State Increment Optimization Methodology for Network-Level Pavement Management

DIMITRI A. GRIVAS, VENKATESH RAVIRALA, AND B. CAMERON SCHULTZ

An optimization methodology is presented for program planning and budget allocation involved in network-level pavement management. It consists of three major components: (a) characterization of pavement condition into discrete states, (b) specification of treatment options for each pavement state, and (c) application of a linear programming technique for constrained optimization and development of the multiyear pavement program. Pavement sections having similar characteristics are classified into states that are defined on the basis of distress and nondistress factors. The network condition is represented as lane miles of pavement distributed among various states. Several treatment options are specified for each state; they are based on the information incorporated in the state definition. For each treatment applied, the time for a complete state transition (or increment) to occur is predicted from historical data and empirical knowledge. A linear program is formulated to model interactions between economic and engineering factors in an effective manner. It enables decisions about the type of treatment, timing, and magnitude of work to be made simultaneously. Both project- and network-level constraints can be imposed to develop a pavement program that meets specified requirements on condition and budget. The developed methodology has been implemented as part of the New York State Thruway Authority's pavement management system. An example is presented to illustrate the methodology and its usefulness to conduct variational analysis. It is concluded that the methodology can be applied to develop an effective multiyear pavement program and ensure optimal budget allocation for the entire network.

An important objective of a pavement management system (PMS) is to develop an optimization methodology useful for conducting pavement program analysis (*1*). The methodology should aim to provide a decision-making capability that enables highway managers to make rational, consistent, and cost-effective about the pavement network.

Most PMSs include specific methodologies for characterizing pavement condition, identifying treatment options, predicting condition, and evaluating the economics. A decision-making method (such as ranking or optimization) is necessary to integrate various aspects of these entities into a complete system useful for planning a pavement program. A review of some of the decision-making methods in a PMS was presented by Ravirala (*2*).

Presented is an optimization methodology that resolves the multiyear planning and budget allocation problem into two subproblems: a project-level planning problem, and a network-level constrained optimization problem. Specific objectives of the study are to

- Characterize the pavement condition using definitive parameters that quantify the distress and nondistress factors affecting the decision process,
- Develop an optimization methodology for multiyear pavement program planning, and
- Illustrate the developed methodology by applying it to analyze the New York State Thruway Authority's (NYSTA's) pavement network.

The project-level planning involves a series of tasks such as condition characterization, treatment options identification, prediction, and cost estimation. Pavement condition is characterized by defining states on the basis of distress and nondistress factors. Several treatment options are associated with each state. The consequences of applying a treatment are specified by predicting the time period over which a state transition would occur. The network optimization problem is formulated as a linear program that has cost minimization as the objective. Constraints related to network condition and annual maintenance budget are also specified. The linear program determines the lane miles of pavement in each state that should receive each of the possible treatment options.

The optimization methodology is illustrated by analyzing a portion of the NYSTA network. The influence of maintenance in prolonging pavement life as well as improving the ride quality is analyzed for 5- and 10-year periods. The changes in the multiyear pavement program are observed for a fixed annual budget, both with and without condition constraints.

CONDITION CHARACTERIZATION

Approach

Pavement condition can be characterized by classifying lane miles of sections into one of many discrete states. A state is a combination of specific levels of the variables (called the state variables) that completely describe the pavement condition. The values taken by each continuous state variable are generally divided into ranges. Each range is called a condition level for that measure. Such an approach to condition characterization was previously used in PMSs of other agencies (*3–6*).

States serve two important functions: (a) predicting condition through a state transition process, and (b) balancing

Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, N.Y. 12180.

the pavement program through proper distribution of the network among states. Pavement state transition is an event that describes the change of state (value of at least one of the state variables) for the pavement as a consequence of action or deterioration over time. The time over which the transition occurs is called transition time. The transition time corresponding to an action is a variable depending on the rate of deterioration after applying the treatment option. The pavement will transition to a specified state as a consequence of the action.

A balanced pavement program can be developed by establishing desirable management policies on the future condition of pavement network. This is achieved by grouping the states into broad classes such as good, fair, and poor. Threshold values are specified on the quantity of pavement that may belong to each class. For example, management may desire to maintain a certain percentage of the network in good states while limiting or gradually upgrading the poor-condition pavement. Thresholds can be specified for each year in the analysis to develop a maintenance and capital program that satisfies the management requirements.

