J. Infrastructure Plan. and Man., JSCE, No.618/IV-43, 83-94, 1999 April

PROPOSAL OF A NEW ROAD SURFACE MANAGEMENT SYSTEM (RSMS) FOR DEVELOPING COUNTRIES

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This paper is aimed to develop a new road surface management system (RSMS) that is simple, practical and affordable for developing countries to adopt it. The method of evaluating pavement surface based on visual inspection is first proposed. The pavement condition index (PCI) is adopted and modified to be flexible so that any particular circumstances in developing countries can be added. A pavement performance model is, then, established to predict road surface distress condition, and used as a basis of estimating pavement maintenance costs. A case study of applying RSMS to Bhutan is conducted to show that RSMS can properly serve decision-makers as an effective tool for road surface management.

Key Words: road surface management system, pavement maintenance, pavement performance model, pavement condition index, cost effectiveness of road maintenance strategies

1. INTRODUCTION

Highway agencies in developing countries are generally facing a dilemma: growing pressure to maintain their road network to provide a reasonable level of service at escalating costs, but with limited budgets. Besides public demands for better service with constrained budgets, other factors complicate this dilemma. For examples, records to keep projects are in poor quality; maintenance procedures are outdated; and coordination regarding network planning is inadequately established. Maintenance decisions are often given in to political pressures, or are taken as response to emergency needs without proper priority evaluation systems. All these reasons make the development of a pavement management system for developing countries an urgent issue that calls for immediate attention.

In developed countries researchers have started to develop pavement management techniques since early 1960s. One of their efforts is focused on inventing and utilizing the state-of-the-art equipements to evaluate pavement conditions, such as video, laser, radar and infrared techniques[1),2)]. Data obtained from these advanced devices are generally required as inputs for road surface management systems. Developing countries with few resources cannot, however, afford to purchase and maintain them. A simple and repeatable condition inspection procedure should be developed for surveying pavement surface.

After data collection, modeling of pavement performance is absolutely essential to road surface management. Performance is a general term for how pavements change their conditions or serve their intended functions with accumulating usage. Pavement performance is usually predicted by probabilistic and/or deterministic models. For example, markovian transition models have been used extensively in infrastructure management systems[3),4),5),6)]. Transition probabilities specify the likelihood that the condition of a road surface will change from one state to another in a unit time. Inherent assumptions in markovian transition models are as follow:

1. The probability of making the transition from one state to another only depends on the present state.

2. The transition process is stationary, and the probability of changing from one state to another is independent of time.

The second assumption does not hold true to pavements because it infers that changes in weather or loading condition will not effect the transition probability, that is, the rate of deterioration. Therefore, pavement deterioration cannot be predicted with certainty by these transition probabilities due to explanatory variables such as weather changes and maintenance and rehabilitation. Transitions are probabilistic in nature, and generally involve relatively complex mathematic calculations. These probabilistic models that are not intuitively clear may cause confusing to engineers in developing countries.

On the other hand, a deterministic model is formulated in a relatively simple regression equation, and can reasonably predict the pavement performance. It originally started in the AASHO Road Test conducted in the early 1960s, in which the concept of present serviceability index (PSI) was first introduced[7)]. PSI is expressed as a function of roughness, rutting and cracking. Since then, researchers have developed different models to determine the current condition of pavements and predict their future condition[8),9),10),11),19)]. One of the promising techniques for rating pavement distress condition is the pavement condition index (PCI) that has received wide acceptance in different agencies. PCI is the direct representation of pavement distress types and their severity; thus, it can be easily apprehended by highway engineers. However, its associated tables and figures used in the United States cannot be universally applied to situations in developing countries. A more flexible evaluation procedure is proposed to modify PCI for developing countries in this paper.

In addition, computer programs, for example MicroPaver[12)] and HDM-III[13)], have been written for the convenience of pavement management. To predict pavement performance, these programs usually rely upon built-in functions that are formulated based upon limited data collected from several particular countries[14),15),16)]. Although an adjustment option is sometimes provided in the programs, calibrating parameters for specific conditions in a developing country is tedious and time-consuming. Besides, calibration is to some degree subject to individual judgment, and these programs may lead to erroneous predictions. Most of computer programs are complicated and require enormous input data, both of which may not be justified for conditions that are observed in developing countries. Therefore, a simple and reliable road surface management system (RSMS) needs to be developed for developing countries. It is the intention in this paper to develop RSMS so that all procedures for road surface management can be easily understood and established in a spreadsheet computer program such as Excel and Lotus.

2. ROAD SURFACE MANAGEMENT SYSTEM (RSMS)

A road surface management systems is a decision support tool to assist administrators and engineers in making cost-effective decisions regarding the allocation of limited resources for the maintenance and rehabilitation of pavements. The process can be divided into following tasks: (1) establishment of agency's goals, (2) collection of data, (3) modeling of pavement performance, (4) estimation of costs, and (5) selection of maintenance strategies. These tasks are shown in **Fig. 1**.

A set of goals should be clearly outlined as to the direction where the agency is heading and how far it wants to pursue. The pavement condition data collected using techniques proposed in this study are applied to two ways. First, they are used in assessing the pavement performance. Second, they provide the initial values in predicting the future performance and estimating the life-cycle costs. With updated information, a maintenance policy can be set. This effect is represented by the feedback loop in **Fig. 1**.

