Abridgment

Optimization Approach for Allocation of Funds for Maintenance and Preservation of the Existing Highway System

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This paper discusses the development and application of goal programming techniques to achieve optimum allocation of federal and state funds for highway system improvement and maintenance. The methodology is applied to the Indiana highway system. An example problem that involves six improvement activities, four routine maintenance activities, and four system objectives is presented. Several scenarios are tested with the model to understand the model's operation and to gain insights into the trade-offs involved. The model is flexible enough to analyze other scenarios that involve revised standards or revised system objectives.

The automotive transportation system is in a state of transition. During the next decade the challenge to transportation agencies throughout the country is how to maintain and preserve this extensive network of facilities. In the face of competing needs for public money and in view of the increasing costs and inflationary effects, transportation agencies at all levels of government are concerned with how to allocate limited financial resources for highway improvement and maintenance.

The problem of highway financing and programming is greatly affected by prevailing energy constraints. The largest portion of the highway revenue is generated through the user tax on fuel. The combined effect of increased vehicle fuel efficiency and conservation efforts has drastically affected the amount of highway revenue available for construction and maintenance. The problem is aggravated because a significant part of the highway system is aging and, due to the increase in heavy truck traffic, maintenance needs have also increased sharply. At the same time, increased public awareness of safety and environmental quality has required a high level of highway service.

The costs of highway construction and maintenance have increased sharply in recent years due to the increased costs of labor, materials, and related items. However, the revenues available for maintenance have not kept pace with the need.

The problem of a shortfall in highway revenue is critical throughout the country. The highway taxation policy, primarily based on a user fuel-consumption tax, needs to be changed. At the same time the funding policy has to be moved from new construction to the maintenance of the existing system so as to increase the operational efficiency.

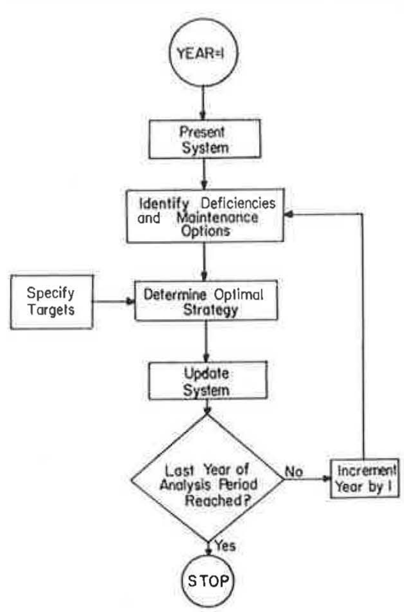
BACKGROUND INFORMATION

A definite need exists to examine possible legislative actions to change the revenue-generating structure and taxation schemes substantially in order to provide sufficient resources for the maintenance and preservation of the highway system. A study has been undertaken at Purdue University to analyze various aspects of the problem of highway maintenance and financing. In the first phase of the study (1) a computer model was developed that can be used to analyze and estimate the complex interactions between the critical factors that influence highway financing and their ultimate impact on the performance of the highway system. In the present phase of the study the model has been extended to incorporate an optimization routine for the allocation of highway improvement and maintenance funds. A schematic framework of this extension is given in Figure 1. The analysis can be done in cycles of one or more years for the entire analysis period. The process begins with initial highway system characteristics described by physical and traffic conditions. Analysis of this information leads to the identification of all feasible improvement and maintenance activities on different sections of the existing highway system. A mathematical optimization technique is then used to select the optimal set of improvement and maintenance activities over the entire system, given limited financial resources and a set of objectives. This completes one cycle of analysis. The performance of the highway system with regard to condition, service, safety, energy, and environment is evaluated after the system characteristics are updated. This process is repeated for each cycle until the last year of the analysis period.

Optimization Approach

This paper outlines the formulation of a model for optimal allocation of funds for highway improvement and maintenance based on the goal-programming technique. Goal programming is an approach for handling multiobjective optimization problems. In this approach, targets or goals are assigned for each of the identified objectives. The goal-programming

Figure 1. Optimal improvement and maintenance strategy model.



algorithm determines a satisficing solution that comes as close as possible to all the given goals or targets.

