Framework for Systematic Decision Making in Highway Maintenance Management

KUMARES C. SINHA AND TIEN F. FWA

The results of a 4-year research study that was undertaken in Indiana are presented. The objective of the study was to develop a systematic decision-making framework to enhance the efficiency and effectiveness of the existing maintenance management practice at the subdistrict highway agency level, where detailed maintenance programs are planned and implemented. The forms of data required and the recommended basis and procedures of decision making are discussed for the following areas: (*a*) assessment of maintenance needs, (*b*) establishment of performance standards, (*c*) determination of the costs of maintenance treatments, (*d*) setting up of an integrated data base, (*e*) priority rating of maintenance activities, and (*f*) optimal programming and scheduling of maintenance activities. Examples of planning data and information obtained from the research study are presented. The proposed decision-making framework is intended to be useful as an aid to management in the planning and monitoring of highway maintenance programs to obtain improved results from better use of available resources.

The weaknesses of the existing maintenance management practice in most state highway agencies may be summarized as follows: (*a*) maintenance needs assessments are made based on subjective judgment and experience of individual unit foremen, (*b*) maintenance work load estimates are established primarily by individual foremen on the basis of historical averages and their own judgment, (*c*) cost estimates for routine maintenance work are based on historical data that may not reflect the actual needs in the field, (*d*) routine maintenance programs are planned without effective coordination with major rehabilitation activities, (*e*) a data base is not available to provide the management with timely access to inventory and capital program data, and (*f*) routine maintenance activities are manually selected and scheduled by unit foremen through experience and judgment.

An improved procedure was developed for the management of maintenance activities in the Indiana state highway system that would eliminate or minimize many of the existing shortcomings. Figure 1 shows the main elements of the proposed highway maintenance management framework. The aim is to enable managers at the subdistrict level to plan a maintenance work program efficiently to achieve an optimal utilization of available funds. The planning of the maintenance program requires input that includes quantitative assessment of maintenance needs in terms of work loads and the relative importance of these needs ranked according to their priority ratings. Also required is a routine maintenance data base that contains relevant budget, cost, and performance information. Figure 1 indicates that the data base needs to be constantly updated to provide the most up-to-date information for planning purposes.

The present study identified the following six areas crucial to achieving the ultimate objective of maintaining and preserving the entire road network effectively:

- Development of a procedure to assess routine maintenance needs to minimize inconsistencies in the needs assessments made by different foremen;
- Establishment of maintenance performance standards to enable better estimates of manpower, materials, and equipment requirements to be made;
- Determination of cost functions for individual routine maintenance activities for reliable cost assessments;
- Setting up of an integrated routine maintenance data base system to ensure timely availability of planning information;
- Priority setting of various maintenance activities to promote adherence of accepted maintenance strategies; and
- Optimal programming and scheduling of routine maintenance work to produce a maintenance program that best satisfies maintenance needs with the available funds and resources.

Descriptions of these six areas in terms of their significance and operational features are presented in the following sections. The procedure is illustrated with data from the Indiana Department of Transportation. Indiana has six districts, each of which is subdivided into six or seven subdistricts. Within each subdistrict, there are two to four maintenance units that are directly responsible for routine maintenance work in the field.

ASSESSMENT OF ROUTINE MAINTENANCE NEEDS

The development of the proposed procedure for assessing routine maintenance needs consists of two parts: devising a reliable and practical procedure of highway condition survey and establishing quantity standards by which work load requirements for each routine maintenance activity can be computed.

K. C. Sinha, School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907. T. F. Fwa, Department of Civil Engineering, National University of Singapore, Kent Ridge, Singapore 0511, Singapore.

