

An Optimal Design Method To Rehabilitate Low-Volume Asphaltic Roads

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A long-term pavement monitoring program that has been ongoing in Brazil for more than 10 years allowed the development of performance prediction models for as-constructed and rehabilitated pavements. The models, developed through multiple-regression analysis, can be used to predict pavement roughness, ravelling, and cracking as a function of significant variables that define pavement structure, environment, and traffic loads. These models are used to develop a design method that selects the optimal rehabilitation strategy over a defined analysis period. The design approach has been implemented as a microcomputer program that generates alternative strategies, predicts the performance of each strategy in comparison with allowable criteria, and finally produces a set of the five best, feasible strategies, according to the predicted life-cycle rehabilitation cost. This design method can be used as a project-level pavement management tool that is compatible with the needs of low-volume road links in tropical and subtropical environments. In addition to producing optimum designs, it can also be used effectively to conduct a sensitivity analysis of the effects of critical input variables.

In most developing and developed countries, significantly large proportions of the road network are carrying relatively low traffic volumes, but have reached a deterioration level that requires rehabilitation. Within any given set of policy and budgetary constraints, low-volume roads must compete for the allocation of maintenance and rehabilitation resources and funds with the more heavily trafficked sections of the road network.

A pavement management system, applied at the network level, should provide the means for orderly identification of those road sections rehabilitation of which will contribute to minimizing the total costs of a road transportation system. The network-level policy constraints must provide a balance between the competing demands of high-volume and low-volume components of the total road network.

Having identified candidate sections, a need exists at the project level to select and quantify the best rehabilitation option for each section, again satisfying a set of design policy and budgetary constraints for the project. Optimization of rehabilitation strategy, within a range of alternative strategies, can only be achieved through consideration of the life-cycle performance and costs of the road section, subject to periodic rehabilitation as defined by the strategy.

A rehabilitation design method is presented that optimizes the selection of a rehabilitation strategy over a defined analysis period. Selection of the optimal strategy is based on the lowest present worth of total rehabilitation costs, predicted over the analysis period. Feasible strategies are ranked only on the basis of future highway agency costs, which do not include road user costs or initial pavement costs.

The method was developed as a result of research into the observed performance of rehabilitated flexible pavements within the Brazilian road network that was conducted by the Brazilian Road Research Institute (IPR/DNER). The method is considered to be well-suited to the selection and design of rehabilitation treatments for low-volume roads, because it makes use of performance models that are empirically derived from an extensive performance data base. The inference space of the data base includes the combined environmental and traffic effects of roads that carry approximately 500 to 5,000 vehicles per day in subtropical and tropical environments.

BACKGROUND OF THE DESIGN METHOD

The scope of this rehabilitation design method encompasses slurry seals, single- and double-surfaced treatments, and asphalt concrete (AC) overlays as feasible treatments that may be employed during the analysis period. The basic hypothesis is that the most reliable and practical method of rehabilitation design is one that relies on pavement performance prediction models developed from experimental observations of rehabilitated field sections over a number of years.

Pavement performance data have been systematically collected on a large number of experimental sections that were specially selected within the Brazilian road network since 1977 to develop empirical performance prediction models (1-3). This work was started as part of the BrazilUNDP Study and has been subsequently continued (4). Some of these sections have received alternative types of rehabilitation. They have provided a satisfactory data base for the development of performance prediction models for treatments such as slurry seals, surface treatments, and asphalt concrete overlays.

The experimental sections that were used to develop the model are representative of unbound, granular-base flexible pavements that are generally located in a tropical to subtropical environment. The sections are all located between 15° and 25° south of the equator, where the mean temperature is about 27°C in summer and 22°C in winter, and the range of extremes is about 10° to 40°C. Rainfall is in the range of 1200 to 1700 mm/yr. These pavements are subject to a wide range of traffic levels. For example, total traffic (AADT) on the AC overlay sections is approximately 500 to 5000 vpd, and commercial vehicles are in the general range of 20 to 60 percent.

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The inference space for the performance models is therefore considered to adequately encompass low-volume roads in subtropical to tropical environments.