(1) Establishing agency's goals

The general goals for an agency to develop the RSMS should be related (1) to provide decision maker with optimum strategies derived through clearly established rational procedures; (2) to evaluate alternative strategies over a specific analysis period; (3) to integrate treatment of all pavement activities, and (4) to estimate maintenance costs for pavement rehabilitation. These goals can be revised according to the outcome of the RSMS within realistic constraints and available resources.

(2) Collecting data

The development of RSMS will not be valid unless it is based on real, detailed, and analytical information. Data collection for RSMS includes road inventory and road surface evaluation.

Table 1 Road surface survey form

Surveyors:
Station Number From:
Length:

Date:
To:
Temperature (°C):

Distress	Severity Level			Severity Extent		
	Low	Medium	High	Scare	Intermittent	Extensive
Raveling (m^2)						
Bleeding (m^2)						
Patch Deterioration (m^2)						
Potholes (m^2)						
Rutting (cm)						
Alligator Cracks (m)						
Transverse Cracks (m)						
Longitudinal Cracks (m)						
Polished Aggregates (m^2)						
Shoving (m^2)						
Edge Cracks (m)						

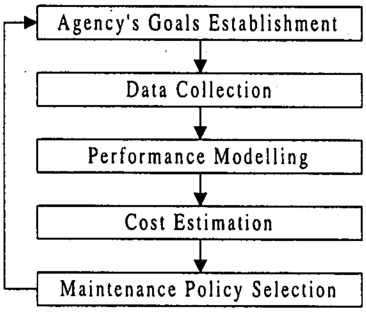

Fig. 1 RSMS development process

a) Road inventory

The road inventory should consist of the following features for each link and segment: (1) the functional classification of roadways, (2) average daily traffic, (3) the elements of road geometry features including horizontal and vertical curves, cross-section dimensions, side slopes, and culverts, (4) annual climate conditions that include precipitation, temperature and altitude, and (5) available records on subgrade properties, road construction, maintenance, and its itemized costs.

b) Road surface evaluation

Because of lack of funding, purchasing sophisticated equipment to test pavement structure or survey pavement surface is unlikely for developing countries. Road surface evaluation should be made simple, reliable and low cost. Visual inspection of pavement surface is proposed in this paper for distress evaluation in developing countries. The identification of pavement distresses can start with creating a standard format of pavement deterioration as a function of distress type, distress severity, and amount or density of distress. **Table 1** shows a proposed evaluation sheet for road surface.

Although there are concerns about the subjectivity of pavement inspectors, good agreement can be achieved when inspectors receive proper practical training beforehand. The results that are obtained from this procedure are repeatable even if evaluation is conducted by different inspection teams. The key is to prepare an approved inspection manual containing distress pictures at various magnitudes so that each inspector has the disposal of a pavement deterioration catalogue. With it at hand, engineers in developing countries can keep up the consistency and the ability of agency's personnel to update information for the continuity of RSMS. Visual inspection proposed in this study is a straight-forward and easy-to-understand condition survey method.

(3) Modeling pavement performance

Conventional methods used single factor such as rutting and structure value for establishing a pavement quality index[3),17),20)]. Even the well known present serviceability index (PSI) developed from the AASHO Road Test is dominantly controlled by pavement roughness. Although the pavement condition index (PCI) was first coined in the Micro Paver[16),21)], its associated figures and tables are only applicable to pavement conditions in the U.S. The foregoing obviously have limited applications to other countries since different regions have their own particular distresses. Furthermore, one type of pavement failure may have more significant impact on pavement performance than the other one. These traditional techniques do not take into account distress extension and severity.

Table 2 Weightage factors for distresses

Distress	Relative Weight %	Weight	Traffic Load	Road Surface Deterioration Due To					
				Pavement			Environment		
				Age	Strength	Geometry	Water	Temperature	Altitude
Raveling	14	20	5	5	X	5	5	X	X
Bleeding	3	5	X	X	X	X	X	5	X
Patch Deterioration	10	15	5	5	5	X	X	X	X
Potholes	10	15	5	X	5	X	5	X	X
Rutting	10	15	5	X	5	X	5	X	X
Alligator Cracks	14	20	5	X	5	X	5	X	5
Transverse Cracks	10	15	X	X	5	X	5	5	X
Longitudinal Cracks	10	15	X	X	5	X	X	5	5
Polished Aggregates	3	5	5	X	X	X	X	X	X
Shoving	7	10	5	X	5	X	X	X	X
Edge Cracks	7	10	X	X	X	X	X	5	5
Total	100	145	35	10	35	5	25	20	15