The problem is to determine how many miles of various sections will receive an improvement or maintenance activity. The decision variable is, thus, the length x_{ij} of the jth section that receives ith activity. In total, there are N highway sections in all of the functional classifications considered, and there are M improvement and maintenance activities. However, not all activities may be feasible for a given section.

System Objectives

System objectives include the improvement of system condition, provision of a higher level of service, increased system safety, and reduction of energy consumption and environmental pollution. Implementation of a highway improvement or maintenance activity helps to achieve some of these objectives, and the extent of the impact is measured by the activity-performance impact matrix, $P = \{p_{ki}\}$, where the matrix elements p_{ki} denote the improvement in system objective k due to activity i. The total (systemwide) improvement in objective k, considering M activities and N sections, is then given by the following expression:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} p_{ki} x_{ij} \tag{1}$$

The problem is to achieve given levels of improvement in condition, service, safety, energy, and environment. If we denote these by T_k, we can express the system objectives as:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} p_{ki} x_{ij} \geq T_k \quad k = 1, \ldots, K \tag{2}$$

In goal programming, the system objectives are represented as constraints that have positive and negative deviational variables to denote overachievement and underachievement of the targets.

The system objectives can then be expressed as:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} p_{ki} x_{ij} + d_k^- - d_k^+ = T_k \quad k = 1, \ldots, K \tag{3}$$

The above expression says that the systemwide improvement in objective k actually achieved may exceed the target T_k (if $d_k^+ > 0$) or may fall short of the target (if $d_k^- > 0$).

Objective Function

The objective function of the optimization problem is to minimize the negative deviations (underachievement) from the targets. This is expressed as

$$\text{Min } Z = \sum_k w_k d_k^- \tag{4}$$

where d_k^- = underachievement in objective k and w_k = weight (penalty) associated with the underachievement of the objective.

The weights or penalties can be assigned separately for different classes of highways and for different objectives. For example, the penalty for not achieving the target for service may be greater than that for system condition for an Interstate class of highway, whereas it could be the reverse in the case of minor arterials and collectors.

System Constraints

System constraints are primarily related to the available financial resources for improvement and maintenance activities. These constraints are developed to reflect the requirements of various funding sources as set by government policies. For example, at present no federal assistance is provided for routine maintenance activities, but many of the improvement activities are funded through federal sources on the basis of specified matching ratios depending on the type of activity. Also, the revenue generated within a particular state can be allocated only on highways within that state. On the basis of these considerations, the budget constraints can be expressed as

$$\sum_{i \in M_F} f_i \sum_{j=1}^{N} c_{ij} x_{ij} \leq B_F \tag{5}$$

$$\sum_{i \in M_F} (1 - f_i) \sum_{j \in N_s} c_{ij} x_{ij} + \sum_{j \in N_s} \sum_{i \in M_s} c_{ij} x_{ij} \leq B_s \quad s = 1, 2, \ldots, S \tag{6}$$

where

- c_{ij} = cost per mile for improvement or routine maintenance activity i for section j,
- B_F = total federal funds available for distribution to states for highway improvement projects,
- M_F = set of all improvement activities that can use federal funds,
- M_s = set of all routine maintenance activities using state funds,
- f_i = matching ratios that indicate fraction of the cost of activity i that can be supported by federal funds,
- B_s = funds generated at a state level for all activities within state s,
- N_s = those highway sections located within state s ($N = \sum_{s=1}^{S} N_s$), and
- S = number of states included in the analysis.

The values of B_F and B_s can be provided exogenously as input information or these figures can be generated endogenously by using the revenue-generation submodel described by Mannering and Sinha (1).