PAVEMENT PERFORMANCE PREDICTION MODELS

The models that are incorporated into the rehabilitation design method are limited to the prediction of pavement condition in terms of roughness, cracking, and ravelling. In this context, cracking includes the occurrence of patching and potholes. Rut depths were consistently small for the experimental sections over the observation period; rutting was therefore not considered a significant performance criterion for this design method.

Each condition variable is associated with several models, as shown in Table 1. Together these provide the ability to predict initiation of cracking and ravelling, and progression of all condition variables for the pavement both before and after a rehabilitation treatment. The improvement in roughness achieved by an overlay is also modelled. It was found that slurry seals and surface treatments do not significantly change pavement roughness.

TABLE 1 PERFORMANCE PREDICTION MODEL TYPES

Condition	Nature of Model	Surfacing Type ^a
Roughness	Progression Improvement due to treatment	EP, OL, SST, DST, SS OL
Cracking	Initiation Progression Progression Initiation/ progression	OL, SS EP ^b OL SS
Ravelling	Initiation Progression	EP ^c , SST, DST EP ^c , SST, DST

^aEP = existing pavement, either surface treatment or asphalt concrete; OL = asphalt concrete overlay; SST = single surface treatment; DST = double surface treatment; and SS = slurry seal.

^bOnly if it is an existing asphalt concrete surfacing.

^cOnly if it is an existing surface treatment.

The Benkelman beam deflection has proved to be a highly significant independent variable for predicting roughness and cracking of overlays. An additional model to predict surface deflection after an overlay has therefore also been included. This model provides the means for estimating the equilibrium deflection after an overlay, on which the ongoing performance predictions are based. The principal model equations that have been adopted for performance prediction within this design method are presented in the following sections together with qualifications or restrictions on their applicability. Development of the equations has been described elsewhere (1-3).

Roughness Models

Road roughness is highly correlated with serviceability, and is the principal measurement of pavement condition that directly relates to vehicle operating costs (4, 5). It is therefore essential to predict roughness to evaluate life-cycle performance and costs.

In this paper, roughness is considered in terms of the QI (Quarter-Car Index). The QI is a standard roughness summary statistic that can readily be calculated from surface profile measurements (e.g., using the rod and level procedure, or other profilometry technique) and also yields strong correlations with the output of response-type roughness instruments (6).

As indicated in Table 1, two types of roughness models have been incorporated. All terms used in these and subsequent models are defined in the list of symbols, abbreviations, and units at the end of this paper.

The roughness progression for both original and rehabilitated pavements was adapted from a study by Queiroz (1). This model expresses QI as a continuous function of age, traffic, structural variables, and initial roughness.

$$QI = 0.393A + 8.66 \log N / SNC + 0.0000717(B \cdot \log N)^2 - DQI \quad (1)$$

In the case of an asphalt concrete overlay, the structural capacity is upgraded, in which case $SNC = SNCa$, and $B = Ba$, which was estimated by use of the deflection prediction model that is discussed in a later section.

The term DQI is a constant offset term to ensure that the predicted QI value at age A is equal to the roughness measured at age A, in the case of an existing pavement, or is equal to the predicted QI after overlay (QIIA), in the case of rehabilitation by AC overlay. The value QIIA is estimated by use of Equation 3.

Because the QI model (Equation 1) is logarithmic in nature, it is not reliable for pavement or overlay ages and accumulated traffic close to zero. Consequently, the following transformation is used to yield more realistic QI trends at early ages.

$$A' = (2/3)A + 0.5 \quad (\text{if } A < 1.5) \\ A' = A \quad (\text{if } A \geq 1.5) \quad (2)$$

Roughness immediately after an AC overlay is expressed as a function of existing roughness and overlay thickness (3).

$$QIIA = 19 + (QIb - 19) / (0.602H + 1) \quad (3)$$

As was noted earlier, the QIIA value is used to determine a new DQI offset for model Equation 1, for continuing prediction of the roughness progression of the overlay.

Cracking Models

Cracking is a critical surface indication of distress within the pavement structure. It represents a loss of pavement integrity that can lead to accelerated deterioration of strength and condition. Models that predict cracking behavior therefore also make an essential contribution to the prediction of life-cycle performance and the costs of alternative rehabilitation strategies.