PCI is simple in nature, rating the condition of pavement on a scale with a range of 0 to 100. Points are deducted when distresses detected on the road surface. To predict pavement conditions reliably, the first step in this study is to develop proper procedures that rate the whole system more objectively. The pavement condition index (PCI) is modified in this paper to identify pavement distress situations in developing countries. The newly developed PCI procedures enables pavement engineers (1) to specify weightages for any special distresses, (2) to consider severity factors and (3) to include extent factors. Thus, this combined index, PCI, is entirely revised in this study to be comprehensive, easy-to-use and fitting the needs of developing countries. Considering the results obtained from previous visual survey, PCI can be estimated by the following relationship:

$$PCI = 100 - \sum_{i=1}^{n} w_i \cdot s_i \cdot e_i \qquad (1)$$

where,

w_i = relative weightage of distress *i*

s_i = distress severity factor

e_i = distress extent factor, and

n = number of distresses observed

PCI is a numerical representation of pavement conditions, ranging from 0 for destroyed pavements to 100 for flawless ones. PCI with 100 being perfect can be reduced because of pavement distresses that are described by their severity, extensiveness and consequence. Equation (1) is, thus, intuitively correct for calculating the PCI value. PCI provides an index as to how integral a pavement structure is up to current usages. The summation of distress weight, severity and extent is called the deduct point. Deduct values indicate the degree of effect of the combination of distress type, severity level and distress extension on road surface condition. The values of these three factors used for the calculation of PCI are discussed as follow.

a) ***Weightage factor***

A number of factors contribute towards the acceleration of pavement deterioration such as traffic, subgrade strength, age, geometry and environment (rainfall, temperature and altitude). Geometry refers to the gradient and superelevation, inadequate provision of which would lead to water getting clogged on the pavement surface, thereby causing the surface to 'ravel.' The relative weights are determined on the basis of the point scores as described in **Table 2**. Assignment of point values depends on the survey from ten highway engineers. Based upon their experiences, each of them rated the importance of causes of pavement distresses on a scale of zero to five. The average number is shown in **Table 2**.

The pavement condition survey is performed on every road segment that normally averages 1 km in length. The observed distresses contribute to a certain degree of pavement failure depending on a number of factors that influence the deterioration. These factors are categorized into traffic load, pavement and environment. Pavements are worn out because of these three major causes that consists of other sub-causes as listed in **Table** 2. To simplify the rating procedure, every sub-cause is assigned a value of 5 so that pavement engineers can indiscriminately identify the real reasons of inducing pavement failure. The selection of 5 is also intended to make calculation easy even without a computer. A mark "X" means that the particular factor does not affect the distress. **Table** 2 was completed based upon field observations on finding the actual causes that result in failures on road surfaces. Since all the possible factors that may influence pavement performance are considered in

Table 3 Severity level for road surface

Distress	Severity Description			Quantitative Severity		
	Low	Medium	High	Low	Medium	High
Raveling	Loss of some fine aggregate.	Loss of some coarse aggregates. Noticeable rough and pitted surface.	Loss of coarse aggregates. Very rough and pitted surface.	0.5	0.75	1.0
Bleeding	Surface relatively discolored by excess asphalt.	Asphalt filling between aggregates to lose surface texture.	Covered by asphalt film. Tire marks evident.	0.5	0.75	1.0
Patch Deterioration	Some deterioration	Partial failure	Needs replacement	0.5	0.75	1.0
Potholes	Diameter < 150 mm Depth < 25 mm	Diameter > 150 mm Depth: 25 - 50 mm	Diameter > 150 mm Depth > 50 mm	0.5	0.75	1.0
Rutting	< 6 mm	6-25 mm	>25 mm	0.5	0.75	1.0
Alligator Cracks	Few connecting cracks. Cracks not spalled.	Interconnected cracks forming alligator pattern. Slighted spalled.	Alligator pattern established. Severely spalled.	0.5	0.75	1.0
Transverse Cracks	< 6 mm	6-19 mm	> 19 mm	0.5	0.75	1.0
Edge Cracks	No breakup or loss of material	Some breakup or loss of material	Considerable breakup and loss of material	0.5	0.75	1.0
Polished aggregate	Slightly lose friction	Lose partial friction	Very smooth surface without friction	0.5	0.75	1.0
Shoving	Slightly uncomfortable ride quality	Uncomfortable ride quality	Very uncomfortably ride quality	0.5	0.75	1.0

Table 2, it is adequate to determine the weightage factor. Each pavement distress may, however, result from various reasons and proportions because each developing country has her own characteristics that lead to pavement failure. Highway engineers with extensive working knowledge and at least five-year experience are selected to put up together **Table 2** after the comprehensive pavement condition survey. It should be noted that this table does not intend to cover all the possible factors that cause road surface deterioration. **Table 2** is to provide the start of RSMS framework, reflect the needs of a developing country, and recognize the differences among various developing countries.

For example, alligator cracking is mainly caused by four deterioration factors, namely, traffic load, pavement strength, water (rainfall) and altitude; each is assessed to have a value of 5. Thus, it is assigned a weight equal to 20 out of a total of 145 points giving a relative weight of 14 percent. **Table 2** is made to be flexible, and can be adjusted to other particular circumstances for a developing country. The factors include all the practical causes that affect road surfaces. This comprehensive list presented in **Table** 2, thus, serves the purposes of determining the weightage factors properly.

b) Severity level

For consistency, severity levels are designated as low, medium or high abbreviated by letters L, M and H respectively. Each distress level is clearly defined to ensure that the data collected will be comparable to other RSMS data. For example, when a distress level is labeled "high severity rutting," it is clear exactly what is meant.

