Nonpreemptive Goal Programming Methodology for Developing Annual Pavement Program

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A nonpreemptive goal programming methodology for developing an annual pavement program is presented. It facilitates decision making on the basis of multiple objectives involved in the decentralized management of a pavement network. The methodology involves three major steps: (a) identification of objective functions that encompass needs at various management levels, (b) assessment of the "importance" of each objective, and (c) formulation of a goal programming model. The methodology is demonstrated by developing an annual pavement program on the basis of data specific to the New York State Thruway Authority. Objective functions with numerical goals are defined on the basis of cost factors, condition evaluation measures, and organizational requirements. Because not all goals can be achieved simultaneously, consideration of management priorities leads to the need to introduce penalties for exceeding or falling short of specified goals. Further use of the defined penalties and their relative importance enables the development of a goal programming formulation. The formulation aims to seek an optimal annual program that minimizes the weighted sum of deviations of the objective functions from their respective goals. It is concluded that the presented methodology provides a simple and versatile tool that is useful for developing an annual pavement program.

The decisions related to pavement preservation and restoration involve multi-million-dollar investments annually. Consequently, the management of a highway network will require informed and cost-effective decisions to develop annual and multiyear programs. It is crucial to optimally allocate resources for maintenance and rehabilitation (M&R) on the basis of sound principles of management and engineering.

The New York State Thruway Authority (NYSTA) and Rensselaer Polytechnic Institute are cooperating to develop a pavement management system (PMS) for the authority's toll network (*1*). An integral component of the PMS development effort is to provide optimization formulations for annual and multiyear pavement programs. The task of developing optimal programs can be accomplished by using network-level optimization methodologies (*2*). A literature review of current pavement management practices and proposed conceptual optimization formulations was presented by Ravirala (*3*). Many formulations use techniques such as dynamic programming, linear programming, or integer programming to aid in decision making. These techniques have the characteristic of selecting an optimal solution with respect to a single overriding or dominant objective. However, management of highway agencies frequently focuses on a variety of objectives—for example, to invest for economic growth, balance preservation and improvement actions, distribute work among various administrative sections, minimize long-term costs, and minimize poor pavement and maximize good pavement. Additionally, the various objectives present conflicting criteria, with different suborganizational levels aiming for specific goals.

Dominant objectives such as maximizing network ride quality may be used for optimization, provided that the decisions made adhere to certain constraints regarding other objectives. For example, the management could impose constraints on maximum investment during each year and the maximum highway mileage allowed in poor condition. An important limitation of this approach is the lack of logic in the modeling scheme to determine the best solution with respect to other objectives. Additionally, some constraints may totally dominate, making several others redundant. The active constraints may even cause infeasibility. Consequently, constraints regarding the other objectives may be satisfied, but different "optimal" solutions may yield different results with respect to many other objectives.

Thus, the problem of concern is enhancement of the optimization procedures to include multiple objectives in the decision-making process. The developed methodology must consider problem situations involving conflicting objectives that may be of varying importance to the decision maker.

The study described here aims to develop a multicriteria optimization methodology by using goal programming. The goal programming technique provides a way of striving toward several objectives simultaneously. A rational method used to determine the importance of each objective is also presented. The methodology would enable highway managers to develop the annual pavement program by considering various objectives in the decision-making process.

METHODOLOGY

The methodology of nonpreemptive goal programming involves four steps:

1. Identification of multiple objectives on the basis of condition evaluation measures and cost factors,
2. Development of policies that aid in establishment of specific goals for each objective,
3. Assessment of penalty weights for exceeding or falling short of each goal, and
4. Formulation of a goal programming model for constrained optimization.

Step 1 formalizes the objectives associated with the development and implementation of the annual program. It includes identification

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of measures for condition evaluation and cost factors that aid in the decision-making process. Multiple objective functions are defined to encompass needs at various levels of pavement management.

Step 2 addresses specific tasks of analyzing the network condition and development of policies leading to establishment of specific maintenance goals. Desirable values for each objective function identified in Step 1 are established as goals.