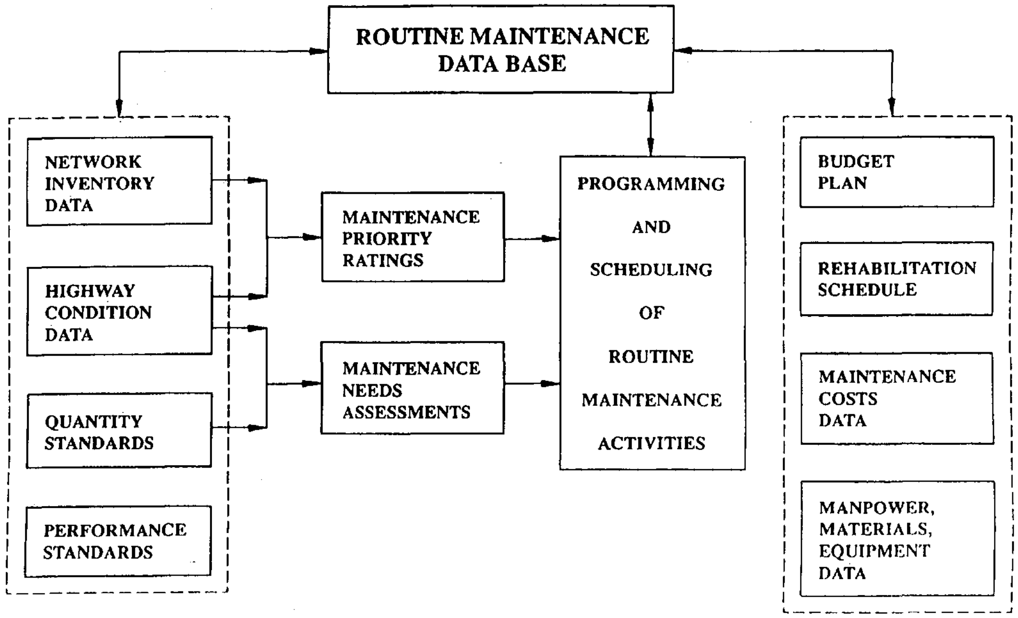

FIGURE 1 **Elements of proposed highway maintenance management framework.**

Highway Condition Survey

The current practice requires unit foremen to drive along the road to be inspected and report any deficiency using their own words. It was recognized in the study that a detailed condition survey completed with physical measurements of distress characteristics was not practical because it would be too time-consuming. It was, however, believed that more guidance could be provided to unit foremen in their field survey work and that standard descriptions and terms should be used in reporting. This led to the design of simple condition survey forms (*1*).

The distress types included in the survey forms were selected on the basis of past records of maintenance needs descriptions and finalized upon consultation with unit foremen and subdistrict maintenance management personnel. Each distress is identified by type, severity level, and extent or frequency of occurrence. Severity was considered in three categories: slight, moderate, and severe. The extent or frequency of occurrence was identified as many (m), some (s), or none (n). Exceptions are the descriptions for ditches and joints of concrete pavements, where the condition is classified as good, fair, or poor.

The use of the above procedure presented an improvement over the existing practice in that standard descriptions would be adopted in reporting of pavement distresses. This is especially important from the standpoint of quantifying maintenance needs, as will be described in the next section. It also provided a common reference for computing funding and resource requirements for different subdistricts on a statewide basis. In the long run, the availability of such systematically recorded distress data would be valuable for routine maintenance studies such as cost analysis of routine maintenance activities and effectiveness evaluation of routine maintenance treatments.

Choice of Maintenance Treatment

For any given distress type of a certain level of severity, several maintenance treatment alternatives are available to maintenance personnel. For example, Figure 2 shows relationships between common types of distress and maintenance treatments.

From the point of view of maintenance management, it is highly desirable that all subdistrict unit foremen be consistent in their choice of maintenance treatments. Whereas there is more than one maintenance treatment for a given distress, there is one treatment that will produce the best solution under the prevailing climatic and pavement conditions. The choice of maintenance treatments for correction of distresses can only be made more consistent through adoption of the most desirable treatment in every case.

A direct approach would be to conduct a survey to ask unit foremen to select the best maintenance treatment for each distress condition on the basis of their experience and judgment. A set of maintenance treatment selection guidelines may then be established on the basis of the collective opinion of unit foremen. Consultation with experienced maintenance personnel in Indiana indeed showed that there was also one preferred treatment for any particular distress.

A more rational approach, which is recommended in the present study, is to select the best maintenance treatment on the basis of cost-effectiveness considerations. This requires information on the cost and service life of different maintenance treatments. A survey was carried out in the study to determine effective service life for routine maintenance activities in the areas of pavement, shoulder, and drainage in Indiana (*2*). The effective service life of a maintenance treatment was defined as the time elapsed from application of the treatment to when, in the opinion of the foremen, it needed to be replaced.