A description of the degree of severity of distresses is presented in **Table 3**. For example, a pothole of diameter less than 15 cm and depth less than 25 mm is designated as low severity, while a pothole with a diameter greater than 15 cm and depth between 25 to 50 mm and depth above 50 mm is designated as medium and high severity respectively. Considering the local expertise of ten highway engineers as mentioned before, the severity weights were assigned as shown in **Table 3**. A factor of 0.5, 0.75 and 1.0 was selected for distress having low, medium and high severity levels respectively. When pavements start to fail, they would deteriorate soon. The reason of choosing 0.5 for low severity is to warn decision-makers that road surfaces are getting worse. Immediate attentions should be paid to stop the trend of aggravating road surfaces even though they are in low severity. As severity approaches to 1, this type of distress is totally unbearable for road users. Pavement's functions of serving traffic do not exist at this moment, and the PCI deduction can be enormous as shown in equation (1). It should be noted that the severity levels listed in **Table 3** are recommended values, and can be adjusted according to particular pavement distresses and funding situations. For example, a developing country has limited resources available for managing road surfaces; one possible solution is to increase low severity of a distress, say rutting, from 0.5 to 0.6. **Table 3** is made to be flexible and reflective. Quantitative severity in **Table 3** can, thus, meet the needs of the developing countries.

Table 4 Extent factors

Extent	Observed Distress Area (%)	Extent Factors (%)
Scare	< 1	20
Intermittent	1 - 5	50
Extensive	> 5	100

c) Extent factor

Certain portions of a pavement feature may exhibit a significantly different condition from the average of the overall feature. This may be due to the variations of materials, construction, subgrade or traffic loading. For example, the defective area of a pavement section is 600 m^2 for medium severity raveling. The length of this section is 1000 meters and its paved width is 3.6 meters, thus giving a section area of 3600 m^2. The distress area is 16.7 percent that is obtained by dividing 600 m^2 by 3600 m^2. An extent factor is, thus, used to take into account the effect of various distress scopes on pavement conditions. The observed distresses can be described as scarce, intermittent and extensive for distress areas less than 1 percent, 1 to 5 percent and above 5 percent respectively. The extent of distresses is designated in the range of less than 20, 50 and 100 for scarce, intermittent and extensive respectively. The recommended extent factors are shown in **Table 4**. Combined with severity level as listed in **Table 3**, repairs can be more efficiently planned and executed, saving the highway agency crew time and money with **Table 4**.

All these three distress factors that account for the deterioration of road surface can be used to determine the PCI value of a pavement section. The PCI changes year by year depending on whether a proper surface treatment is applied. After calculating the PCI values for collected data, the next step is to develop a general form of pavement performance. Traditional methods have been based on the hypothesis that road surfaces will develop distresses with increasing traffic[6),13),18)]. The field observations in this study, however, indicate that PCI is related to pavement age, and the pavement distresses are developed at an increasing rate with increasing time. The PCI values obtained from the equation (1) can be plotted against pavement service time. A simple procedure is developed for determining the timing of maintaining the road surface and for selecting the best maintenance alternatives. This study proposes an exponential curve to express the PCI value that is reduced as results of pavement distresses. The shape of the curve is proposed as follows:

$$PCI = 100 - b \cdot x^{m} \qquad (2)$$

where,

x = pavement age in months or years

b = slope coefficient, and

m = value that controls the degree of curvature of a pavement performance curve

This equation defines the general shape of the distress function as a curve with a slow rate of growth in the initial part, an increasing rate in rate in the middle, and a rapidly increasing rate at the end. Field inspections appear to match well with the trend described in the equation (2). This pavement performance prediction model can be used to analyze the condition and select specific rehabilitation alternatives to meet expected traffic and climatic conditions. In addition, it serves as a base for budget planning for pavement maintenance and rehabilitation.

(4) Estimating costs

Pavement maintenance costs comprise of two components — initial cost for the application of the maintenance alternative and the routine (or recurrent) maintenance costs incurred during its service life. Initial cost includes surface preparation cost that is associated with the repairs of the defective areas of the existing surface prior to the application of the maintenance alternative itself and the cost of maintenance alternative. The cost involves for applying recurrent (day to day) maintenance activities such as crack sealing and pothole patching related to recurrent cost. These costs, which are a function of PCI, can be determined by multiplying the repair cost of the defective area by the unit cost applicable to that repair activity. At any PCI level, the average defective area and the corresponding required repair action and cost are estimated; thus, the recurrent maintenance cost at the PCI level can be calculated.

The cost of repairing a particular distress can be simply obtained by multiplying the defective area by the unit cost applicable to the type and severity of the concerned defect. The costs of surface preparation and recurrent cost are calculated as follows:

$$(SP)_k = (D_{ij})_k \cdot (C_{ij})_{SP} \qquad (3)$$

$$(RM)_k = (D_{ij})_k \cdot (C_{ij})_{RM} \qquad (4)$$

where,

$(SP)_k$ = surface preparation cost at the k-th PCI value

$(RM)_k$ = recurrent maintenance cost at the k-th PCI value

$(D_{ij})_k$ = average density of the i-th distress type with the j-th severity level combination at the k-th PCI value

$(C_{ij})_{SP}$ = unit cost of the required surface preparation action for the j-th severity level of the i-th distress type