Definition of Pavement States

Pavement states are defined according to three state variables, namely, pavement type, traffic volume, and distress measures. The pavement type parameter enables differentiation between types of distress and specification of appropriate treatments for increased accuracy of network-level analysis. Average annual daily traffic (AADT) is classified into three levels to differentiate between sections with different levels of traffic. The distress condition is summarized by developing indexes for three measures: structural rating, slab/surface rating, and joint/crack rating. A weighted average approach to calculating condition indexes was developed by Grivas and Schultz (*7*). Distress measures contributing to each index and specific levels defined for the state variables are as summarized in Table 1. There are 270 possible states obtained from combinations of variables at each level.

PROBLEM FORMULATION

Model Description

The multiyear pavement program development and budget allocation is modeled as a modified minimal network-flow problem (*8*). Pavement states act as nodes that are connected by links that represent various treatment options. Lane miles of pavement that transit through the states would constitute the flow. The modeling process can be described by the following five-step procedure:

1. Classification of each nominal pavement section into one of many states for the initial time period,
2. Identification of treatment options that drive the pavement from one state to another over a period of time,
3. Estimation of treatment costs and other resource requirements,
4. Specification of management condition goals and budget constraints, and
5. Formulation of a linear program.

The linear program determines the lane miles of pavement in each state that should receive each of the possible treatment options.

Treatment Options Identification

Identification of treatment options on the basis of engineering considerations is an important project-level requirement. Each

TABLE 1 Components of NYSTA Pavement States

VARIABLE	MEASURE	LEVELS	CODE
Pavement Type	-	Overlaid Concrete	O C
Traffic	AADT (per lane)	< 15,000 15,000 - 30,000 > 30,000	L M H
Structural Rating	<u>Concrete</u> • Transverse Jt. Spalling • Transverse Jt. Faulting • Slab Cracking <u>Overlaid</u> • All lane distresses	0 - 20 21 - 40 41 - 60 61 - 80 80 - 100	E G F P B
Slab/Surface Rating	<u>Concrete</u> • Slab Surface Defects • Slab Cracking <u>Overlaid</u> • Surface Defects • Rutting	0 - 33 34 - 66 67 - 100	E G F
Joint/Crack Rating	<u>Concrete</u> • Joint distresses <u>Overlaid</u> • Crack distresses	0 - 33 34 - 66 67 - 100	E G F

Rating: E = Excellent G = Good F = Fair P = Poor B = Bad

L = Low M = Medium H = High

pavement state is assigned several maintenance, rehabilitation, and reconstruction (MR&R) actions. Subsequently, it is necessary to specify the consequences of performing an action (or deferring it) in order to evaluate the differences between the cost-effectiveness of MR&R actions. In particular, two issues need to be addressed through proper planning: reduced maintenance costs due to higher investment, and extended life of a pavement due to preventive maintenance.

A novel method of specifying a suitable MR&R action is in the form of a control. A control is a conjunction of treatments planned and the resulting change in pavement condition as a function of time. A complete control is defined by specifying both the type of action and the subsequent time for state transition. An action must be chosen after observation of the pavement state; on the basis of only the state at that time and the action chosen, the probability density function corresponding to the transition time required to arrive at a future state must be specified.

The process of identifying treatment options for each state is facilitated by answering two types of questions: What is the expected time to arrive at a future state if an action is taken (for example, a partial restoration such as slab replacement)? and, What level of maintenance (type, magnitude, and frequency) needs to be planned to achieve certain performance (in terms of state transition)?

The time interval over which a given control is applied varies with each control. The interval is determined as the time required for a state to change by a specified increment. That is, instead of planning MR&R actions as one-time actions, they are planned as controls that correspond to short-term plans (or sequence of treatments) that achieve a certain performance. This unique feature incorporates a planning and prediction process that relies not only on historical data but also on engineering expertise. This method of planning MR&R actions as controls that achieve a complete state transition is called state increment control.

Linear Program Formulation

The linear program expresses the network optimization problem as linear functions of the decision variables. In a general form it is formulated as

Decision variable:

y_{ijt} = lane miles of pavement in state i that should receive action j at time t

Objective:

Minimize

$$\sum_{t=1}^{T} \sum_{i \in I} \sum_{j \in J_i} w_{ijt} y_{ijt} \qquad (1)$$

where

T = number of time intervals in planning horizon (years),
I = set of condition states for pavement,
J_i = set of all actions for pavement in state i, and
w_{ijt} = present worth of expected cost for pavement in state i with action j applied in year t.