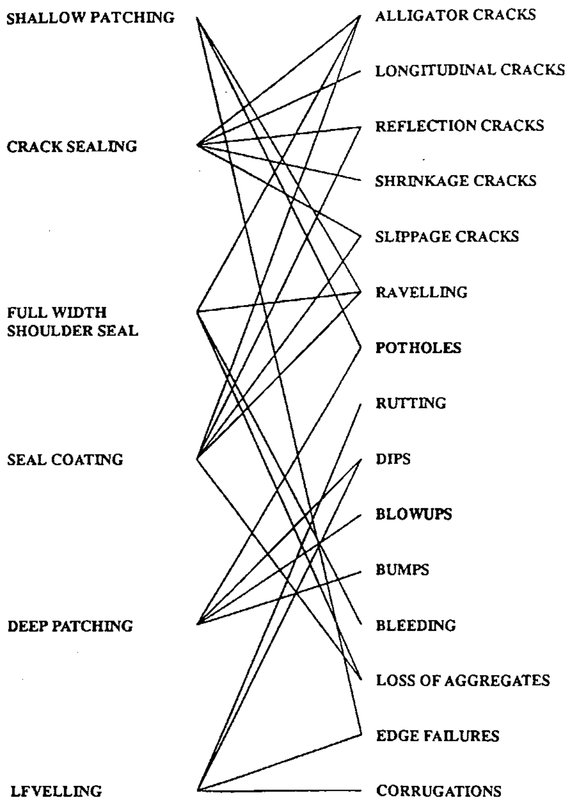

FIGURE 2 Relationship between maintenance treatments and distresses.

Because the effective service life of a treatment is highly dependent on the overall structural condition of the pavement concerned, estimates were obtained for the general condition levels of the entire roadway, namely poor, fair, and good. Estimates of minimum, average, and maximum effective service life were obtained from unit foremen. The average value can be used as a parameter for comparison purposes. It is an estimate by unit foremen of the average effective service life attainable when appropriate work practices are followed, with all necessary equipment, manpower, and time available to carry out the treatment work satisfactorily. These effective service life data can be combined with associated cost (to be discussed in a later section) to compute the desired cost-effectiveness of maintenance treatments.

Quantification of Maintenance Needs

Quantification of maintenance needs can be achieved by first identifying the appropriate unit of measure of work load for each maintenance treatment, followed by establishing quantity standards for work load estimation. Quantity standards express maintenance work load requirements in terms of appropriate units of measure for various distress types with different severity-extent combinations. The availability of such standards would help to reduce the uncertainties and variations involved in work load estimating in the existing practice that relies on the judgment of individual unit foremen. Two procedures were developed in this study for work load estimation: a statistical sampling approach and a computer-based expert system approach.

Statistical Sampling Approach

In this procedure the experience and collective know-how of subdistrict unit foremen were tapped to develop quantity standards for various distress type-severity-extent combinations. A statistical random sampling process was used to obtain representative values of foremen's estimates of expected work loads for various distress conditions. A statistical experiment was conducted to acquire the required information.

A total of 18 maintenance units were included in the study. The survey covered asphalt and concrete pavements in both the Interstate and the state highway systems. A stratified random sampling scheme (*3*) was used to select a total of 965 lane-mi of road for the experiment. The stratified random sampling scheme is a restricted randomization design in which experimental units are first sorted into homogeneous groups and then the required number of experiment units are randomly selected within each group. Unit foremen were asked to estimate the work load for every distress found on the test sections. A multivariable regression analysis, based on least squares fit, was used to develop equations that estimated maintenance work load on the basis of ratings of distress severity and frequency. Some examples of the derived quantity standards resulting from statistical analyses are given in Tables 1 through 4.

Computer-Based Expert System

An expert system using the LISP programming language (*4*) was developed to demonstrate its application in estimating maintenance work load. It can be used by subdistrict unit foremen to estimate maintenance needs on the basis of field observations of pavement distresses.

The program has three major components: input module, knowledge base, and output module. The input module is interactive in nature. It asks the user for information in the following two categories: (*a*) highway section geometric features, such as section length, number of lanes, lane widths, and shoulder widths; and (*b*) distress conditions such as distress type, severity, and frequency.

The knowledge base component stores all the rules. It has two distinct subdivisions. The first, known as the conversion module, converts qualitative assessment of distresses into numerical values. The second, the rules module, includes the rules to estimate maintenance work load requirements. The

TABLE 1 Example of Maintenance Quantity Standards for Work Load Computation—Clipping Unpaved Shoulder

	Frequency of Buildups	
Severity of Buildups	Some	Many
Slight	0.10	0.33
Moderate	0.25	0.50
Severe	0.45	0.90

NOTE: Quantity is in miles per shoulder mile (1 mi = 1.609 km).

TABLE 2 Example of Maintenance Quantity Standards for Work Load Computation—Shallow Patching

Severity of Potholes	Frequency of Potholes	
	Some	Many
Slight	0.50	1.20
Moderate	1.10	2.10
Severe	1.90	3.10

NOTE: Quantity is in tons per lane mile (1 ton/mi = 0.631 tonne/km).

lower and upper bounds of the 95 percent confidence interval for the estimated work load are computed.

The output module summarizes the estimated work load requirements for all the highway sections in standard units of measurements and displays all the values with proper titles and units. It also computes the estimated costs for various work load requirements when information on unit costs of maintenance activities is available. Figure 3 shows the input and output of an example problem.

