighting of them. However, it probably helps to select just one of the two if they are very closely related.

Evaluate the Way Each Alternative Meets Each Objective

Assume, for this example, that values of the pertinent descriptors of each alternative have been estimated by various suitable techniques. Discussion of the actual techniques used are not important to this paper and will not be discussed. The estimates assumed for the five alternatives in the example appear as follows:

Measure		A	B	C	D	E
1.	a. Increase in annual operating balance ($ millions)	0.780	0.812	0.550	0.702	0.675
	b. Annualized capital cost of building the extension and purchasing rolling stock ($ millions)	6.000	5.800	5.000	5.200	4.500
	c. Annual return on investment (= a/b) (%)	13.0	14.0	11.0	13.5	15.0
2.	Daily inbound riding (thousands)	25.0	23.0	20.0	18.0	17.0
3.	Average percent seated, peak hour (%)	25.0	35.0	40.0	50.0	50.0
4.	Miles of extension into corridor	8	7	6	5	5
5.	Peak-hour auto users diverted to transit (thousands)	3.5	3.0	2.0	1.5	1.5

The simplest method of evaluating the alternatives with respect to a particular objective is to arbitrarily say that within each objective, the best alternative in the category receives the full number of points under the weighting scheme, and the worst alternative receives no points. Each other alternative receives a number of points which is linearly proportional to where this alternative lies in this category relative to the best and worst alternatives. For example, in meeting objective 4 (length of extension), alternative A rates highest with 8 miles and receives a full 3 points. Alternatives D and E each get zero points since they are the shortest with 5 miles. Alternative B gets 2.0 points since it is ⅔ of the way from the worst alternative to the best $\left(\frac{7-5}{8-5} \times 3 \text{ pts. max.} = 2 \text{ pts.}\right)$. Similarly, alternative C receives 1.5 points.

Selecting the Best Alternative

When each objective is evaluated for all alternatives, the rated points can be summed for each alternative and the alternative with the highest number of points is said to best meet the combined objectives of the transit agency. Had the fractional weighting scheme been used (sum of all weights equals one), the sum total for any alternative would be a fraction less than or equal to one. The fraction would express how close this alternative was to the "ideal" alternative, that is, one which ranked best in each category. With the point scheme used in this example, dividing each alternative's total by the number of points possible, 20, accomplishes the same thing. Complete results for this example are shown below.

Objective Measure	A	B	C	D	E
1.	4.0	6.0	0.0	5.0	8.0
2.	4.0	3.0	1.5	0.5	0.0
3.	0.0	1.2	1.8	3.0	3.0
4.	3.0	2.0	1.0	0.0	0.0
5.	2.0	1.5	0.5	0.0	0.0
Total	13.0	13.7	4.8	8.5	11.0
% Total of Ideal	65.0	68.5	24.0	42.5	55.0

It should be pointed out that some objectives might not be so easily quantifiable. In this case it would be perfectly legitimate to use a quality judgment scale such as high—3 points, medium—2 points, low—1 point.

One shortcoming of the particular "relative" rating scale chosen for each objective in this example is that the best alternative gets a full score even though it may be far from perfect, while the worst alternative gets zero, even though it may be almost as good as the best alternative. However, for other objectives there may be large differences between two alternatives and they can end up with about the same number of points. This shortcoming is illustrated by considering what happens in category 4 (mileage of extension) if a new alternative is added. Before the inclusion of the new alternative, alternative A had 3.0 points in this category, while alternative D had zero. Suppose the new alternative proposes only 2 miles of extension into the corridor. Alternative A still has 3.0 points but now alternative D has 1.5 points since the new alternative becomes the zero point on the scale. Thus it is conceivable that addition of the new alternative, even if it is the worst of the six, has the ability to change the recommended outcome from one alternative to another. This problem may be avoided by the use of utility curves[2] to evaluate alternatives within each objective. However, in defense of the simple-to-use "relative" rating scale, the problem is not as severe as it may appear at first glance. The original weights could be attached to each objective, keeping in mind the magnitude of variation within the alternatives to be evaluated. If, for any objective, a large range of values among the alternatives is anticipated, more or less weight may be assigned to that category to properly express the importance of the objective. Thus, the addition of another somewhat different alternative could very well mean that a new weighting of the objectives is in order, and therefore the problem cited in this example is unlikely to occur.