In the context of this design method, cracking values (measured as a percentage of total pavement area) represent the occurrence of Class 2 cracking or worse (i.e., a crack width greater than 1 mm), and include the presence of potholes and patching.

Four cracking models are used to predict the age at which cracking first appears and the rate of progression of a cracked area of an existing asphalt concrete pavement, an AC overlaid pavement, and a slurry seal treated pavement.

In this design method cracking is assumed to be the primary distress determinant for pavements with asphalt concrete or slurry seal surfaces, but not for single- and double-surface treatments.

The cracking progression for an existing asphalt concrete pavement is expressed as a function of surface deflection, accumulated traffic since construction, and age (I).

$$CR = B \cdot \log N(0.0456 + 0.00501A) - 18.53 - DCR \quad (4)$$

The term DCR is a constant offset term calculated so that cracking values conform to the defined extent of cracking at the start of the analysis period. If the existing pavement has no cracks, it is assumed that it will begin to crack at the start of the analysis period.

Cracking initiation for an AC overlaid pavement is expressed as a function of cracking in the existing pavement before overlay, thickness of overlay, surface deflection after overlay, and traffic since overlay (3).

$$AICR = (212.8 - 0.917CRb) (H^{0.681}) / (((Ba - 19.45)AANC^{0.336}) + 0.01) \quad (5)$$

Because this expression includes the term AANC, it must be evaluated iteratively for nonzero traffic growth rates. A minimum limit on Ba of 20 is assumed.

The cracking progression model for an AC-overlaid pavement has a form similar to, and is related to, the progression model for an existing AC pavement, with the addition of the overlay thickness term (3).

$$CR = Ba \cdot \log N(2.257 + 0.248A) \cdot H^{(-1.806)} - DCR \quad (6)$$

In this case, the DCR offset term is calculated to ensure that predicted cracking progresses from zero after age A equals AICR. As in the case of the roughness prediction model, the age transformation given in Equation 2 is used when AICR is less than 1.5 to avoid inaccuracy of the logarithmic model at early ages.

Cracking initiation and progression of a pavement that was rehabilitated with a slurry seal surfacing is expressed as a function of deflection and cracking before treatment, and age since the slurry seal application (7).

$$CR = (0.219B + 1.43CRb) \cdot Y \quad (7)$$

where

$$Y = A - (10/CRb) \text{ for } Y > 0 \\ \text{otherwise} \\ Y = 0 \quad (8)$$

Ravelling Models

Cracks on surface-treated pavements are often difficult to identify because of the open texture. The alternative approach, which is used in this design method, is to quantify distress of surface treatments in terms of the amount of ravelling caused by traffic and environmental effects.

As in the case of cracking, separate models are used to predict the onset of ravelling of either an existing or new surface treatment, and to predict the progression of ravelling.

The initiation of ravelling in a surface treatment is expressed as the surface treatment age at the onset of ravelling as a function of surfacing quality and average annual heavy traffic (2).

$$\ln AIR = 2.465 - 0.45CF - 0.189AAHV \quad (9)$$

where

$$AAHV = 0.00001327N/A \quad (10)$$

Equation 10 was developed from a study of the relative distribution of heavy vehicle axle groups (single, double, and triple) that prevail in Brazil.

The progression of the extent of ravelling is expressed as a function of average annual heavy traffic, age, and age of onset of ravelling.

$$RA = (2.226AAHV + 16.6) \cdot (A - AIR) \quad (11)$$

Surface Deflection Model

The models that were presented earlier to predict the performance of asphalt concrete overlays (specifically, the models for roughness progression, Equation 1; cracking initiation, Equation 5; and cracking progression, Equation 6) require a Benkelman beam surface deflection after the overlay. These models clearly show that although the deflection is not a measure of pavement deterioration, it influences the rate of deterioration.

Another model that was developed from the data base of experimental overlay sections has been incorporated to predict surface deflection after an overlay, as a function of average deflection before the overlay and overlay thickness.