PERFORMANCE STANDARDS FOR MAINTENANCE TREATMENTS

A maintenance treatment performance standard establishes the following for the maintenance treatment concerned: (*a*) the standard crew size needed, (*b*) the kinds and amount of equipment required, (*c*) the major types of materials that should be used, (*d*) recommended procedures for performing the work, and (*e*) an estimate of expected average daily accomplishment with standard crew size, equipment, and procedures. This information allows expected work load activity to be converted into manpower and work hour requirements.

Performance standards provide a basis for development of work programs and budgets at the subdistrict level. A set of performance standards is contained in the *Field Operations Handbook for Foremen* (*5*). This approach has functioned reasonably well in Indiana since it was implemented in 1975. However, a large variation in the average daily accomplishment of maintenance work still exists. Currently, a range of daily accomplishment quantity is specified for each maintenance treatment. However, it has been observed that daily accomplishments of maintenance work are dependent on roadway condition (*2,6*). An improvement in the estimation of daily accomplishment can therefore be made by identifying the accomplishment quantities for different roadway conditions.

A survey questionnaire was adopted for the maintenance work accomplishment investigation conducted in the present study. This survey was conducted together with the effective service life survey. Estimates of the number of accomplishment units attainable per day for each cell in the matrix for different maintenance treatments were obtained from the maintenance personnel interviewed. Table 5 gives examples of the survey results.

TABLE 3 Example of Maintenance Quantity Standards for Work Load Computation—Deep Patching, Potholes

Frequency of Potholes	Frequency of Bumps/Surface Failure		
	None	Some	Many
None	0.00	0.04	0.50
Some	0.10	0.50	1.30
Many	0.90	1.70	3.25

NOTE: Quantity is in tons per lane mile (1 ton/mile = 0.631 tonne/km).

TABLE 4 Example of Maintenance Quantity Standards for Work Load Computation—Deep Patching, Ditches

Condition of Ditch	Work Load (ft per ditch mile)
Poor	693.0
Fair	190.0
Good	2.0

NOTE: 1 ft/mi = 0.189 m/km.

COST OF MAINTENANCE TREATMENTS

Considerable research has been undertaken in Indiana in recent years into the cost of routine maintenance treatments (*7,8*). The general form adopted in the present study for estimating the costs of maintenance treatments is given by

$$T_k = \sum_i \sum_j F_{ijk} * R_{ijk} * C_{ijk} \quad (1)$$

where

T_k = total cost per production unit of the kth maintenance treatment (dollars),
F_{ijk} = usage factor of the jth element of the ith resource when required to produce one unit of the kth maintenance treatment,
R_{ijk} = rate of consumption of the jth element of the ith resource required to produce one unit of the kth maintenance treatment, and
C_{ijk} = unit cost of the jth element of the ith resource.

The usage factor, F_{ijk}, is calculated as

$$F_{ijk} = \frac{n_{ijk}}{N_k} \quad (2)$$

where n_{ijk} is the total number of jobs observed using the jth element of the ith resource in the kth maintenance treatment and N_k is the total number of jobs in the kth maintenance treatment.

The consumption rate, R_{ijk}, is obtained from

$$R_{ijk} = \frac{u_{ijk}}{U_k} \quad (3)$$

where u_{ijk} is the total number of units of the jth element in the ith resource used in the kth maintenance treatment and U_k is the total number of units of the kth maintenance treatment produced.

The cost components included were labor costs, materials costs, and fuel costs. Labor and materials unit costs were obtained from the Indiana Department of Transportation (*5*). Fuel consumption rates were obtained from the results of a field study conducted by Sharaf et al. (*7*).

INPUT			
ROAD SECTION LENGTH		:	10 MILES
NUMBER OF LANES - ONE WAY ONLY		:	1
LANE WIDTH		:	11.5 FT
INSIDE SHOULDER WIDTH		:	3 FT
OUTSIDE SHOULDER WIDTH		:	6 FT
CRACKS	SEVERITY	:	MODERATE
	FREQUENCY	:	MANY
POTHOLES	SEVERITY	:	SLIGHT
	FREQUENCY	:	FEW
RAVELING	SEVERITY	:	SLIGHT
	FREQUENCY	:	NONE
BLOWUPS / BUMPS / SURFACE FAILURES	FREQUENCY	:	MANY
RUTTING AND DIPS	SEVERITY	:	SEVERE
	FREQUENCY	:	MANY

OUTPUT	
AMOUNT OF WORK	
SHALLOW PATCHING	5.2 - 6.1 TONS
CRACK SEALING	1359 - 1584 GALLONS
FULL WIDTH SHOULDER SEALING	0 - 7 FT-MILES
SEAL COATING	0 - 1.7 LANE-MILES
DEEP PATCHING	8.6 - 9.8 TONS
LEVELING	161 - 162 TONS
ESTIMATED COSTS	
SHALLOW PATCHING	$ 596 - 701
CRACK SEALING	$ 2,827 - 3,294
FULL WIDTH SHOULDER SEALING	$ 0 - 832
SEAL COATING	$ 0 - 2,858
DEEP PATCHING	$ 575 - 655
LEVELING	$ 7,411 - 7,477

FIGURE 3 Example of maintenance work load estimation by expert system.