Table 5 Calculation of deduct point for a typical section

Distress	Weightage Factor	Severity Level			Extent Factor (%)			$\Sigma w_i \cdot s_i \cdot e_i$
		L	M	H	S	I	E	
Alligator Cracks	0.14	0.5	-	-	-	50	-	3.5
Edge Cracks	0.07	-	0.75	-	20	-	-	1.0
Patch Deterioration	0.10	-	0.75	-	20	-	-	1.5
Rutting	0.10	-	0.75	-	20	-	-	1.5
Bleeding	0.03	0.5	0.75	-	20	50	-	1.9
Raveling	0.14	-	0.75	1.0	-	50	100	17.5

Note: L = Low, M = Medium, H = High
S = Scarce, I = Intermediate, E = Extensive

$(C_{ij})_{RM}$ = unit cost of recurrent maintenance for the j-th severity level of the i-th distress type

(5) Selecting maintenance policy

It is obvious that there is a wide variety of distress treatments available for road surface. To select the best treatment in terms of initial construction costs and maintenance costs, one of the best answers is related to the life-cycle costs. This analysis can be done by calculating the equivalent uniform annual costs (EUAC) of constructing and maintaining a pavement during its service time. All continuing costs such as pavement repair and maintenance are annual costs and should be added to the equivalent uniform annual costs for initial construction year by year. The best time and lowest equivalent uniform annual cost for each life-cycle alternative can be estimated this way. The life-cycle cost alternative that produces the least annual cost is the best choice for both time and treatment. In the long run, a maintenance policy can be, then, established with the feedback from the updated information.

3. CASE STUDY - APPLICATION OF RSMS TO BHUTAN

Bhutan is a landlocked country surrounding by China and India, with areas of 46,600 km^2 and population of 1.7 million. Most of the existing highway network in Bhutan was constructed only over a decade ago, and its condition is declining rapidly. The tasks of road construction and maintenance are, indeed, difficult owing to its rugged mountainous terrain and severe climatic conditions. In particular, the East-West Highway that provides the most vital and only link between Thimphu, the capital of Bhutan, and the most populous district of Tashigang in eastern Bhutan, is deteriorating at a much faster pace than it can be repaired. In the absence of a systematic needs' appraisal the government only allocates approximately Nutan 18,000 (1 U.S.$ = 37 Nu.) per km annually on routine maintenance. Although road surface maintenance is conducted by the Public Works Division (PWD), the backlog of rehabilitation works resulting from improper management of limited funds is overwhelming. RSMS developed in this study is, then, used to model pavement performance, to estimate costs, and to recommend maintenance strategies based on a systematic needs' appraisal.

(1) Data collection and calculation

a) Study area

The East-West Highway between Semtokha and Nobing was selected for this study. This highway segment traversing an average altitude of about 2500 meters is a single lane highway with a paved width of 3.6 meters and an average roadway way width of about 6.5 meters.

b) Inspection of road surface

Visual inspection of pavement surface was employed in this study along with standard guidelines as listed in **Tables 2, 3 and 4**. These tables are developed in this study to provide a consistent, uniform basis for collecting distress data for RSMS. Served as pavement inspection procedures for highway engineers, these tables will improve communications within pavement community to have objective observations by fostering more concrete definition of pavement distress. The observed distresses including their location, size, severity and amount were recorded in a standard format as shown in **Table 1**. It is shown in this study that, after highway engineers receive proper training, the repeatability is reasonably well. As an engineer evaluates a section of roadway, he is required to keep the manual with distress pictures handy, and to determine the type and severity of distress, and to find the definition and illustration that best matches the pavement section being surveyed.

c) Road surface evaluation

A sample calculation of deduct point for a pavement section is demonstrated in **Table 5**. The deduct point contributed by each of these six distresses is calculated separately and summed up to obtain the total deduct point for this section. It should be noted that the distresses in this case study merely reflect what is actually observed on the road surface, and that they do not necessarily include all the distresses described in **Table 2**. The calculation of deduct point contributed by raveling is illustrated below. The extent factor in percentage for medium severity level of distress density 16.7% is 100, and that to be used for high severity level having distress density of 4.6% is 50. From **Table 3** the severity weightages are 0.75 and 1.0 for medium and high severity levels respectively. The deduct point contributed by raveling with weightage factor equal to 0.14 is calculated as follows:

$$\text{deduct point for ravelling} = \sum_{i=1}^{1} w_i \cdot s_i \cdot e_i$$

$$= 0.14 \cdot 0.75 \cdot 100 + 0.14 \cdot 1 \cdot 50 = 17.5$$

The deduct points due to the other five distresses are calculated as shown in **Table 5**. The total deduct point is given by:

$$\text{total deduct points} = \sum_{i=1}^{6} w_i \cdot s_i \cdot e_i$$

$$= 3.5 + 1.0 + 1.5 + 1.5 + 1.9 + 17.5 = 26.9$$

Therefore, PCI = 100 - 26.9 = 73.1

The PCI corresponding to each pavement section can be calculated according to equation (1). Since the weightage factor, severity level and extent factor have been clearly defined by previous tables, trained highway engineers are shown to be capable of visually inspecting pavement distresses objectively. PCI values resulting from human errors are, thus, limited. The mean, maximum and minimum PCI values in this study are 71.6, 88 and 58 respectively. There are no predetermined PCI intervals because PCI values are decided by the data collected for pavement distresses.