Step 3 involves development of a procedure for rating the importance of various objective functions in attaining their goals. The procedure involves assigning a priority for each objective—by setting a penalty weight for exceeding or falling short of each goal.

Step 4 concentrates on formulation of a mathematical model that uses goal programming techniques to conduct multiple-objective optimization. Goal programming can be used to incorporate conflicting objectives whose priority levels and relative importances can be preserved. Two cases that can be considered are (a) nonpreemptive goal programming, in which all of the objectives are of roughly comparable importance, and (b) preemptive goal programming, in which there is a hierarchy of priority levels for the objectives. In the latter case, the objectives of primary importance will receive first-priority attention, those of secondary importance will receive second-priority attention, and so forth.

In the present study nonpreemptive goal programming in which all the objectives are of comparable importance is used. Commercial and customized software was used to formulate the mathematical functions and solve the problem.

IDENTIFICATION OF OBJECTIVES

Objectives are specific to the agency needs and must be defined to be compatible with the decision makers' perspectives. The objectives should encompass needs at various levels of highway management. The following are some categories of objectives at various organization levels (in decreasing order of scope):

- Socioeconomic purpose,
- Overall organization objectives (strategic),
- Network-level (short- and long-range),
- Division-level (performance, cost, etc.), and
- Project-level (condition, implementation, etc.).

Examples of important objectives identified during this study are described next.

Socioeconomic

An important socioeconomic objective is to stimulate economic development and provide jobs. According to an FHWA study, 10.2 on-site construction jobs are created for every $1 million spent on roadway rehabilitation. NYSTA committed more than $300 million in 1992 toward its 8-year, $1.7 billion highway and bridge rehabilitation program. It is conservatively estimated that about 3,060 jobs were created. The goal for 1993 is to invest another $235 million ($68 million for highway work), creating 2,400 construction jobs.

Strategic

An important strategic objective is to allocate funds equitably among the agency's administrative divisions. This objective aims to minimize the total difference between the funds allocated for each division from that of the divisions' respective goals, which are determined on the basis of several criteria. Another strategic objective is to attain an acceptable balance between maintenance work done by contract and that done by agency forces and to ensure that unacceptable travel delays are not imposed on the patron.

Network Level

Some of the network-level objectives are to improve the ride quality and correct distressed pavement condition by setting up goals on the basis of condition measures, extend benefits to as many users as possible, equitably distribute funds to preservation and improvement programs, develop an annual program that is compatible with the multiyear program, and so on.

Division Level

The division objectives include minimizing the implementation costs and disruption to traffic. This can be achieved by limiting the number of projects by considering the equipment and personnel resources and other practical implementation considerations.

Project Level

Some of the project-level objectives are to minimize deferment of treatment to critical distress condition, implement preventive maintenance on an as-needed basis, select treatments that address as many problem situations as possible, and so on.

ASSESSMENT OF OBJECTIVES

In multiple-objective decision making it is imperative to associate a relative numerical degree of "importance" to each objective. The decision-making process involves an assessment of which objective is more important and of how much more. Rational methods are available to determine the importance of each objective with a specific goal (*4,5*).

Several objectives identified in this paper have goals whose underachievement and overachievement are undesirable, for example, capital investment and number of lane-miles desired at various condition levels. Hence, of utmost importance is the deviation of each objective function value from its goal. Two measures that demand particular attention are (a) maximum deviation of each objective from its goal, and (b) total (sum) deviation of all objectives from their goals. Both measures can be assigned penalty weights when determining the importance of objectives and their deviations from respective goals. However, minimizing one or the other might yield different results. The present study adopted the scheme of minimizing the weighted sum of deviations. This scheme provides better control over the decisions for management. Excessive deviations can be prohibited by establishing bounds on the maximum deviation of each objective from its goal.