The field data suggest that deflection after the overlay decreases gradually over a 1- to 2-yr period following placement of the overlay, and finally reaches a "stabilized" value, which is denoted as Ba .

$$Ba = B^{(1 - 0.0687)} (H^{0.4153}) \quad (12)$$

The design method assumes that the surface deflection B for any pavement configuration remains constant throughout its service life, until it is adjusted by the addition of an AC overlay. No reduction in deflection is attributed to slurry seals or surface treatments that were used as rehabilitation measures.

REHABILITATION DESIGN METHOD

Like most pavement design methods, this method requires a sequence of four major stages:

- Selection of design sections,
- Characterization of pavement and traffic,
- Generation of rehabilitation alternatives, and
- Selection of rehabilitation design.

Execution of the first three stages requires the generation of a range of design inputs that can be grouped as the following six types:

- Surface deflection,
- Roughness and present surface condition,
- Existing traffic and growth projection,
- Pavement and subgrade properties,
- Rehabilitation unit costs, and
- Criteria for terminal pavement condition and budget limitations.

Within these groups, the actual data items listed in Figure 1 can be generated by a highway agency relatively easily, without excessive commitment of expense or resources. A large-scale commitment to collect project-level pavement data on an extensive low-volume road network will commonly be difficult to justify. In this case, the data requirements of this design method are considered to be compatible with the practical limitations of data collection for a low-volume road network.

The performance models demonstrate a reliance on surface deflection as a major independent variable. Deflections are measured with a Benkelman beam and an 18-kip single-axle load. It is recommended that tests include at least one deflection profile, with measurements taken every 40 m along the outer wheelpath of the existing pavement. Two staggered lines of profiles in the outer wheelpath on either side of the centerline are desirable for two-lane roads.

The roughness and condition of the existing pavement must be carefully documented using consistent measurement procedures. Roughness measurement also requires attention to calibration to ensure that the scale of a statistic remains consistent over time. In Brazil, roughness is measured with the locally developed Linear Displacement Integrator, a response-type device that is calibrated to the QI scale by the rod and level procedure (6, 8).

The primary structural property required, apart from deflection, is the modified structural number (SNC), which is defined as the pavement structural number corrected for the effect of subgrade strength (CBR) (9). Evaluation of the SNC will therefore require some knowledge of layer thicknesses and material types, and the subgrade CBR, which should preferably be evaluated for the in situ equilibrium moisture condition and density. Layer strength coefficients for the calculation of the structural number are normally selected by referring to normal agency practice, or published tables (9-11).

GENERATION OF REHABILITATION ALTERNATIVES

The objective of this design method is to arrive at a degree of optimization of rehabilitation treatment, in terms of comparison