(2) Establishment of pavement performance model

In order to establish the criteria for major maintenance, the pavement performance curve over time should be determined. Then, the time of pavements that need repairs can be estimated.

a) Estimation of parameters *m* and *b*

After the calculation of PCI values as described previously, it is possible to determine the pavement performance curve based upon equation (2). By conducting the logarithmic transformation of equation (2), the parameters *m* and *b* can be estimated by regressing the pavement age (obtained from construction records) on the calculated PCI values. For the Bhutan case, The pavement sections are grouped into two categories for the purpose of analyses depending on the surface type: premix carpet and surface dressing. Premix carpet application is an overlay with a seal coat directly laid on the surface manually. Surface dressing on the other hand consists of two layers of stone chips rolled on a tack coat of bitumen. The pavement performance curves for both surfaces are as follows:

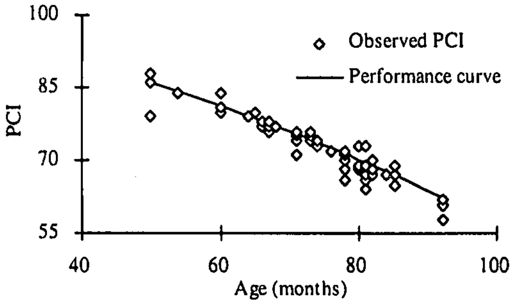

Fig. 2 Pavement performance curve for premix carpet

Premix carpet:

$$PCI = 100 - 0.0247 \cdot x^{1.625} \qquad R^2 : 0.90 \qquad (5)$$

Surface dressing:

$$PCI = 100 - 0.0376 \cdot x^{1.637} \qquad R^2 : 0.89 \qquad (6)$$

Daily traffic is measured for all road sections in this study, and classified counts for every road segment are categorized by traffic conditions. Equations (5) and (6) take into account the traffic volume and condition by summarizing them in the pavement age. As an example for performance curve, the scatter plot of pavement age versus PCI is shown in **Fig. 2** for premix carpet. An observed PCI point represents the deterioration condition for a pavement section being evaluated. If a pavement is rehabilitated by premix carpet technique, its initial PCI would be equal to 100. After accumulated usages, the road surface shows distresses. Causes of each distress are considered in weightage factor since one country may have more serious problem on a factor than the other one. Distress severity and extent are recorded by the visual inspection. PCI can be calculated for the pavement section after a pavement section serves for a certain period of time. PCI values for all the sections under premix carpet treatment are plotted against their ages as shown in **Fig. 2**.

b) Determination of pavement age for major maintenance

From the above two equations, the PCI of a given pavement section can be estimated for different ages, x. The terminal PCI is the PCI at which the pavement is considered to have reached its failure state. Several PCI values have been suggested for a pavement under consideration to reach its failure state.[17),18)]. Indeed the choice of the terminal PCI is a matter of judgment that, to a large extent, depends on the agency experience. For this case study the terminal PCI equal to 60 is adopted because most of the sections having PCI in the vicinity of 60 receive major maintenance (rehabilitation) at the time the survey is conducted. The age for major maintenance was determined by substituting PCI equal to 60 in equations (5) and (6). The age for major maintenance for pavement with premix carpet application is estimated to be equal to 96 months, i.e., 8 years, whereas that for surface dressing application is found to be equal to 72 months, i.e., 6 years.

(3) Cost effectiveness of pavement maintenance strategies

In order to convince an agency the benefits of RSMS, the cost effectiveness of pavement maintenance strategies should be conducted. The Bhutan practice is used as an example here to demonstrate the basic concept of cost-effectiveness analysis.

a) Surface preparation policy matrix

The surface preparation policy matrix or recurrent maintenance policy matrix contains the unit cost of each repair activity for a given level and distress type. **Table 6** shows a recommended surface preparation and recurrent maintenance policy matrix for Bhutan.

The highways in Bhutan have either premix carpet surface constructed largely based on a traditional labor intensive method, or surface dressing application that is a mechanized construction method. This study, therefore, focuses on the maintenance alternatives between these two existing practices of surface treatments.

The direct costs comprise of the initial construction cost and the subsequent maintenance costs incurred to maintain the facility. The service lives of the alternative maintenance treatments are calculated from the performance Equations (5) and (6) to determine the life cycle costs. The steps for selection of alternative maintenance treatments are based on the least equivalent uniform annual cost (EUAC).

b) Initial cost calculation

The initial cost comprises of surface preparation cost and the cost of applying the maintenance alternative. The cost of maintenance alternative itself is derived from the prevailing unit cost related to that alternative. The initial cost of applying premix carpet is Nu. 0.456 million per kilometer of road length, whereas the cost for surface dressing application is Nu. 0.406 million. Thus, the initial cost of mechanic-base surface dressing is less than one of labor-extensive premix surfacing.