A significant aspect of evaluating objectives and ascertaining weights is the use of experts' judgments. It is necessary to synthesize different judgments when more than one person is involved in the assessment. The weights are derived on the basis of individual assessments by using the following equations:

$$P_{ij} = \beta_{ij}/\sum_{i=1}^{m} \beta_{ij} \qquad (1)$$

$$P_i = \sum_{j=1}^{n} P_{ij}/\sum_{j=1}^{n}\sum_{i=1}^{m} P_{ij} \qquad (2)$$

where

P_{ij} = penalty weight computed for objective i by expert j,
β_{ij} = penalty assessed for objective i by expert j, and
P_i = penalty weight computed for objective i.

MODEL DESCRIPTION

The annual program development and budget allocation is modeled as a modified *assignment problem* (*6*). Nominal sections receiving specific treatments represent the origins, and fixed-length projects represent the destinations [Figure 1 (*a*)]. Each nominal section should receive only one type of treatment and should be assigned to only one project.

The modeling process can be described by the following four-step procedure:

- Establish tentative projects at fixed intervals along the entire network,
- Determine the nominal section boundaries and identify three neighboring projects to which each nominal section can be assigned,
- Specify the treatment alternatives for each nominal section, and
- Formulate the goal program.

In the present study tentative projects are established at every 8-km (5-mi) interval along the network [Figure 1 (*b*)]. Treatment alternatives are defined after analyzing the condition of each nominal section and assessing their individual needs [Figure 1 (*c*)].

As applied to this model the goal program assigns each nominal section to a project and determines the type of treatment to be performed for each nominal section. It also determines the optimal set of projects to be implemented as part of the annual program.