Subject to

$$\sum_{j \in J_i} y_{ij1} = L_{i1} \qquad \text{for all } i \in I \qquad (2)$$

where L_{i1} is the lane miles of pavement entering state i at initial time.

$$\sum_{k=1}^{t-1} \sum_{i \in T_d} \sum_{j \in J_{id}} P_{ijd}^{t-k} y_{ijk} = \sum_{j \in J_d} y_{djt}$$

$$\text{for all } d \in I \text{ and } t = 2 \text{ to } T \qquad (3)$$

where

I_d = set of states that have some action leading pavement to state d,
J_{id} = set of actions that have transitions from state i to state d,
J_d = set of all actions for pavement in state d, and
p_{ijd}^{t-k} = probability that pavement in state i would move to state d at time t after receiving action j at time k.

$$\sum_{k=1}^{t} \sum_{i \in I} \sum_{j \in J_i} c_{ijk}^{t} y_{ijt} \leq \mathrm{B}_t \qquad \text{for all } t \qquad (4)$$

where c_{ijk}^{t} is the cost of action j for a lane mile of pavement in state i at time k (the decision is made at time k, and cash flow occurs at time t), and B_t is the funding available at time t.

$$\sum_{k=1}^{t} \sum_{i \in I} \sum_{j \in J_i} a_{ijc}^{t-k} y_{ijk} \geq L(I_c, t)$$

$$\text{for all } c \text{ and } t = 2 \text{ to } T \qquad (5)$$

where

a_{ijc}^{t-k} = probability that pavement in state i after receiving action j at time k would at time t be in some state belonging to class c;
I_c = set of states classified under class c;
c = 1, 2, 3 for good, fair, and poor, respectively; and
$L(I_c,t)$ = threshold for lane miles of pavement to be in state I_c at time t.

$$y \geq 0 \qquad (6)$$

(i.e., nonnegativity of all y's)

Equation 2 provides the input corresponding to the initial time condition of the network. Initial condition is determined as lane miles of pavement distributed in various states. The left-hand side of the equation represents, for a particular state, a summation of the total lane miles that can receive various actions in the first year. This is equated to the actual number of lane miles present in that state during the first year.

Equation 3 imposes network length conservation during transitions between states. The summation on the left side represents the total quantity of pavement entering a particular state and time. The network length is conserved by equating the left-hand term to a summation totaling all lane miles leaving the state.

Equation 4 imposes budget constraints for each year in the analysis period. The left side represents a summation of total expected treatment cost incurred during a year. This is constrained to be no more than the specified MR&R budget for that particular year.

The objective of Equation 5 is to group different states into good, fair, and poor and denote them by a class, I_c. This constraint controls the amount of pavement that is allowed in each class per year; it corresponds to management goals for overall network condition. The left side is a summation of total lane miles belonging to a particular class at a given time. This is constrained to be no less than certain lane miles of pavement desired to be in that class. The direction of inequality can be reversed for undesirable classes. This will constrain the total lane miles in undesirable classes (e.g., poor) to be no more than a specified amount.

Variable Coefficient Determination

The coefficients for variables in the objective function are determined as present-worth costs of planned treatment options. Figure 1 illustrates state transition and cash flow for a control action. The probabilities are indicated for state transition to occur over a 3-year period. The costs incurred during each year are determined according to the cash flow. The expected cost associated with choosing an option is calculated by summing over transition timesthe product of yearly costs and the probability of pavement remaining in the current state.

The cost coefficients for the budget constraint depend on both the year in which the decision is made and the year in which the cash flow occurs. The formula for calculating these costs is given as

$$c^t_{ijk} = c_{ijq} \times (1 + \text{inf})^t \times \left(1 - \sum_{r=0}^{q} p^r_{ijd}\right) \quad \text{for any future state } d \qquad (7)$$

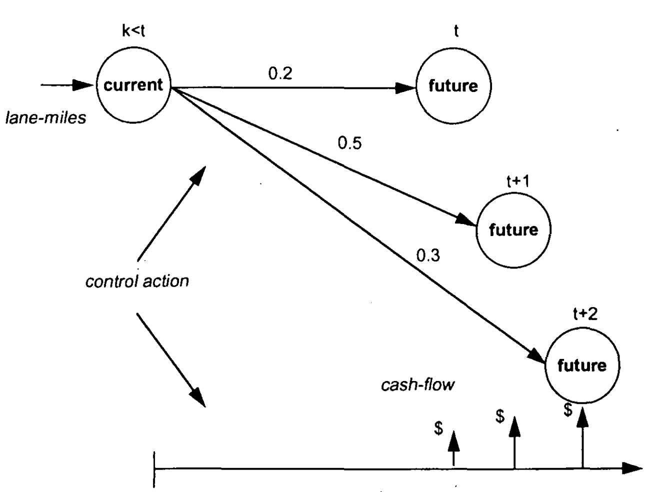

FIGURE 1 Illustration of state transition.