Other constraints necessary for the optimization routine require that the total length of a section that receives improvement or maintenance activity does not exceed the length of that section (ℓ_j). In order to ensure this, a set of constraints of the following form are used in the model:

$$\sum_{i=1}^{M} x_{ij} \leq \ell_j \quad j = 1, \ldots, N \tag{7}$$

State Funding of Improvement Activities

It is desirable to provide for diversion of state funds on improvement activities when federal matching grants are not available. The model can incorporate an additional set of activities that represent those improvement projects that could be financed entirely by the state, after the federal matching funds are fully used. For the example problem, resurfacing alone was considered to be such an activity.

Equity Considerations

Attempts to optimize condition, service, safety, and energy and environmental objectives simultaneously will result in inequity if all activities cannot be done due to limited resources. In practice, it may be necessary to guarantee a predetermined minimum of some improvement activities so that serious deficiencies are corrected. These minimum levels may be specified as a fraction of current needs for each activity. They may depend on the number of years within which it is desired to catch up with the backlog and the proportion of the system expected to need the respective activities each year. A minimum of 1 percent of each improvement activity needed and 30 percent of routine maintenance was specified as minimum needs to be fulfilled for the example discussed.

EXAMPLE PROBLEM: INDIANA CASE STUDY

The optimization model was tested on Indiana data. Physical and traffic characteristics for the base year of the Indiana highway system were generated by a Monte Carlo sampling of 1976 national highway summary data (2). Six periodic improvement activities and four routine maintenance activities were considered, as shown in the list below.

Periodic improvement activities are as follows:

1. Reconstruction,
2. Major widening,
3. Minor widening,
4. Restoration and rehabilitation,
5. Resurfacing, and
6. Safety and other traffic engineering improvements.

Routine maintenance activities are as follows:

1. Pavement maintenance,
2. Shoulder maintenance,
3. Appurtenance maintenance, and
4. Right-of-way and drainage maintenance.

The four routine maintenance activities are of such a nature that any one or any combination of two or more of them can be carried out on a particular section of highway, depending on the type and extent of deficiency. Any combination of periodic improvement and routine maintenance activities can also be considered.

Identification of Maintenance Needs

The highway system data as generated by sampling were stored and analyzed to identify feasible improvement and maintenance activities that can be undertaken. This was accomplished through a set of threshold values for the performance measures and associated improvement and maintenance activities. The thresholds were developed along the lines of minimum tolerable standards used in similar studies (3,4).

Activity-Performance Impact Matrix

This matrix, {P}, was developed primarily on the basis of an opinion poll. The responses from a group of experts in the area of highway planning, programming, construction, and maintenance were collected. The elements of this matrix give the expected value of the gain in each objective as a consequence of a highway section that gets the appropriate improvement or maintenance activity. The values were adjusted to reflect the difference in the number of years or duration of the effectiveness of various improvement and maintenance activities.

Financial Resources

The sources of funding were broadly divided into funds from federal sources and funds from state sources. For the purpose of testing the optimization model, the financial resources and budget allocations for Indiana were given as input data.

In order to gain insights into the problem of funding levels and also to understand the various trade-offs involved, three funding scenarios were considered, as given in the table below in 1975 dollars.

Funding	Amount Available ($000s)		
Source	Scenario 1	Scenario 2	Scenario 3
Federal	94 029	190 000	280 000
State	36 093	70 000	110 000

The federal-state matching ratios for various improvement activities were obtained from the Indiana State Highway Commission.

Unit Activity Costs

The costs associated with periodic improvement activities were estimated by developing an average cost per mile by using the national data provided in the 1972 National Highway Needs Report (5). The unit costs for routine maintenance were derived from maintenance budget information furnished by the Indiana State Highway Commission for FY 1979-1980. All figures were converted to 1975 dollar equivalents by applying the construction cost index.

Targets for System Objectives

The targets for the achievement of system objectives were set as values on a scale of 0-100. A value of 100 for a system objective represents total fulfillment of that objective. These values can be changed for sensitivity analysis to gain further insights into the problem.