GOAL PROGRAM FORMULATION

The general form of a goal program can be expressed as follows (*4*): Minimize

$$\sum_{g \in G} (P_{og} d_g^+ + P_{ug}\, d_g^-) \qquad (3)$$

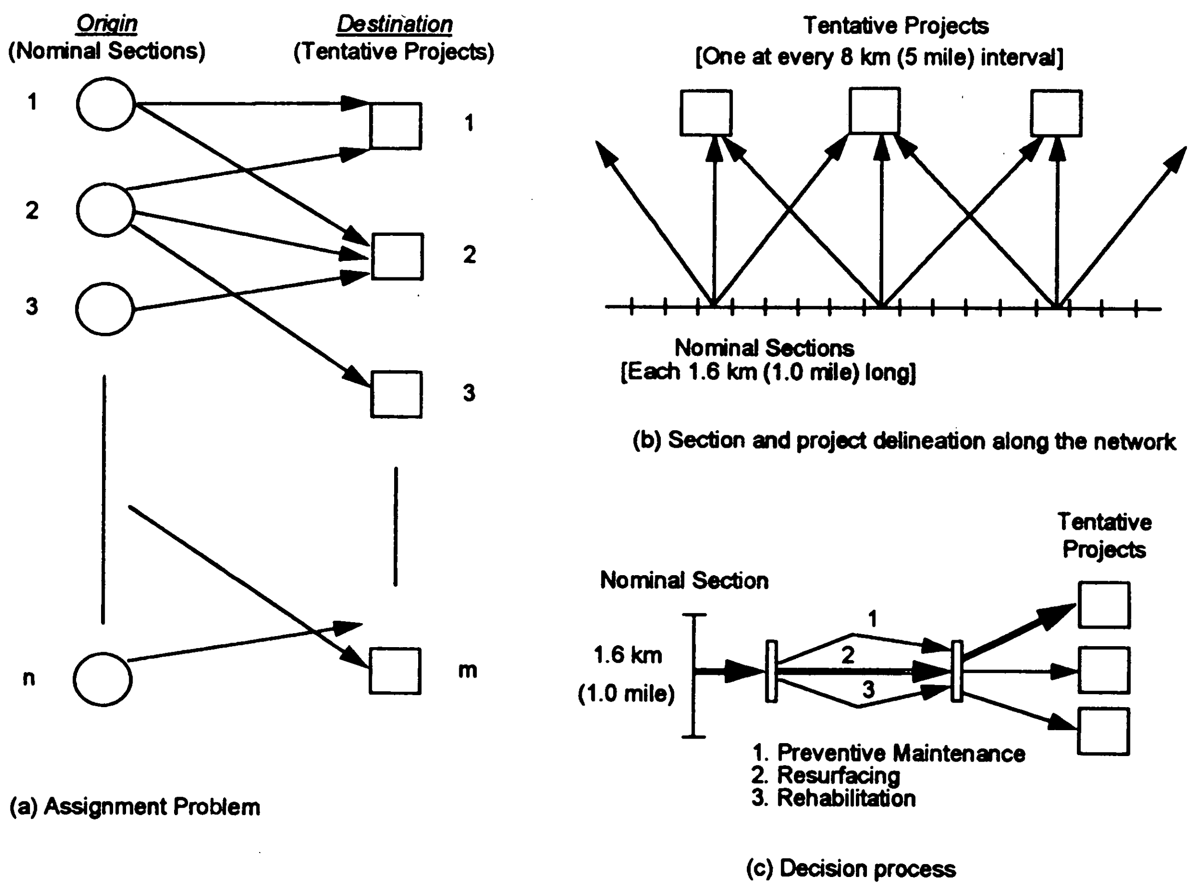

FIGURE 1 Illustration of assignment model and decision process.

Subject to

$$\sum_{v \in V} (a_{gv} X_v) + d_g^- - d_g^+ = b_g, \text{ for } g \in G \quad (4)$$

$$X_v, d_g^+, d_g^- \geq 0, \text{ for } g \in G \text{ and } v \in V \quad (5)$$

where

G = set of goals,
d_g^+ = overachievement of goal g,
P_{og} = penalty associated with d_g^+,
d_g^- = underachievement of goal g,
P_{ug} = penalty associated with d_g^-,
V = set of basic variables,
X_v = basic variables in the individual objective functions (or goal equations),
a_{gv} = coefficients of basic variables, and
b_g = targeted goals.

Equation 3 represents the unified objective of minimizing the weighted sum of deviations of individual objective functions from their respective goals. Equation 4 represents the goals to be approached as closely as possible.

Basic variables, objectives (with goals), and constraints specifically defined to conduct a case study are as follows:

Basic Variables

$$X_{ijk} = \begin{cases} 1 \text{ if section } i \text{ is assigned to project } j \text{ and receives treatment } k \\ 0 \text{ otherwise} \end{cases} \quad (6)$$

Objectives (with Goals)

Equation 7 addresses the socioeconomic objective of capital investment and the strategic objective of equitable allocation of funds among administrative divisions. The left side of the summation represents the total M&R expenditure within each geographical class, which is equated to the investment goal on the right side.

$$\left(\sum_{i \in I_s} \sum_{j \in J_i} \sum_{k \in K_i} l_i \, c_{jk} \, x_{ijk}\right) + d_{s1}^- - d_{s1}^+ = b_{s1} \text{ for all } s \quad (7)$$

where

I_s = set of all nominal sections within geographical class s [$s \in$ (Network, New York, Albany, Syracuse, Buffalo)],
J_i = set of projects to which section i can be assigned,
K_i = set of treatment alternatives for section i,
l_i = length of section i,
c_{jk} = unit cost of treatment k in project j, and
b_{s1} = M&R capital (total annual funds) goal for geographical class s.

Equation 8 represents the goals defined on the basis of condition measures. The left side is a summation of the total lane-miles that belong to a geographical class and that would be in a certain condition class after applying treatments. The right side goal is the desired number of lane-miles in that particular condition class. For example, the left side of a particular goal equation may represent the total mileage in New York that would be in *Excellent* ride quality after implementing the annual program.

$$\left(\sum_{i \in I_{sn}} \sum_{j \in J_i} \sum_{k \in K_i} l_i \, p_{ikn} \, X_{ijk}\right) + \mathrm{d}_{sn}^- - \mathrm{d}_{sn}^+ = b_{sn} \text{ for all } s \text{ and } n \quad (8)$$

where

I_{sn} = set of nominal sections belonging to geographical class s that would be in condition class n after implementing the annual program,
p_{ikn} = probability that nominal section i would be in class n after receiving treatment k, and
b_{sn} = condition goal (total lane-miles) for geographical class s and condition class n.