where $q = t - k$. The decision is being made in year k, and the cash flow is occurring in year t. The first factor is the cost of treatment option j applied after q years to pavement at state i. The second term is an inflation factor, and the third is the probability of pavement remaining at state i in year q. This probability is determined by summing the transition probabilities for previous years and subtracting that value from 1. Figure 1 is again helpful in understanding the derivation of these coefficients. For example, by time t there is only an 80 percent probability of pavement remaining in the current state because there is a 20 percent probability of transitioning to a future state in the preceding year. Only the probability of remaining in the current state is used in determining the costs associated with each year.

The coefficients for the condition constraint are calculated in a similar manner. The formula used is given as

$$a^q_{ijc} = \begin{cases} \left(1 - \sum_{r=0}^{q} p^r_{ijd}\right) & \text{for } i \in I_c \text{ and any } d \\ \left(\sum_{r=0}^{q} p^r_{ijd}\right) & \text{for } i \notin I_c \text{ and } d \in I_c \end{cases} \qquad (8)$$

Constraint 8 is concerned with the amount of pavement in a particular condition class at time t. The appropriate coefficient is calculated as one of two cases: the probability of pavement remaining in states belonging to the class, or the probability of pavement moving from a different class into states belonging to the class.

ILLUSTRATIVE EXAMPLE

Condition Data

The NYSTA network is divided into nominal sections of approximately 1 lane-mi based on 1991 survey data. Each section has at least the following properties: (a) pavement type, (b) AADT, (c) structural rating, (d) surface/slab rating, (e) crack/joint rating, and (f) length (lane miles). The problem size is reduced by analyzing only the overlaid pavement with less than 15,000 AADT per lane (this helps in presentation of results). Table 2 gives the classification of network inventory as distributed among various states. Column 1 has a five-letter code to denote each state with specific levels to the five state variables. Column 2 indicates the total lane miles of pavement classified into each state.

Treatment Options

Treatment options are identified for each pavement state. Each option is defined as a control action that consists of several specific treatment methods. According to the current practices of NYSTA pavement management, a set of eight treatment methods was identified:

- Do nothing (DN),
- Routine maintenance (RM),
- Preventive maintenance (PM),
- Heavy maintenance (HM),
- Resurfacing (RS),

TABLE 2 Assumed Distribution Among States

STATE	LANE-KM (in 1991)
11BFF	679.6
11BFG	356.8
11BGF	85.1
11BGG	37.0
11EEE	57.1
11FEE	0.0
11FFF	0.0
11FGF	0.0
11FGG	9.5
11GEE	14.5
11GGF	0.0
11GGG	0.0
11PEE	0.0
11PFF	1.6
11PFG	67.1
11PGG	15.3

1 km = 0.6 mi

- Rehabilitation of 4-in. overlay (RH1),
- Rehabilitation of 6-in. overlay (RH2), and
- Asphalt reconstruction (RC).

Preliminary cost estimates were obtained from construction and maintenance records of the most recent projects.

The notion of complete state transition control facilitates specification of treatment methods that vary (in type, frequency, and magnitude) from year to year. For example, routine maintenance that corresponds to fill-type patching may vary in terms of type (Grade 1 or 2 asphalt material), frequency (once or twice a year), and magnitude (square yards of patching). Although cost of applying maintenance (such as routine and preventive maintenance) can vary from state to state, such distinction is not made at this early stage.

Treatment options suitable for each state were assumed following simple guidelines developed by consulting NYSTA personnel. Sixteen states were developed, and each state was assigned at least two options. A sample of treatment methods and control action unit costs is given in Table 3. Columns 1, 2, and 3 indicate the current state, action number, and future state, respectively. Column 4 indicates treatment information for each control action. Specific treatment methods are planned for each year that the pavement remains in the current state.

Transition Probabilities

Transition probabilities associated with each state and control combination are based on condition data supplemented with engineering expertise accumulated over years of experience with NYSTA pavements. A computer program has been developed to display sequentially the information associated with each control action and enable the experts to predict the transition times. Each control action leads the pavement from one state to another over a random length of time. For each control action three transition times are specified:

- Lower limit (LL),
- Most common length of time (CL), and
- Upper limit (UL).