TABLE 5 Examples of Estimated Daily Accomplishment as a Function of Roadway Condition

Maintenance Treatment	Accomplishment Per Crew Day			Unit of Measurement
	Poor Roadway Condition	Fair Roadway Condition	Good Roadway Condition	
Shallow patching (Hot mix)	$\bar{x}$ = 7.2 σ = 1.5	$\bar{x}$ = 4.2 σ = 0.8	$\bar{x}$ = 2.8 σ = 0.5	Tons of Mix
Shallow patching (Cold mix)	$\bar{x}$ = 7.1 σ = 2.6	$\bar{x}$ = 3.9 σ = 1.2	$\bar{x}$ = 2.6 σ = 0.8	Tons of Mix
Premix leveling	$\bar{x}$ = 120.0 σ = 38.7	$\bar{x}$ = 88.6 σ = 36.6	$\bar{x}$ = 55.0 σ = 34.8	Tons of premix
Seal coating (Chip Seal)	$\bar{x}$ = 6.3 σ = 2.0	$\bar{x}$ = 6.9 σ = 1.7	$\bar{x}$ = 7.5 σ = 1.7	Lane miles
Seal coating (Sand Seal)	-*	$\bar{x}$ = 8.2 σ = 2.0	$\bar{x}$ = 8.2 σ = 2.0	Lane miles
Full width shoulder seal	-*	$\bar{x}$ = 73.5 σ = 16.8	$\bar{x}$ = 74.5 σ = 14.0	Foot miles
Sealing longitudinal cracks and joints	$\bar{x}$ = 6.3 σ = 2.1	$\bar{x}$ = 8.4 σ = 2.4	$\bar{x}$ = 10.2 σ = 3.8	Linear miles
Sealing cracks	$\bar{x}$ = 1.5 σ = 0.6	$\bar{x}$ = 3.0 σ = 0.9	$\bar{x}$ = 4.5 σ = 1.6	Lane miles
Spot repair of unpaved shoulders	$\bar{x}$ = 46.4 σ = 1.3	$\bar{x}$ = 30.5 σ = 8.2	-*	Tons of aggregate
Blading shoulders	$\bar{x}$ = 10.6 σ = 1.3	$\bar{x}$ = 13.2 σ = 2.2	-*	Shoulder miles
Recondition unpaved shoulders	$\bar{x}$ = 3.4 σ = 1.1	$\bar{x}$ = 4.5 σ = 1.1	-*	Shoulder miles
Clean and reshape ditches	$\bar{x}$ = 696 σ = 269.7	$\bar{x}$ = 1255 σ = 419.8	-*	Linear feet of ditch

Notes: (1) *indicates treatment is not applicable
(2) 1 mile = 1.609 km, 1 foot = 0.3048 m, 1 ton = 1.016 tons

ROUTINE MAINTENANCE DATA BASE

Extensive data are required for successful implementation of a highway maintenance management system. Figure 1 shows clearly the wide scope and diversity of the types of information needed for effective decision making in arriving at the final maintenance work program. The establishment of a routine maintenance data base with automated data handling and management capability is essential to efficient management of modern road networks. The data base facilitates collecting, storing, processing, and retrieving of information required in a maintenance management system. The following features are desirable:

- There must be a common referencing system to ensure compatibility and transferability of information derived from different data files.
- Linkages with information systems of other management levels (such as the central and the district levels) should be provided. Such linkages help to avoid duplicative data collection efforts. They also enhance coordination between work program planning at different management levels.
- The data base should be structured to facilitate constant updating to include the most up-to-date data. It must also allow for future improvement and expansion.

Types of Data

Three categories of data can be identified in Figure 1: subdistrict-specific data, policy and standards guidelines, and district and central office planning information. Subdistrict-specific data include network inventory data, highway condition data, and resources data. Network inventory data consist of highway functional classification, roadway geometry records, pavement structural characteristics, and roadside appurtenance records. Highway condition data are to be periodically updated through condition surveys performed by unit foremen, as described earlier. Resources data are information on the available manpower, materials, and equipment within the subdistrict concerned.