Use of Utility Curves in Evaluating Alternatives

One way of avoiding the problem altogether is to use a predetermined absolute scale for each objective instead of using the relative scale. For example, the agency may decide before examining any physical alternative that a 10-mile extension is the ultimate and should be worth 3 points, while building no extension at all should be the zero point alternative (see Figs. 1a and 1b for comparison of the two scales). As can be seen, alternative B now rates 2.1 points instead of 2.0 under the relative scheme. The utility curve approach has the advantage of not being affected by the addition of another alternative.

The relationship represented in Figure 1b need not be linear. For example, the first mile extension into the corridor may be more desirable than the second, and so on, until the marginal utility (with respect to achieving the proposed objective) approaches zero beyond a 10-mile extension. Figure 1c expresses this relationship.

Figures 1b and 1c are utility curves in statistical decision theory terms. They represent the agency's feelings about the utility of each mile of extension with respect to the satisfaction of the particular objective.

There are pros and cons to each of the two methods of evaluating objectives—or three methods if the linear utility curve is thought of as different from the nonlinear one because the simplicity of the former requires only two points to be defined. The utility curve approach is more difficult to use, yet it forces the planner to think in terms of the complete range of values of an objective within which any of the possible alternatives may lie. It may be advantageous to carry out this thought process before proceeding to examine the alternatives in detail. The relative technique has the advantage of simplicity of use, and bypasses having to define the utility curve. (However, one of the bigger objections to utility curves is the difficulty in getting a person to define his utility curve.) In reality there is no reason why a mixture of techniques could not be

[2]Utility curves are described in detail in: Schlaifer, R., Probability and Statistics for Business Decisions, McGraw-Hill, 1959; Shelly, M. W., and Bryan, G. L., Human Judgments and Optimality, John Wiley and Sons, 1964; and others.

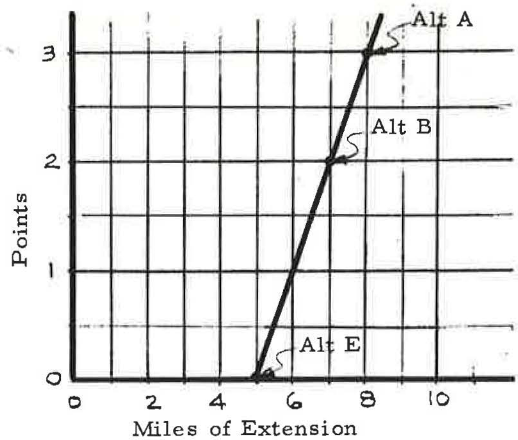

Figure 1a. Relative technique for evaluating objective in example.

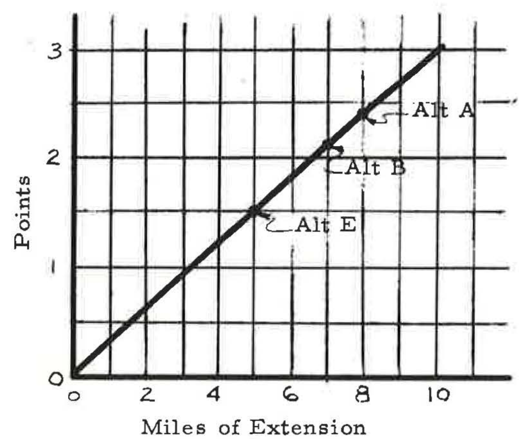

Figure 1b. Linear utility curve technique for evaluating objective in example.

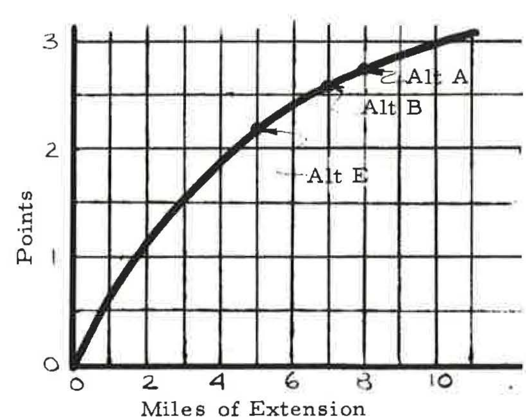

Figure 1c. Nonlinear utility curve technique for evaluating objective in example.

used for different objectives, if so desired. For example, automobiles taken from a highway might well be measured using a nonlinear utility curve, whereas net operating balance increase could be analyzed using the relative technique.