These transition times are used to construct a triangle of unit area representing the probability density function for the transition time. Table 4 presents a summary of the transition probabilities derived using the transition times predicted for some of the controls.

Variational Analysis

The linear programming problem is formulated and solved for a fixed annual budget, with and without condition constraints. First, the problem is solved considering only the budget constraints with an analysis period of 5 years. Second, additional constraints are introduced on the network condition in order to satisfy the long-term goals of management. Finally, the analysis period is extended to 10 years and only the budget constraints are considered. The problem may be extended to conduct a more rigorous analysis depending on the availability of data and the ability to define appropriate budget and condition constraints.

Results

Five-Year Analysis

Case 1: Budget Constraints Only An annual budget of $30 million is specified. The results from the linear program are given in Table 5. Major work including rehabilitation and

TABLE 3 Treatment Methods and Costs of Control Actions

Current State	Action Number	Future State	Treatment Information Code_Year Of Action	Unit cost ($1000/Lane-km)
OLBFF	1	OLEEE	RH1_1	39.77
OLBFF	2	OLEEE	RC_1	93.21
OLBFF	3	OLGEE	RH2_1	59.65
OLBFG	1	OLBFF	DN_0	0.00
OLBFG	2	OLBFF	PM_1, HM_2	14.29
OLBGF	1	OLBFF	DN_0	0.00
OLBGF	2	OLBFF	PM_1, HM_2	14.29
OLBGF	3	OLBFG	HM_1	9.32
OLBGG	1	OLBGF	DN_0	0.00
OLBGG	2	OLBFF	PM_1, PM_1	11.18
OLEEE	1	OLGGF	RM_2, RM_3	4.35
OLEEE	2	OLGGG	PM_2, PM_3	11.18
OLEEE	3	OLGEE	RM_1, RM_2, PM_2	9.32

TABLE 4 Example Transition Times and Probabilities for Control Actions

Current State	Action Number	Future State	Transition Times (Years) LL	CL	UL	Transition Probabilities Yr(1)	Yr(2)	Yr(3)	Yr(4)	Yr(5)
11BFF	1	11EEE	2.00	2.50	3.00	0.00	0.00	1.00	0.00	0.00
11BFF	2	11EEE	2.00	3.00	3.50	0.00	0.00	0.67	0.33	0.00
11BFF	3	11GEE	1.00	2.00	3.00	0.00	0.50	0.50	0.00	0.00
11BFG	1	11BFF	1.00	2.00	2.50	0.00	0.67	0.33	0.00	0.00
11BFG	2	11BFF	2.00	3.00	4.00	0.00	0.00	0.50	0.50	0.00
11BGF	1	11BFF	1.00	1.50	2.50	0.00	0.67	0.33	0.00	0.00
11BGF	2	11BFF	2.00	2.50	3.50	0.00	0.00	0.67	0.33	0.00
11BGF	3	11BFG	1.00	1.50	2.00	0.00	1.00	0.00	0.00	0.00
11BGG	1	11BGF	1.00	1.50	2.50	0.00	0.67	0.33	0.00	0.00
11BGG	2	11BFF	1.50	2.50	3.50	0.00	0.50	0.50	0.00	0.00
11EEE	1	11GGF	2.50	3.50	4.00	0.00	0.00	0.67	0.33	0.00
11EEE	2	11GGG	3.00	4.00	5.00	0.00	0.00	0.00	0.50	0.50
11EEE	3	11GEE	1.50	2.50	3.00	0.00	0.67	0.33	0.00	0.00

resurfacing is scheduled for 1045.9 lane-km (649.9 lane-mi) over a 5-year period. RH1 has been chosen as the optimal treatment for all lane miles of pavement in state OLBFF. DN_0 was chosen for 356.8 lane-km (221.7 lane-mi) of pavement in state OLBFG. Do nothing as opposed to preventive and heavy maintenance causes the pavement to deteriorate faster to state OLBFF. Consequently, rehabilitation is necessitated by 1993 and 1994. This indicates that maintenance is more expensive than do nothing because of the insignificant gain in pavement life with maintenance. Clearly, this result is a direct consequence of data used. But if funds were to be insufficient in 1993 and 1994, a maintenance action in 1991 would probably be chosen to defer the major work until funds are available. Such decisions are of great significance to pavement managers.