Policy and standards guidelines refer to quantity standards, performance standards, and cost information of maintenance treatments. The guidelines are essential for systematic decision making in maintenance management, and they reflect directly the maintenance policy of the central office. They are typically established on a statewide basis. The procedures for developing them have been presented earlier.

Budget plan and rehabilitation schedule come under the category of district and central office planning information. Unfortunately, as in many other states, the routine maintenance programs at the district and subdistrict levels in Indiana had not been effectively coordinated with major rehabilitation programs planned at the central office (*9,10*). Highway maintenance consists of corrective and preventive activities performed on a regular or continual basis, whereas rehabilitation includes major facility improvement such as replacement, reconstruction, overlays, resurfacing, and surface recycling. Although the criteria for the development of major highway facility replacement or rehabilitation programs may differ from those of routine maintenance programs, both programs have a goal of preserving the condition of the highway system. Effective coordination between the two programs can result in considerable savings. A major emphasis in the routine maintenance data base development undertaken in the current study was therefore to establish an efficient link between the two types of program.

Coordination of Maintenance and Rehabilitation Planning

After rehabilitation schedule information is made available to the subdistrict maintenance personnel, a natural question to ask is how this information could be used in maintenance planning. A highway agency would do certain adjustments to its routine maintenance program once the schedule of a rehabilitation project on a given highway section is known. Currently no specific information is available as to what maintenance treatments should be withheld or how long before the rehabilitation project such treatments should be discontinued. Because these are useful decision-making aids in maintenance planning, a project was initiated in this study to obtain the information (*11*).

The approach adopted was similar to the service life survey described earlier. A total of 36 representatives of maintenance staff were randomly selected from the subdistricts in the state. The factors included in the survey were maintenance treatment type, highway class, and pavement distress level of the highway section needing treatment. A suspension period was defined as the length of time before a rehabilitation work that a given maintenance treatment would not be carried out at all. Each maintenance staff member surveyed was asked to indicate the length of suspension period for different maintenance treatments by highway class and pavement distress severity level. On the average, for each highway class, more than two-thirds of the maintenance treatments surveyed had suspension periods longer than 3 months. This clearly indicates that the planning of most maintenance treatments can benefit from knowledge of the rehabilitation schedule.

PRIORITY RATING OF MAINTENANCE ACTIVITIES

Priority ranking of highway sections according to their maintenance needs is an integral part of a highway maintenance management system. It provides the required input for programming and scheduling maintenance activities. The relative priorities of different maintenance needs have a direct impact on the final outcome of a highway maintenance programming analysis. Because of the lack of priority information on routine maintenance activities in Indiana, a survey was conducted in the study to acquire the necessary data (*12*).

To reduce the rating items to a manageable size, a partitioned survey approach was used. In Partition I, priority scores were assigned by raters to individual maintenance activities in accordance with their relative importance in preserving the condition of a given highway section. In Partition II, priority scores were assigned to road sections of various highway classes by distress severity level according to the relative urgency of the need for maintenance treatments. Surveys for the two partitions were conducted separately.

The final priority ratings for all routine maintenance activities were computed as follows:

$$P_{ijk} = (f_{\mathrm{I}})_i \times (f_{\mathrm{II}})_{jk} \qquad i = 1, 2, \ldots, N_1; \; j = 1, 2, \ldots, N_2; \; k = 1, 2, \ldots, N_3 \tag{4}$$

where

P_{ijk} = priority rating for routine maintenance activity i on highway class j with distress severity level k, $1 \le P_{ijk} \le 100$;
$(f_{\mathrm{I}})_i$ = priority score obtained from Partition I survey for routine maintenance activity i in relation to all other routine maintenance activities, $1 \le (f_{\mathrm{I}})_i \le 10$;
$(f_{\mathrm{II}})_{jk}$ = priority score obtained from Partition II survey for combination of highway class j and distress severity level k in relation to all other combinations of the two factors, $1 \le (f_{\mathrm{II}})_{jk} \le 10$;
N_1 = total number of routine maintenance activity types;
N_2 = total number of highway classes; and
N_3 = total number of distress severity levels.

Experience gained from the survey indicated that the rating procedure was well received by raters, and satisfactory results were obtained. The final form of priority ratings is given in Table 6.

OPTIMAL PROGRAMMING OF MAINTENANCE ACTIVITIES

At the subdistrict level, maintenance units have to perform diverse routine maintenance activities on a large number of highway routes over extended areas. Because of constraints of resources, not all maintenance needs identified can be attended to as and when required. Selection of highway sections to be included in a maintenance work program has so far been made on a subjective judgmental basis in Indiana. To ensure that consistent decisions are made by different subdistrict maintenance personnel that achieve the best return for the funds and resources committed, an analytical optimization tool for maintenance activities programming is needed. In the present study, an integer-programming optimization model was recommended for maintenance management at the subdistrict level in Indiana. The detailed mathematical formulation of the model is described elsewhere (*13,14*). The major components of the model are explained below.