Analysis and Results

With the model set up as described above, computer runs were made for each of the three funding scenarios. Solutions were obtained for two different policy options under scenario 2. One option assumed noncategorical funding, wherein the state government is free to use federal funds on maintenance activities. A second option assumed equal weights for all four system objectives across all classes of highways, as in Equation 4. These analyses were done without equity constraints. From the output of the optimization routine, reports can be generated that give miles that receive various activities, dollars spent, and achievement in each system objective. These can be done at any level of aggregation of interest to the user, such as all rural highways, all Interstate highways (urban and rural), and all improvements, to mention a few. These results for the sample problem are discussed in detail elsewhere (6).

A comparison of the two policy alternatives is useful in revealing trade-offs among objectives and highway classes. These are shown graphically in Figures 2 and 3. The numbers in these figures are the improvement scores achieved on a scale of 1-100. The optimization with unequal weights has resulted in more overall improvement of urban minor arterials at the cost of rural minor arterials and urban principal arterials (Figure 2). This brings out the conflict between system optimization under one value system (reflected in the priority weights assumed) and another. Figure 3 illustrates the trade-off among objectives in one class of highway. The greater importance given to the achievement of safety under the unequal weights option has resulted in improving safety at the cost of other objectives.

CONCLUSIONS

A major challenge to transportation agencies

Figure 2. Trade-off among highway classes.

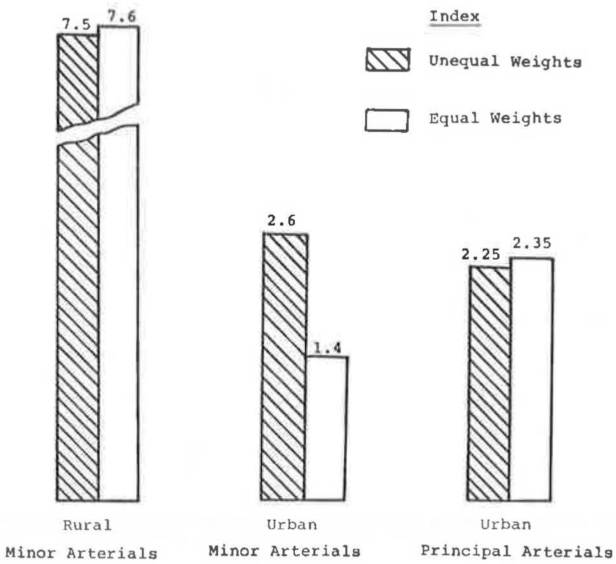
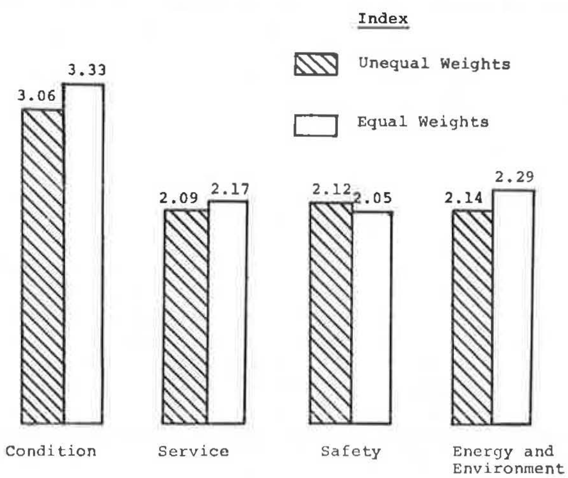


Figure 3. Trade-off among objectives—urban principal arterials.



throughout the country today is how to maintain and preserve the extensive network of highway facilities in the face of competing needs for public money, increasing costs, and inflation. A technique that has great potential to address this issue of optimal use of limited resources in a multiobjective decision situation is goal programming. The experience of the research at this point is encouraging and confirms the suitability of this approach to highway system programming and management. The overall methodology being developed will enable decision makers to address various issues, such as trade-offs among system objectives, among highway classes, and among activity types. It is also possible to analyze the impacts of different policy decisions on the needs and performance of highway systems.

The model is being expanded for application to the nationwide highway system. The model also has the potential for multiyear analysis and the flexibility to address different sets of system objectives and maintenance or improvement activities.

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