It is interesting that relatively good pavement (in states OLFGG, OLGEE, etc.) received the do nothing option whereas pavement in fair condition (in states OLPFF, OLPGG, etc.) received maintenance actions. This indicates that the appropriate time to conduct maintenance is when the deterioration (not just the rate of deterioration) is high enough that the maintenance effort will be cost-effective. In other words, maintenance at an early stage will decrease the deterioration rate but probably not improve the condition significantly. On the contrary, maintenance at a later stage can improve the condition as well as decrease the deterioration rate and consequently extend the life relatively more. Again, this result is a direct consequence of the data used.

Case 2: Budget and Condition Constraints In Case 2 additional constraints on future pavement condition are imposed. Four condition classes are established: safety with excellent and fair ratings, and ride quality with excellent and fair ratings. Threshold values are specified for the final year to target an increase in total lane miles distributed among each of the four classes.

The results of this case are presented in Table 6. Both RH1_1 and RH2_1 have been chosen as the optimal treatments for pavement in state OLBFF. In contrast with Case 1 (in which mostly do nothing was chosen), most of the pavement in other states received routine, preventive, or heavy maintenance. This is expected since the condition constraints achieve the targeted goals that correspond to increased lane miles among excellent and fair classes of safety and ride quality. The total expected present worth cost for the 5-year program increased from $46 million to $57 million.

It is necessary to note that the programmed lane miles correspond to a sequence of treatments (defined as part of the control). For example, in Table 6, 57.1 lane-km (35.5

TABLE 5 Results of 5-Year Analysis (Case 1)

Current State	Ln-km (in 1991)	Optimal Treatment	Programmed Lane-km 1991	1992	1993	1994	1995
OLBFF	679.6	RH1_1	679.6	-	238.0	118.8	-
OLBFG	356.8	DN_0	356.8	-	-	-	24.6
		PM_1, HM_2	-	-	85.1	-	-
OLBGF	85.1	DN_0	-	-	-	57.1	29.1
		HM_1	85.1	-	24.6	-	-
OLBGG	37.0	DN_0	37.0	-	10.1	6.1	0.5
OLEEE	57.1	RM_2, RM_3	57.1	-	-	679.6	-
OLFGF	0.0	RS_1	-	-	6.3	3.2	-
OLFGG	9.5	DN_0	9.5	-	-	-	-
OLGEE	14.5	DN_0	14.5	-	-	-	-
OLGGF	0.0	DN_0	-	-	-	38.1	19.0
OLGGG	0.0	DN_0	-	-	-	6.3	3.2
OLPEE	0.0	DN_0	-	-	-	6.3	3.2
OLPFF	1.6	HM_1	1.6	-	-	-	-
OLPFG	67.1	RM_1, RM_2, RM_3	67.1	-	-	-	-
OLPGG	15.3	RM_1, RM_2	15.3	1.6	-	-	-

TABLE 6 Results of 5-Year Analysis (Case 2)

Current State	Ln-km (in 1991)	Optimal Treatment	Programmed Lane-km				
			1991	1992	1993	1994	1995
OLBFF	679.6	RH1_1	428.4	-	46.0	166.9	143.9
		RH2_1	251.2	-	-	-	-
OLBFG	356.8	DN_0	69.0	-	-	-	-
		HM_2	287.7	-	85.1	-	-
OLBGF	85.1	DN_0	-	-	-	-	11.9
		PM_1HM_2	-	-	24.6	12.4	-
		HM_1	85.1	-	-	-	-
OLBGG	37.0	DN_0	37.0	-	17.9	36.9	14.0
OLEEE	57.1	RM_1RM_2PM_2	57.1	-	-	428.4	-
OLFGF	0.0	RM_1	-	-	-	6.3	-
		RS_1	-	-	-	-	3.2
OLFGG	9.5	PM_1PM_2	9.5	-	-	-	-
OLGEE	14.5	RM_1PM_2PM_3	-	-	163.7	-	-
		DN_0	14.5	-	-	144.7	-
OLGGG	0.0	DN_0	-	-	14.5	-	-
OLPFF	1.6	HM_1	1.6	-	-	-	-
OLPFG	67.1	RM_1HM_2RM_2PM_3	67.1	-	-	-	-
		RM_1RM_2RM_3	-	-	15.3	-	-
OLPGG	15.3	RM_1RM_2	-	1.6	-	-	-
		DN_0	15.3	-	-	-	-

lane-mi) in state OLEEE are programmed to receive routine maintenance for the first year and both routine and preventive maintenance during the second year. Although nothing appears in the column corresponding to 1992 (Table 6), treatments are still planned to be performed during that year.