Constraints

Equation 9 ensures that each nominal section gets assigned at most to one project and will receive at most one treatment type.

$$\sum_{j \in J_i} \sum_{k \in K_i} X_{ijk} \leq 1 \text{ for all } i \in \mathrm{I} \quad (9)$$

Equation 10 ensures that the total mileage within each geographical class will remain constant during the transitions between condition classes. (Equations for several other types of goals identified earlier are not presented here for the sake of brevity.)

$$\sum_{n} d_{sn}^+ - d_{sn}^- = 0 \text{ for all } s \quad (10)$$

CASE STUDY

Inventory and Condition Data

The goal programming methodology was applied to develop an annual program by using information specific to NYSTA. The thruway consists of approximately 1,024 km (640 mi) of Interstate highway in each direction. It was originally constructed as portland cement concrete (PCC) pavement, but over the years approximately 87 percent has been overlaid with asphalt. For efficient management NYSTA is organized into four administrative divisions (New York, Albany, Syracuse, and Buffalo) and several administrative sections within each division.

NYSTA annually conducts distress survey and records severity and extent of 14 distress types on every 0.16-km (0.1-mi) segment. This information is used to derive two types of condition measures, namely, crack (joint) rating and surface (slab) rating for overlaid (concrete) pavement.

The network is divided into nominal sections of approximately 1.6 km (1.0 mi). For each nominal section the average value of both condition measures is derived. Cutoff values were established to define *Excellent, Good,* and *Fair* classes for each condition measure. Table 1 shows the distribution of mileage (percentage of network) among various divisions and condition classes. Only 931.6 km (582.3 mi) was rated in the year 1992.

TABLE 1 Percentage of Thruway Mileage in Each Condition Class

Condition Measure	Condition Class	Division							
		New York		Albany		Syracuse		Buffalo	
		OVL	PCC	OVL	PCC	OVL	PCC	OVL	PCC
Crack/ Joint Rating	Excellent	10.6	0.0	7.8	0.0	12.0	-	11.2	0.0
	Good	3.1	0.0	4.7	0.0	4.3	-	7.4	0.1
	Fair	4.4	8.3	8.6	2.6	7.3	-	6.1	1.5
Surface/ Slab Rating	Excellent	11.3	0.0	12.6	0.0	18.9	-	9.0	0.0
	Good	4.3	0.0	3.5	0.0	4.2	-	3.3	0.0
	Fair	2.5	8.3	5.0	2.6	0.5	-	12.4	1.6

OVL = Overlaid PCC = Concrete

(-) indicates mileage non-existent

Objectives and Goals

Two important types of objectives, namely, capital investment and condition improvement, have been included in this case study. It was necessary to demonstrate the model's capability to address the decentralized nature of decision making in highway management. Hence, different goals were defined for the four administrative divisions and the overall network. The capital goals were specified as millions of dollars to be invested for pavement M&R. The condition goals were specified as desired percentage of network within various condition classes.

In all, 35 goals were targeted—5 capital goals (one for each geographical class) and 30 condition goals (six condition classes for each geographical class). The capital investment goal for each of the four administrative divisions was specified as $10 million, and overall it was $40 million. The percentages of mileage desired in each condition class are given in Table 2.