The objective function of the model was to maximize total work units within the analysis period to accomplish the needed maintenance treatments as much as possible according to their relative priority ranking. In doing so, it was first necessary to convert work measurement units into a common basis of reference. Equivalent workday was chosen because routine maintenance tasks are assigned to field crews on a daily basis in Indiana. Such tasks are authorized daily at the subdistrict

TABLE 6 Examples of Priority Ratings of Routine Maintenance Activities by Highway Class and Distress Severity Level

Routine Maintenance Activity	Interstate			High Volume OSH*			Low volume OSH*		
	Distress Severity Level			Distress Severity Level			Distress Severity Level		
	Severe	Moderate	Slight	Severe	Moderate	Slight	Severe	Moderate	Slight
Shallow patching	99	86	62	93	77	43	73	49	10
Deep patching	96	84	60	90	75	41	71	47	10
Premix leveling	72	63	45	68	56	31	53	35	7
Full-width shoulder seal	49	43	31	46	38	21	36	24	5
Seal coating (chip seal)	64	56	40	60	50	28	47	31	6
Sealing longitudinal cracks and joints	67	58	42	63	52	29	50	33	7
Crack sealing	68	59	43	64	53	29	50	33	7
Sand seal	56	49	35	53	44	24	41	27	6
Spot repair of unpaved shoulders	78	68	49	73	61	34	58	38	8
Blading shoulders	70	61	44	67	55	30	52	34	7
Clipping unpaved shoulders	46	40	29	43	36	20	34	23	5
Reconditioning unpaved shoulder	42	37	26	39	33	18	31	21	4
Clean and reshape ditches	37	32	23	35	29	16	27	18	4
Motor patrol ditching	19	17	12	18	15	8	14	9	2

*High volume OSH are other state highways that carry 400 or more vehicles per day. Low volume OSH are other state highways that carry less than 400 vehicles per day.

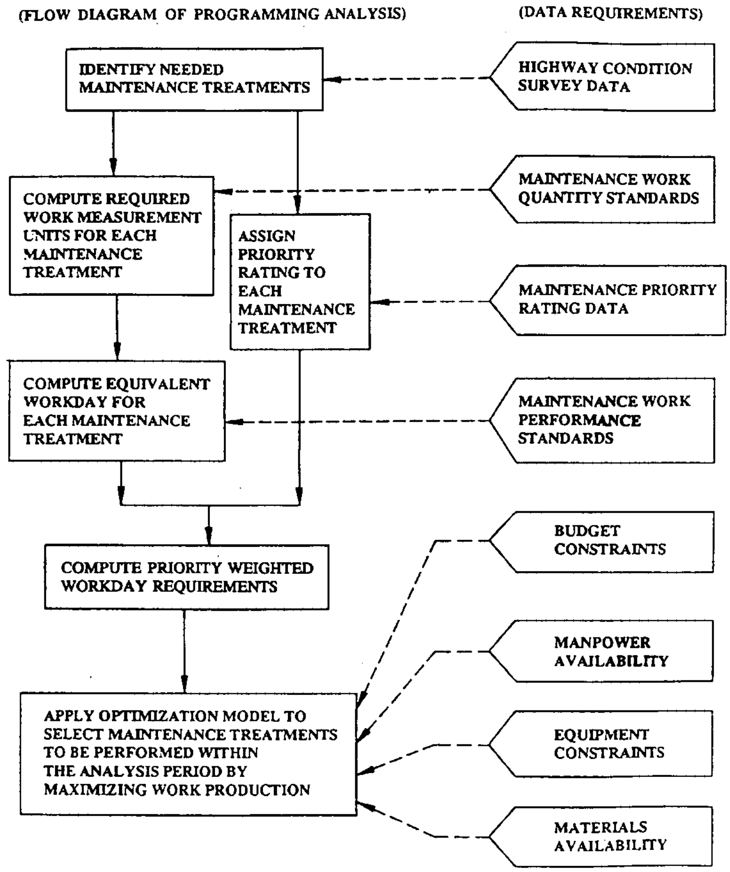

FIGURE 4 Programming maintenance activities using optimization model.

level by unit foremen to each crew by means of crew day cards (*5*). There is also a well-defined relationship between work quantity and workdays established by the performance standards (for example, see Table 2). Expressing work quantity of a routine maintenance treatment in terms of equivalent workdays therefore has a direct practical meaning easily understood by both field and planning personnel.