Ten-Year Analysis

Ten-year analysis is a simple extension of Case 1 in 5-year analysis. This case presents the long-term effect on the overall costs. The results are given in Table 7. Increase in analysis period caused insignificant changes in pavement program. This indicates that the long-term economic trade-offs (for this simple case) are less significant than the economic trade-offs between pavement sections at different condition levels and their treatment options. Indeed, it highlights the need for conducting a network optimization.

DISCUSSION OF RESULTS

Pavement States Definition

The definition of pavement states on the basis of pavement distress condition will facilitate the project-level planning process. Important advantages of defining pavement states according to condition measures include the abilities to (a) provide meaningful information to assess the extent of pavement damage, and (b) correlate states with other engineering factors and establish broad classes to which various states may belong. The former is essential to define specific treatment options. Specificity in identified treatment options would alleviate the variability in cost estimation and prediction. States would also allow better estimates for extent of repair based on actual distress condition.

Grouping of states into classes considering safety, ride quality, and so on will enable management to define specific con-

TABLE 7 Results of 10-Year Analysis

Current State	Ln-km (in 1991)	Optimal Treatment	Programmed Lane-km									
			1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
OLBFF	679.6	RH1_1	679.6	-	238.0	118.8	-	16.4	12.1	4.0	-	-
OLBFG	356.8	DN_0	356.8	-	-	-	24.6	-	-	-	23.7	11.6
		PM_1, HM_2	-	-	85.1	-	-	-	-	29.8	-	-
OLBGF	85.1	DN_0	-	-	-	57.1	29.1	-	-	-	-	-
		HM_1	85.1	-	24.6	-	-	29.8	23.7	11.6	5.5	3.4
OLBGG	37.0	DN_0	37.0	-	10.1	6.1	0.5	8.5	3.9	3.2	4.2	2.1
OLEEE	57.1	RM_2, RM_3	57.1	-	-	679.6	-	294.8	147.1	16.4	16.4	12.1
OLFGF	0.0	RS_1	-	-	6.3	3.2	-	-	-	-	3.2	1.6
OLFGG	9.5	DN_0	9.5	-	-	-	-	-	4.8	-	-	-
		DN_0	-	-	-	-	-	-	-	9.7	-	-
OLGEE	14.5	DN_0	14.5	-	-	-	-	-	-	-	-	-
OLGGF	0.0	DN_0	-	-	-	38.1	19.0	-	453.7	251.7	221.9	202.8
OLGGG	0.0	DN_0	-	-	-	6.3	3.2	19.0	-	-	-	-
OLPEE	0.0	DN_0	-		-	6.3	3.2	-	-	-	-	3.2
OLPFF	1.6	HM_1	1.6	-	-	-	-	-	-	-	-	-
OLPFG	67.1	RM_1, HM_2, RM_2, PM_2	67.1	-	15.3	1.6	-	-	-	-	-	-
OLPGG	15.3	RM_1, RM_2	-	-	-	-	-	4.2	4.2	1.1	-	-
		DN_0	15.3	-	-	-	-	-	-	-	-	-

dition goals to be targeted. For example, pavement states may be classified as comfortable or uncomfortable by correlating a road user's perceptions of ride quality with pavement states. Then the management can impose a constraint to maintain less than a certain number of lane miles in uncomfortable states for each year in the planning horizon. A target level of network ride quality may also be specified for each year in the analysis period.

Some of the disadvantages in basing pavement states on condition measures include the relatively large number of states, the difficulty in defining state transitions, and the analytical complexity. Because of the large number of states (270), the overall size of the problem (considering several alternatives to each state and several years in the analysis period) is relatively large. Considerable effort may be required to implement the whole system.

Treatment Options Identification

Identifying suitable treatment options requires engineering expertise. It is essential to communicate clearly the pavement distress condition to the experts. As discussed, condition states are an effective way to assess the extent of pavement damage and assign several treatment options for each state. (Note that the treatment options are irrespective of individual sections classified into each state.) Each treatment option is planned using the state increment control approach as a short-term action.

The state increment control approach incorporates planning that relies not only on historical data but also on engineering expertise. Condition data alone are often insufficient to predict condition as a consequence of action. Alternatively, empirical knowledge applied using state increment control can facilitate both planning and prediction.

Nominal Sections Classification

Classifying nominal sections into pavement states can be improved on the basis of the specific characteristics of each nominal section. For example, consider an unrated (existing or new) 20-lane-mi section that is undergoing repair or construction (which may take 2 years). Such a section can be specified to reach the state of OLEEE in the third year.