Assessment of Objectives

Although specific numerical goals have been defined for various objectives, it is well recognized that the deviations are not of equal importance. For example, a unit deviation from the overall capital goal is relatively more undesirable compared with a unit deviation from individual division capital goals. Hence, the penalty of deviating from the overall capital goal must be higher. In addition, the penalty for overachieving and underachieving a goal could be different. For example, exceeding the targeted mileage (overachieving) in excellent condition need not be penalized, whereas falling short of the targeted mileage (underachieving) must be penalized. Table 3 shows the penalty weights defined for capital and crack condition rating classes. Note that overachieving the excellent condition goals and underachieving the fair condition goals have a zero penalty. Also, as a simple case all four divisions have been judged to be equally important in achieving their respective goals.

TABLE 2 Magnitude of Condition Goals Targeted and Achieved

Condition Measure	Condition Class	Overlaid Mileage (%)		Concrete Mileage (%)	
		Targeted	Achieved	Targeted	Achieved
Crack/ Joint Rating	Excellent	45.85	58.09	0.62	0.00
	Good	24.04	22.66	0.71	0.58
	Fair	17.65	12.63	11.13	6.04
Surface/ Slab Rating	Excellent	56.21	52.55	0.62	0.00
	Good	19.72	27.16	0.62	0.62
	Fair	11.61	13.71	11.21	5.95

Computer Implementation

The presented goal programming methodology involves a large-scale mixed-integer programming formulation. It requires extensive computer programming to process the input data, generate the equations, determine the optimal solution, and finally process the output to summarize the results. It was decided to develop customized software that included four main modules. The first module consists of data base routines that store and retrieve information on inventory, pavement condition, treatment alternatives, costs, and so on. The second module has routines that allow the user to (a) define the objectives to be included in the formulation, (b) specify numerical goals, and (c) set penalty weights. The third module has routines that (a) define meaningful names for basic and deviation variables, (b) generate the variable coefficients for the objective function, goal, and constraint equations, and (c) formulate the goal program using the mathematical programming system (MPS) file format (*7*). Finally, the fourth module consists of routines that generate reports that summarize the input data and the results.

The LINDO commercial software was used to read the formulation in MPS format and solve the goal program. Although the basic variables are defined as 0–1 integer variables, this restriction was relaxed and the problem was solved as a linear program.

Results

The most important result that enables assessment of the annual program's effectiveness is the magnitude of deviations from the targeted goals. For all divisions the target was to increase the Excellent and Good mileage by 5 percent and correspondingly to decrease the Fair mileage by 10 percent. Table 2 shows the magnitude of condition goals targeted and achieved. There is a substantial increase (13 percent) in the Excellent condition mileage of overlaid

TABLE 3 Penalty Weights for Various Goals

Geographical Class	Goal Type: Capital Investment	Overachieving Crack Rating: Ex	Gd	Fr	Underachieving Crack Rating: Ex	Gd	Fr
New York	0.25	0.0	0.25	0.5	0.5	0.25	0.0
Albany	0.25	0.0	0.25	0.5	0.5	0.25	0.0
Syracuse	0.25	0.0	0.25	0.5	0.5	0.25	0.0
Buffalo	0.25	0.0	0.25	0.5	0.5	0.25	0.0
Overall	0.5	0.0	0.5	1.0	1.0	0.5	0.0

Ex = Excellent Gd = Good Fr = Fair

pavement crack rating. Also, there is a significant decrease (5 percent) in the Fair condition mileage. This can be attributed to the zero penalty associated with either case. The Excellent mileage of the surface condition has slightly decreased, but the Good mileage has increased significantly (8 percent).

Table 4 summarizes the capital investment data for each geographical class. Although goals and penalties are set to be equal, the funds allocated among the four divisions vary widely. This variation can be attributed to several factors, such as (a) disparity in the current condition, (b) differences in the condition goals, and (c) penalty weights. For example, the New York Division has significant mileage of concrete pavement in Fair condition, which is undesirable. Hence, it was targeted to decrease the Fair condition mileage by 10 percent. Also, a higher penalty was given to the overachievement of target mileage in the Fair condition class. This decision demonstrates the control that management can exercise on the decision making.