Table 6 Surface preparation policy matrix in Bhutan

Distress Type	Severity	Repair Method	Unit Cost (Nu./m^2)
Fatigue Crack	L	Fog Seal	45
	M	Skin Patch	45
	H	Deep Patch	88.6
Edge Crack	L	Skin Patch	88.6
	M	Deep Patch	88.6
	H	Deep Patch	194.8
Patch Deterioration	L	Fog Seal	65
	M	Skin Patch	88.6
	H	Deep Patch	194.8
Pothole	L	Skin Patch	88.6
	M	Skin Patch	950
	H	Deep Patch	1298
Rutting	L	Skin Patch	88.6
	M	Skin Patch	88.6
	H	Deep Patch	194.8
Shoving	L	Skin Patch	88.6
	M	Skin Patch	88.6
	H	Deep Patch	198.8
Bleeding	L	Add Sand & Roll	25
	M	Add Chips & Roll	35
	H	Add Chips & Roll	35
Polished Aggregate	L	Chip Seal	32
	M	Chip Seal	32
	H	Chip Seal	32
Raveling	L	Skin Patch	50
	M	Skin Patch	50
	H	Skin Patch	105

c) Equivalent uniform annual cost (EUAC)

The equivalent uniform annual cost method converts the investment costs to a single sum that is equivalent to all disbursements during the pavement's service life when spread uniformly over that period. The EUAC of a cost is determined by the following formula:

$$\mathrm{EUAC} = \mathrm{cost} \cdot (A/P,\ i,\ n)$$
$$= \mathrm{cost} \cdot i \cdot (1+i)^n \ / \ [(1+i)^n - 1] \qquad (7)$$

where,

A/P= representative form to calculate annual cost based on present value with interest rate, i, within n years,

i = interest rate, assumed to be 8% in this study,

n = service life.

It has been determined previously that pavement service life is 8 years for premix application at the PCI equal to 60. In the case of surface dressing application, the terminal PCI is reached within 6 years. From the agency's point of view it would be desirable to determine the least annual maintenance cost in order to justify the annual expenditure. In this paper, the calculation procedure for premix carpet is demonstrated while the results of surface dressing are

Table 7 Present worth value for premix carpet

Year, n	PCI	AMC (10^6 Nu.)	PWV (10^6 Nu.)
1	98	0.025	0.023
2	96	0.025	0.021
3	92	0.025	0.020
4	87	0.033	0.024
5	81	0.033	0.022
6	75	0.055	0.035
7	68	0.076	0.044
8	60	0.086	0.046
		Total =	0.237

Table 8 Total equivalent uniform annual cost (EUAC)

Alternative	Initial Cost (10^6 Nu.)	Recurrent Cost (10^6 Nu.)	Total EUAC (10^6 Nu.)
Premix Carpet	0.079	0.041	0.120
Surface Dressing	0.088	0.042	0.130

listed only for comparison. The EUAC of initial cost for premix carpet is shown as follows:

EUAC of initial cost = $(0.456) \cdot 0.08 \cdot (1+0.08)^8 / [(1+0.08)^8-1] = 0.079$ million Nu.

Similar calculation leads to 0.088 million Nu. for surface dressing. The next step is to calculate the annual maintenance cost (AMC) as shown in **Table 7**. The AMC for various PCI values can be obtained from the unit cost in **Table 6** according to pavement severity. The PCI values in **Table 7** are based upon the performance equation (5) for years 1 through 8.

The present worth value (PWV) of all AMC is computed from the following equation:

$$PWV = \sum_{j=1}^{n} AMC_j \cdot (P/F, i, n)$$

$$= \sum_{j=1}^{n} AMC_j \cdot (1+i)^{-n} \qquad (8)$$

where,

P/F = representative form to calculate present value based on future value with interest rate, i, within n years,

PWV = present worth value of all annual maintenance costs during the service life of an alternative,

AMC_j = annual maintenance cost at the j-th service life of an alternative

PWV is calculated to be 0.237 million Nu. for premix carpet. The EUAC is computed as follows:

EUAC = $(0.237) \cdot 0.08 \cdot (1+0.08)^8 / [(1+0.08)^8-1] = 0.041$ million Nu.

The total equivalent uniform annual costs of the two maintenance alternatives are summarized in **Table 8**. The total EUAC of Nu. 0.120 million for premix application is lower than one of surface dressing that is Nu. 0.130 million. Therefore, premix carpet appears to be cheaper than surface dressing in the cost-effective analysis.

d) Maintenance budget estimation

One of objectives in RSMS is to perform maintenance budget estimation using the PCI method. The recurrent cost is a function of PCI that is computed from the cost matrices developed for various ranges of PCI. **Table 9** shows a typical maintenance cost forecast performed for a portion of pavement consisting of eleven test sections, of which each one is kilometer long for a five-year planning period (1996-2000). The PCI for each year of the planning period is calculated using the performance equations (5) and (6) for premix carpet and surface dressing applications respectively. For example, the predicted PCI of the pavement section number 457 for the planning year 1996 is 80 that lies between 71 to 80 PCI range. It should be noted that sections 447 and 455 in **Table 9** suffer tremendous PCI reduction from 1995 to 1996 due to the fact that pavements at these sites are subject to a poor drainage system, thus lead to accelerate their deterioration.

The recurrent cost corresponding to this PCI range (during the year 1996) is Nu. 55100. The predicted PCI's of this section in the year 1996, 1997 and 1998 are 80, 73 and 66 respectively. By the year 1999 the PCI value drops to 57 that is below the terminal PCI, i.e., 60. Therefore, the section needs major maintenance (or rehabilitation) during the year 1999. The estimated cost of major maintenance during the year 1999 is Nu. 452,000 as shown in **Table 9**. After receiving major maintenance the PCI can be considered to have reached PCI 100 theoretically. It then drops to 98 by the end of the first year of service life according to equation (5). Thus, the recurrent cost during the year 2000 is estimated to be Nu. 25,000. As PCI comes down to 60, actions will be taken to rehabilitate the pavement; thus, the total cost for maintenance involves with pavement sections that are under PCI 60. It is the goals of RSMS to reduce the maintenance cost by identifying problematic conditions of roads, and providing in-time rehabilitation.