An important exercise which could be very interesting as well as very revealing in the examination of certain controversial highway or transit projects would be to have (or to simulate having) each different faction involved in the controversy—planning staff, city officials, academics, etc. —weight the objectives and evaluate the alternatives according to their own value schemes. The question to be answered is, How do the different value schemes affect the decision reached? Often the decision is the same for the different spheres of interest. However, the decisions sometimes differ, and the knowledge gained as to why they differ may be valuable. Persons familiar with the thought processes of the various interest groups in a community can gain much insight into underlying reasons for controversies surrounding a project. They may thus more easily achieve a suitable compromise for implementing the transportation improvement as well as promote good planning. In addition, a user may find it valuable to vary his own weights where he is unsure about them, to test the sensitivity of the final decision to his weights.

THE COMPLETE SYSTEM SOLUTION

In an earlier section, the five-step technique for aiding in decision-making was presented in the context of alternative proposals for a single transportation project.

One objective which was not explicitly mentioned previously, but which is a legitimate one in some single transportation facility studies, is the goal of minimizing capital cost. In fact, using this decision technique, the capital issue could even be handled by plotting various total values of the objectives against the capital necessary to achieve this degree of satisfaction of objectives. This sensitivity analysis on capital cost could then be analyzed and the most desirable combination of cost and level of satisfaction could be chosen. Another variation involving capital cost might be the introduction of an objective such as maximizing total utility per dollar spent for situations where there is no budget as such.

A more common situation, however, is one in which the transportation agency has a limited but definite budget and a number of projects to be constructed from that budget. Now the emphasis is on optimal allocation of the budget among projects rather than the minimization of capital expended on all projects. The expansion of the decision-making technique from a single project to a system-wide set of projects, each with several alternatives, may thus be considered. The decision technique becomes part of the structure of an integer linear program for complete system analysis.

Assume that several transit extensions into various corridors are being considered and that a limited capital budget exists with which to carry them out. These corridors can be generalized as subsystems, since corridor extensions need not be the only projects which the agency is contemplating. Within each subsystem there is a set of alternatives to be evaluated, including the null or do-nothing alternative. The agency defines four objectives, weighted as indicated:

No.	Weight	Description
1.	Z_1 pts	Maximize daily passengers hauled
2.	Z_2 pts	Divert as many cars as possible from the highways during the peak hour
3.	Z_3 pts	Exhibit the maximum annual net operating balance with the new system
4.	Z_4 pts	Operate the most comfortable and convenient service possible during the peak hour

The agency has decided that for each alternative the parameters which best reflect the above objectives are, respectively, (a) total daily volume carried; (b) total peak hour volume carried; (c) increase in net annual operating balance (increased revenue minus increased operating cost); and (d) average percent seated during peak hour.

The agency has decided to use the linear utility curve for evaluation of objectives (although the formulation is identical if the relative technique or the nonlinear utility curve method is used). The formulation is as follows.

Define:

N = number of subsystems or corridors
n_i = number of alternatives in subsystem i
B = total budget available
Z_k = weight assigned to the k th objective
c_{ij} = total capital cost of subsystem i, alternative j
v_{ij} = total daily volume carried under subsystem i, alternative j
w_{ij} = total peak hour volume carried under subsystem i, alternative j
b_{ij} = net annual operating balance estimated for subsystem i, alternative j
p_{ij} = average percent seated, peak hour, for subsystem i, alternative j
$\overline{v}, \underline{v}$ = upper, lower limits of utility curve for daily volume chosen so that no v_{ij} lies outside the range $\underline{v}$ to $\overline{v}$ (or $\overline{v}$, $\underline{v}$ could be the largest and smallest volumes among each subsystem's alternatives if the relative technique is used)
$\overline{w}, \underline{w}$ = upper, lower limits of utility curve for peak hour volume
$\overline{b}, \underline{b}; \overline{p}, \underline{p}$; etc. = respective upper, lower limits

(Note: the above terms all are estimated parameters whose value is fixed for this analysis.)

Let x_{ij} be the variable describing subsystem i, alternative j such that $x_{ij} = 1$ indicates project is selected and $x_{ij} = 0$ means it is not; x_{ij} can only be 0 or 1.