Table 5 summarizes the percentage of mileage receiving each treatment type. The program recommends rehabilitation on 12 percent of the network and resurfacing on 6 percent, which are realistic recommendations. The program also suggests that more than 70 percent of the thruway requires some form of maintenance. This indicates the need to increase the scope of the case study to include a complete set of treatment alternatives and objectives. Both the numerical goals and penalty weights need to be refined after further analysis.

DISCUSSION OF RESULTS

Identification of Objectives

The objectives identified in the present study encompass the needs at various levels of highway management. However, a distinction can be made between the single-year and multiyear objectives involved in overall pavement management. The presented goal programming methodology incorporated only the single-year objectives. This assumes that the single-year objectives are compatible with the multiyear objectives. An agency must have an established multiyear program to ensure such compatibility. A state increment optimization methodology is used to develop an optimal multiyear program for NYSTA (*2*). The optimal multiyear program defines the capital investment options, long-term condition goals, and M&R strategies for the entire network. The results from multiyear analysis provide the capital and condition goals for the annual program. The state increment method also determines the lane-miles of

TABLE 4 Comparison of Capital Investment Data for Each Geographical Class

Division	Capital Goal ($Million)	Deviation ($Million)	Achieved ($Million)	Mileage (km)	Investment $1000/km
New York	10.00	1.43	11.43	492.96	23.20
Albany	10.00	-3.58	6.42	441.76	14.32
Syracuse	10.00	-6.91	3.09	440.64	7.02
Buffalo	10.00	-4.50	5.50	487.84	11.26
Overall	40.00	-13.56	26.44	1863.2	14.18

pavement in each state that should receive each of the possible treatment options. This information can be used to define additional goals on treatment quantities for the annual program and ensure congruency between the single-year and multiyear programs. For example, if the multiyear program recommends a 10 percent network rehabilitation in the first year, then an additional goal would be to develop an annual program that targets a 10 percent network rehabilitation.

Assessment of Objectives

Assessment of objectives, in the context of multiple-criteria optimization, is a process of defining the relative importance of criteria. This process involves ranking the criteria with *priority* or *weight.* Priority refers to the case in which the criteria are ordered according to importance and, unless the higher-level criterion is considered, the next one does not come into play. In other cases weights are attached to differentiate the relative importance of several criteria with equal priority.

The case study presented here involved only a few objectives of comparable importance. It was assumed that all objectives are of equal priority. Hence, the importance of each objective was assessed by assigning penalty weights, and the nonpreemptive goal programming technique was used to obtain an optimal solution. The methodology can easily be extended to include multiple objectives with different priority levels. Such objectives can be unified into a single objective function by manipulating their weights, thus converting a preemptive goal program into a nonpreemptive goal program. To accomplish this conversion the weights of the highest-priority objectives need to be multiplied by a number that is vastly larger than the weights of the objectives at the next priority level.

TABLE 5 Percentage of Mileage Receiving Each Treatment Type

Treatment Type	Division							Overall
	New York		Albany		Syracuse	Buffalo		
	OVL	PCC	OVL	PCC	OVL	OVL	PCC	
Do Nothing	0.88%	0.00%	2.26%	0.00%	3.80%	0.72%	0.00%	7.66%
Maintenance	15.78%	1.06%	16.30%	0.26%	19.15%	21.12%	0.77%	74.44%
Resurfacing	0.60%	1.00%	1.70%	0.17%	0.70%	1.55%	0.52%	6.23%
Rehabilitation	0.86%	6.28%	0.88%	2.15%	0.00%	1.25%	0.26%	11.66%
Total	18.12%	8.34%	21.13%	2.58%	23.65%	24.64%	1.55%	100.00%

OVL = Overlaid PCC = Concrete

Evaluation of Computational Aspects

The presented goal program is a mixed-integer type program that has both 0–1 integer variables (basic variables) and real variables (nonnegative deviation variables). It is well recognized in practice that it is computationally expensive to solve large-scale integer programs. In this case study the restriction on obtaining an integer solution was relaxed, and the problem was solved as a linear program. This resulted in a significant reduction in computation time. For example, a formulation—with approximately 3,400 variables and 1,300 rows—was solved within 5 min by using an IBM 3090–200S computer. An equivalent integer program requires several hours. Only 2 (of more than 3,300) 0–1 integer variables resulted in noninteger solutions, indicating that the formulation can be efficiently solved as a linear program.