As shown in **Table 9**, the estimated cost for recurrent maintenance from 1996 to 2000 for the 11 sections is Nu. 1.566 million, and the estimated cost

Table 9 Maintenance budget estimation for premix surfacing

Section	Age (Months)	Current (1995) PCI	PCI in the Year of					Cost (10^3Nu.)				
			1996	1997	1998	1999	2000	1996	1997	1998	1999	2000
447	92	62	53	44	34	24	13					
			98	96	92	87	81	452	25	25	25	33
448	115	77	35	25	14	3	1					
			98	96	92	87	81	452	25	25	25	33
449	92	62	53	44	34	24	13					
			98	96	92	87	81	452	25	25	25	33
450	92	58	53	44	34	24	13					
			98	96	92	87	81	452	25	25	25	33
451	80	68	62	53	44	34	24					
			62	98	96	92	87	76	452	25	25	25
452	80	73	62	53	44	34	24					
			62	98	96	92	87	76	452	25	25	25
453	80	69	62	53	44	34	24					
			62	98	96	92	87	76	452	25	25	25
454	60	81	74	67	59	50	41					
			74	67	98	96	92	55	76	452	25	25
455	95	87	51	42	32	21	10					
			98	96	92	87	81	452	25	25	25	33
456	60	80	74	67	59	50	41					
			74	67	98	96	92	55	76	452	25	25
457	50	86	80	73	66	57	49					
			80	73	66	98	96	55	55	76	452	25

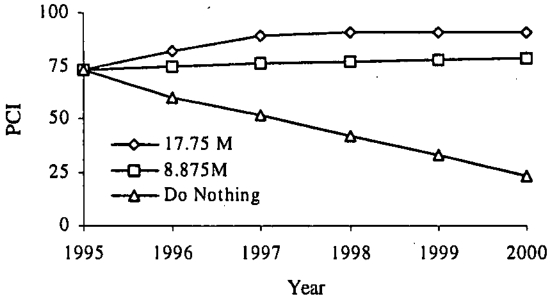

Fig 3. Impact of funding level on road surface condition

of major maintenance is Nu. 4.972 million. The total budget for recurrent and major maintenance of 95 kilometers of Semtokha to Nobding Highway is estimated to be Nu. 17.75 million.

By projecting the average road surface condition over a reasonable analysis period of time, one can visualize the impact of alternative funding levels on the overall pavement performance in the entire highway. **Fig. 3** shows the road surface condition from 1995 to 2000 that will result from expenditure levels of Nu. 17.75 million, 8.875 million, and do-nothing. Average pavement condition would rapidly deteriorate if no maintenance and rehabilitation were applied. At least Nu. 8.875 million are needed to keep road surface above its minimal acceptable condition, whereas 17.75 million can significantly update this highway. The estimated budget 17.75 million in this study is to make sure that every road section will be maintained above PCI 60, and overall the PCI values are enhanced as pavement service time increases. Spending 8.875 million is shown to maintain the pavement at its exiting condition while some portions of pavement sections have reach the terminal PCI value. As of 1995, the amount of 8.875 million is what was spent on road surface maintenance.

4. CONCLUSIONS

The road surface management system (RSMS) for developing countries is proposed in this study. RSMS consists of three major components: road surface survey, pavement performance modeling, and cost estimation. It has been shown that all these threeprocedures are practical, simple, and flexible; thus, local officials and engineers can easily understand, implement and update RSMS to satisfy their needs on road surface management. At the same time, RSMS is developed to retain its objectivity and completeness.

The pavement distress evaluation method presented in this paper is reproducible on determining the pavement condition. Careful consideration has been given to make visual inspection a technically appropriate choice of road surface evaluation for developing countries.

Pavement condition index (PCI) is modified to take into account particular distress causes in developing countries. After computing PCI for various pavement sections, the pavement performance model can be adequately established in a systematic manner. The life-cycle cost for a pavement can be estimated based upon the equivalent uniform annual costs. Furthermore, by showing road surface conditions with various levels of funding, RSMS can be used to justify budget requests for future pavement maintenance and rehabilitation. All the RSMS procedures are developed with the intention that they can be customized in a spreadsheet program such as Excel and Lotus. Highway engineers with proper training and common sense can easily establish their own version of RSMS.

A case study in Bhutan has indicated that RSMS provides a simple and practical procedure to assess pavement conditions, to predict pavement performance, to recommend maintenance strategies, and to estimate the maintenance budget for developing countries. Therefor, RSMS is an effective tool to aid pavement manager to take proper actions to maintain roads within a reasonable surface condition.

ACKNOWLEDGEMENT: The financial support from the National Science Council under contract number NSC87-2211-E006-043 is greatly appreciated. The authors wish to express their sincere gratefulness to the advice provided by Professor Hisa Morisugi and Dr. Yasushi Takeyama.

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(Received November 28, 1996)