Normalize each of the parameters v, w, b, and p for ease in notation:

$$v_{ij}' = \frac{v_{ij} - \underline{v}}{\bar{v} - \underline{v}} \quad \text{for all i, j}$$

(Such normalization applies to the two linear methods only. The nonlinear case is no more difficult, however.)

This calculates the percentage of full points to be awarded to subsystem i, alternative j under the highest daily volume objective. For example, if Z_1 was 4 points, $\underline{v}$ was 1000, $\bar{v}$ was 5000, and v_{ij} was 4000, then v_{ij}' would be 0.75 and the value of that alternative and that objective would be (0.75) · (4 points) = 3 points.

Now the problem can be stated as

Maximize

$$\sum_{i=1}^{N} \sum_{j=1}^{n_i} Z_1 v_{ij}' x_{ij} + \sum_{i=1}^{N} \sum_{j=1}^{n_i} Z_2 w_{ij}' x_{ij} + \sum_{i=1}^{N} \sum_{j=1}^{n_i} Z_3 b_{ij}' x_{ij} + \sum_{i=1}^{N} \sum_{j=1}^{n_i} Z_4 p_{ij}' x_{ij}$$

or equivalently,

Maximize

$$\sum_{i=1}^{N} \sum_{j=1}^{n_i} \left[(Z_1 v_{ij}' + Z_2 w_{ij}' + Z_3 b_{ij}' + Z_4 p_{ij}') x_{ij} \right]$$

Subject to

(1) $\displaystyle\sum_{i=1}^{N} \sum_{j=1}^{n_i} c_{ij} x_{ij} \leq B$ (Budget constraint.)

(2) $\displaystyle\sum_{j=1}^{n_i} x_{ij} = 1$ for all i (One and only one alternative will be selected within each subsystem. If it is feasible to build more than one project within a subsystem, let a new alternative be defined to describe each such combination.)

(3) all $x_{ij} = 0$ or 1 (All or none of a project must be built.)

The formulation is now an integer linear program and can be solved as such. However, it is really a special, simpler case, since $x_{ij} = 0$ or 1 only. This special zero-one variable case can be solved by some different, shorter algorithms which are available[3].

It should be noted that this full system example was formulated assuming that the same objectives and objective weights apply to each subsystem. However, it is usually relatively simple to extend the linear programming formulation to a group of subsystems which do not have the same set of objectives or objective weights by reverting to the fractional weighting scheme. The possibility of having different objectives and weights in different project areas is a realistic one and each sector can set its own criteria.

One other direction which may be taken from this point is the use of parametric programming techniques[4] to study the behavior of the system under a wide variety of assumptions for costs, benefits or budgets—for example, the sensitivity of various objective measures to a wide variety of changes in budget assumptions.

CONCLUSION

Although the examples used in this paper generally refer to a transit situation, the technique appears equally applicable to a state highway department situation, or any number of other public works situations. The technique is not offered as a panacea for all transportation alternative evaluation problems. It is presented as one other, perhaps more systematic, way of handling such an analysis, and appears to have several advantages over conventional economic analysis procedures in certain applications. It is characterized by the inclusion of judgment and subjective feeling in an organized framework and provides for the mixing of subjective measures with those derived by rigorous mathematical technique. This would seem to be in tune with recent tendencies to emphasize judgment and subjective probabilities more, possibly a natural backlash to the rapid expansion in development of computer models.

This concept of weighting objectives and evaluating the degree to which each alternative meets the objective is not a new one, although it may be relatively new to the transportation field. It is similar to techniques currently being used in personnel evaluation as well as in other fields of engineering.

It should also be pointed out that, while the examples in this paper deal primarily with the benefit side of the economic picture, the same techniques are equally useful in dealing with the cost side.

This decision-making process was applied to the Massachusetts Bay Transportation Authority's 1966 Master Plan for system modernization and expansion. All actual numbers, formulation of objectives, and statements of policy used in the examples in this report are fictitious and were not intended to reflect the results of any MBTA studies.

---

[3]Examples of algorithms: Glover, Fred, A Multiphase Dual Algorithm for the Zero-One Integer Programming Problem, Operations Research, Vol. 13, No. 6, Nov.-Dec. 1965; Balas, Egon, An Additive Algorithm for Solving Linear Programs with Zero-One Variables, Operations Research, Vol. 13, No. 4, July-Aug. 1965.

[4]Dantzig, George B., Linear Programming and Extensions, Rand Research Corp. Study, Princeton Univ. Press, p. 245, 1963.