SUMMARY AND CONCLUSIONS

This paper presented a nonpreemptive goal programming methodology for developing an annual pavement program. The emphasis was on incorporating multiple objectives into the decision process involved in the decentralized management of a pavement network. Three major steps of the methodology are (a) identification of objective functions with specific numerical goals on the basis of condition evaluation measures and cost factors, (b) assessment of the importance of each objective in the form of penalty weights for exceeding or falling short of each goal, and (c) formulation of a goal programming model for constrained optimization. The formulation aims to seek an optimal solution that minimizes the weighted sum of deviations of the objective functions from their respective goals. The usefulness of the methodology was demonstrated through a case study. Presented is an annual pavement program that was developed on the basis of information specific to NYSTA.

From the findings of the study, the following conclusions may be drawn:

- Developed goal programming methodology effectively incorporates multiple, conflicting, and prioritized objectives that are present in highway management.
- Presented assignment model for annual program development has the advantage of simplicity and versatility because it yields simple linear functional forms for objectives and constraints.
- Employment of objective functions and their deviations from their respective targeted values provides a useful tool to decision makers in their effort to explicitly prioritize objectives and establish an acceptable trade-off.

GLOSSARY

Attributes: Characteristics that are used for certain physical and functional features of the infrastructure, for example, condition, safety, ride quality, and costs.

Constraints: Mathematical expressions for restrictions on attribute levels.

Goals: Although objectives are aspirations *without* the decision maker specifying their levels, goals are aspirations with given a priori levels of desired attributes.

Nominal Section: A continuous length of pavement that can be classified into a pavement state and has properties "similar" to those of any other section classified into the same state. Such sections may be aggregated in the decision process.

Objectives: Mathematical expressions for aspirations that indicate directions of improvement of selected attributes such as minimize costs and maximize ride quality.

Pavement Program: A plan that identifies the maintenance, rehabilitation, and reconstruction projects (either specific or nominal sections) tentatively scheduled for implementation. It can be either an annual (single year) or a multiyear program.

State: A combination of specific levels of variables that describe the dynamic behavior of the system. The variables used for the definition of state may be pavement condition parameters, traffic parameters, or any others that affect the decision process.

ACKNOWLEDGMENTS

This study is part of a broader research effort to develop and implement a pavement management system for NYSTA. The funding provided by the authority and the assistance of maintenance management personnel during the research and development effort are gratefully acknowledged.

REFERENCES

1. Grivas, D. A. *Development of a Pavement Management System, Phase I: The Plan.* Rensselaer Polytechnic Institute, Troy, N.Y., 1988.
2. Grivas, D. A., V. Ravirala, and B. C. Schultz. State Increment Optimization Methodology for Network-Level Pavement Management. In

Transportation Research Record 1397, TRB, National Research Council, Washington, D.C., 1993.
3. Ravirala, V. *A Network Optimization Methodology for Pavement Management.* M.S. thesis. Rensselaer Polytechnic Institute, Troy, N.Y., 1992.
4. Tabucannon, T. M. *Multiple Criteria Decision Making in Industry.* Elsevier Science Publishers B.V., Amsterdam, the Netherlands, 1988.
5. Zeleny, M. *Multiple Criteria Decision Making.* McGraw-Hill Book Company, New York, 1982.
6. Hillier, F. A., and G. J. Lieberman. *Introduction to Operations Research.* Holden-Day, Inc., Calif., 1986.
7. Schrage, L. *Linear, Integer, and Quadratic Programming with LINDO.* The Scientific Press, Calif., 1984.

The views and opinions expressed in this paper do not necessarily reflect those of NYSTA.