In general, not all network inventory needs to be classified into states for the first year in the analysis (as done in the illustrative example; see Table 2). A more appropriate classification of the inventory can be achieved by analyzing the condition data and the maintenance status of each nominal section.

Linear Program Formulation

The optimal decisions at various levels of pavement management are mostly dictated by the trade-offs between economic and engineering factors. These factors exhibit subtle interactions since the decisions are bound by constraints. Hence, simultaneous determination of the treatment, timing, and magnitude of work is an important part of the decision process. The presented decision-making methodology achieves this task using a linear programming formulation.

The emphasis in the presented methodology has been on aggregating pavement sections of similar condition characteristics. Aggregation into states according to lane miles significantly reduces the complexity of the problem. It enables the application of a relatively simple linear programming technique for constrained optimization. In contrast, dynamic and integer programming have several limitations. In specific, it is very difficult to deal with multiple constraints in a dynamic programming application. It limits the control over decisions as needed for network optimization. Often large-scale integer programming problems are very difficult to formulate as they require alternatives to individual projects over multiple years (*9*). In practice it may be difficult to develop methodologies for treatment identification and cost estimation that are needed to support such formulations. Lack of explicit condition measures and a prediction model makes the decision process subjective. To minimize the subjectivity, it may be necessary to identify a few well-understood characteristics and achieve consistency in evaluation (in which case aggregation may be a better approach). The size of an integer programming problem could be significant for large networks, adding computational complexity. The number and nature of constraints on the problem (depending on the number of pavement characteristics and project interactions considered in the decision process) can add to the complexity.

Analytical Aspects Evaluation

The presented optimization methodology recognizes the role of project-level analysis as planning treatment options to each state while applying engineering expertise in prediction process. The management specifies the threshold condition levels and available budget for the entire network. A linear programming formulation is used to best allocate the budget and determine a feasible multiyear pavement program.

The objective function provides an economic comparison of the alternatives in terms of expected long-term costs. Minimizing costs rather than maximizing benefits alleviates the problem of finding a "correct" benefit value function. Specifying appropriate condition goals and constraints is essential to obtaining effective results in either case.

Life-cycle cost analysis is traditionally conducted on an individual project basis without explicit consideration of pavement condition. Consequently, costs and savings incurred between two different projects cannot be directly compared (a value judgment of other factors is necessitated). In contrast, state increment control approach explicitly considers the pavement condition at each stage. The differences in the costs as well as other aspects related to states (such as condition, safety, and ride quality) may be integrated into network-level analysis for constrained optimization. Once the management goals and constraints are explicitly stated, trade-offs between projects are essentially captured without the need for value engineering judgments.

The current formulation can provide answers to many "what if" scenarios. For example, the implications of maintaining less than 10 percent of the network in "unsafe" states compared with that of 20 percent that might boost the rehabilitation program could be considered in terms of increased costs (or increase in savings if user costs as a function of safety are included in the objective function). And variations in the pavement program as the budget limitations vary may be observed through sensitivity analysis.

SUMMARY AND CONCLUSIONS

The network optimization methodology presented in this study is an essential requirement for program planning and budget allocation involved in NYSTA's PMS. Preliminary investigation was conducted to identify the most important parameters that quantify distress and no-distress factors affecting the decision process. Specific values taken by these parameters describe the pavement condition state. The network condition was represented as lane miles distributed into various states. This was achieved by dividing the network into nominal sections of varying lengths and classifying each section into one of the states according to condition characteristics. Each state was assigned several treatment options that transform the pavement condition over time. The transitions between states are defined to model the consequences of each treatment option. A linear programming application was used for constrained optimization and determination of an optimal pavement program. An illustrative example was presented with details on data collection, network constraint formulation, and variational analysis for obtaining desirable results. The results demonstrate the ability of the mathematical model to provide answers to network-level pavement management questions.

From the research and developed methodology, the following conclusions are drawn:

- Representing network condition as lane miles of pavement distributed among various states reduces the problem complexity, thus enabling application of linear programming optimization techniques that are simple.
- Specifying treatments as controls that achieve a complete state transition enables the use of historical data and engineering expertise in the prediction process.
- Modeling interactions between economic and engineering factors (e.g., cost, budget, condition, timing of MR&R) is essential to evaluate the consequences of decisions in a effective manner.
- Using the illustrated optimization methodology may help to develop an effective multiyear pavement program and ensure optimal budget allocation for the entire network.

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