Six forms of constraints were considered in the model. They were production requirements, budget constraints, manpower availability, equipment availability, material availability, and rehabilitation schedule constraints. Production requirements simply state that the amount of maintenance work assigned for each treatment type should not exceed the need for it. Budget, manpower, equipment and material availabilities represent resources constraints, which ensure that the total amount of maintenance work selected will be within the means of the subdistrict concerned. Rehabilitation constraints are specified such that unnecessary maintenance treatments will be suspended on highway sections that have been scheduled for rehabilitation.

Figure 4 shows the steps involved in the programming analysis of routine maintenance activities and the data requirements for the analysis. Besides functioning as a tool for programming maintenance work, the model can also be used to analyze the impacts of shortfalls of resources. Possible benefits of reallocating resources can be investigated by performing parameter sensitivity analysis. The amount of certain resources to be made available may be adjusted to achieve better results. For example, the number of temporary laborers to be hired over a given period of the year could be determined by means of such analyses.

SUMMARY AND CONCLUSIONS

This paper addressed the important elements in a routine maintenance management system proposed for the Indiana Department of Transportation. Six key areas of concern were highlighted and discussed in detail: (*a*) maintenance needs assessments, (*b*) establishment of performance standards, (*c*) determination of the costs of maintenance treatments, (*d*) setting up of an integrated data base, (*e*) priority rating of maintenance activities, and (*f*) optimal programming and scheduling of maintenance activities. The types of data required and the procedures for acquiring them were explained in each case. The proposed framework can be followed by other highway agencies with appropriate modifications.

REFERENCES

1. F. M. Montenegro and K. C. Sinha. A Procedure for Assessing Routine Maintenance Needs of Highways. In *Transportation Research Record 1109*, TRB, National Research Council, Washington, D.C., 1987, pp. 18–27.

2. K. J. Feighan, K. C. Sinha, and T. D. White. Estimation of Service Life and Cost of Routine Maintenance Activities. In *Transportation Research Record 1102*, TRB, National Research Council, Washington, D.C., 1986, pp. 13–21.
3. J. Neter, W. Wasserman, and M. H. Kutner. *Applied Linear Statistical Models*, 2nd ed. Richard D. Irwin, Inc., Homewood, Ill., 1985.
4. R. Wilensky. *LisPcraft*. W. W. Norton and Company, New York, 1984.
5. *Field Operations Handbook for Foremen 1986–1987*. Division of Maintenance, Indiana Department of Transportation, Indianapolis, 1986.
6. E. A. Sharaf and K. C. Sinha. Analysis of Pavement Routine Maintenance Activities in Indiana. In *Transportation Research Record 985*, TRB, National Research Council, Washington, D.C., 1984, pp. 19–21.
7. E. A. Sharaf, K. C. Sinha, and E. J. Yoder. *Energy Conservation and Cost Savings Related to Highway Routine Maintenance: Pavement Maintenance Cost Analysis*. FHWA/IN/JHRP-84-15. School of Civil Engineering, Purdue University, West Lafayette, Ind., 1984.
8. E. A. Sharaf and K. C. Sinha. Estimation of Pavement Routine Maintenance Costs. In *Transportation Research Record 951*, TRB, National Research Council, Washington, D.C., 1984, pp. 55–58.
9. L. G. Byrd and K. C. Sinha. Concepts of Integrating Maintenance Management in Pavement Management. *Proc., Second North American Conference on Managing Pavements*, Toronto, Ontario, Canada, Nov. 1987, pp. 2.314–2.360.
10. K. Ksaibati and K. C. Sinha. Development of a Routine Pavement Maintenance Data Base System. In *Transportation Research Record 1109*, TRB, National Research Council, Washington, D.C., 1987, pp. 36–42.
11. T. F. Fwa, K. C. Sinha, and J. D. N. Riverson. Influence of Rehabilitation Decisions on Pavement Maintenance Planning. *Transportation Engineering Journal of ASCE*, Vol. 116, No. 2, March 1990, pp. 197–212.
12. T. F. Fwa, K. C. Sinha, and J. D. N. Riverson. Priority Rating of Highway Routine Maintenance Activities. In *Transportation Research Record 1246*, TRB, National Research Council, Washington, D.C., 1989, pp. 54–64.
13. T. F. Fwa and K. C. Sinha. Optimal Highway Routine Maintenance Programming at Network Level. *Transportation Engineering Journal of ASCE*, Vol. 114, No. 5, Sept. 1988, pp. 539–554.
14. K. C. Sinha. *Assessment of Routine Maintenance Needs and Optimal Use of Routine Maintenance Funds*. FHWA/IN/JHRP-88/18. School of Civil Engineering, Purdue University, West Lafayette, Ind., Aug. 1988.

Publication of this paper sponsored by Committee on Maintenance and Operations Management.