STRUCTURAL EVALUATION OF PAVEMENTS - STEP2 PROGRAM		
PROBLEM DESCRIPTION: LOW VOLUME ROAD - 10% ALLOWABLE CRACKING		
1.00 - CHARACTERISTICS OF EXISTING PAVEMENT		
1.01 - CONDITION SURVEY DATE (MM/YY)		06/86
1.02 - SURFACE TYPE (AC OR ST)		ST
1.03 - SECTION LENGTH (KM)		1.00
1.04 - STRUCTURAL NUMBER CORRECTED (SNC)		3.5
1.05 - QUARTER-CAR INDEX (QI)		50.0
1.06 - PERCENT CLASS 2 AND ABOVE CRACKING		0.0
1.07 - PERCENT RAVELLING		0.0
1.08 - BENKELMAN BEAM DEFLECTION (.01 MM)		80
1.09 - AGE OF EXISTING PAVEMENT (YEARS)		0
1.10 - PAVEMENT WIDTH (M)		7.0
2.00 - TRAFFIC DATA		
2.01 - INITIAL YEARLY (18-KIP) ESAL	150,000	
2.02 - GROWTH RATE (PERCENT PER YEAR)		3.0
3.00 - UNIT COSTS		
3.01 - SLURRY SEAL (CZ\$/M^2)		1.80
3.02 - SINGLE SURFACE TREATMENT (C7\$/M^2)		3.60
3.03 - DOUBLE SURFACE TREATMENT (CZ\$/M^2)		4.90
3.04 - ASPHALT CONCRETE OVERLAY (CZ\$/M^3)		275.00
4.00 - OVERLAY SURFACE CHARACTERISTICS		
4.01 - DOUBLE SURFACE TREATMENT THICKNESS (CM)		2.0
4.02 - DOUBLE SURFACE TREATMENT LAYER COEFFICIENT		.04
4.03 - ASPHALT CONCRETE MINIMUM THICKNESS (CM)		3.0
4.04 - ASPHALT CONCRETE MAXIMUM THICKNESS AT ONE TIME (CM)		12.0
4.05 - ASPHALT CONCRETE MAXIMUM TOTAL THICKNESS (CM)		20.0
4.06 - ASPHALT CONCRETE LAYER COEFFICIENT		.17
5.00 - CONSTRAINTS		
5.01 - MAX. ALLOWABLE ROUGHNESS (QI)		60.0
5.02 - MAX. PERCENTAGE OF CRACKING		10.0
5.03 - MAX. PERCENTAGE OF RAVELLING		30.0
5.04 - ANALYSIS PERIOD (YEARS)		20
5.05 - MIN. TIME BETWEEN OVERLAYS (YEARS)		8
5.06 - MAX. NUMBER OF OVERLAYS WITHIN ANALYSIS PERIOD		3
5.07 - MAX. INITIAL CONSTRUCTION COSTS (CZ\$/KM)	100,000.00	
5.08 - PRESENT VALUE OF FUTURE COSTS (CZ\$/KM)	50,000.00	
5.09 - AVERAGE DISCOUNT RATE (PERCENT PER YEAR)		11

FIGURE 1 Sample printout of STEP2 inputs.

and ranking of a range of feasible alternative strategies according to their relative life-cycle rehabilitation costs. A microcomputer program for Structural Evaluation of Pavements, STEP2, was written to perform the data handling and computations necessary to achieve this objective (12).

In this program, the existing pavement performance is simulated, using models that were presented in this paper, for the length of the analysis period or until a limiting criterion (roughness, cracking, or ravelling) is reached. The pavement condition descriptors of roughness, cracking, and ravelling are estimated at biannual intervals.

If the defined limit for any of the condition descriptors is reached, rehabilitation is required. In this case, STEP2 begins to generate rehabilitation strategies by selecting from eight permissible treatments (slurry seal, single- and double-surface treatments, and five thicknesses of asphalt concrete overlay, calculated between user-defined limits). Performance simulation continues with the selected treatment, again until a pavement condition limit is reached, in which case a further treatment is selected and simulated, or until the end of the analysis period is reached.

In this way, a great number of rehabilitation strategies (different treatments scheduled in different years) are generated. Many of these will be rejected because they are not feasible if they do not satisfy the user-defined constraints of minimum

treatment life, maximum number of treatments, maximum allowable roughness, cracking and ravelling, and budget limitations. The feasible strategies are stored and sorted by total rehabilitation cost, which is discounted to net present values.

The output from STEP2 consists of an echo-print of input data, the performance simulation (i.e., accumulated traffic and condition descriptors versus time) of the existing pavement, a ranked summary of the five least-cost strategies, and the performance simulations for each of these strategies.

The results of a rehabilitation design for an existing new double-surface treated pavement that carries 200 commercial vehicles per day are shown in Figures 1 and 2. The as-constructed pavement has a modified structural number of 3.5, a Benkelman beam deflection of 80 hundredths of a mm, an initial roughness (QI) of 50 counts/km, and no cracking or ravelling. The analysis period is 20 yrs, with a maximum of three treatments allowed, and a minimum treatment life of 8 yrs. The criteria for future rehabilitation intervention are a maximum roughness of 60 counts/km, a maximum ravelling of 30 percent, and, in this case, a particularly stringent maximum allowable cracking of 10 percent, to test the effect on the life-cycle cost of imposing a policy of a high condition standard.

The performance models assume that, for the existing pavement, ravelling begins immediately. Intervention is therefore needed after 1.5 yrs. In this case, the five best designs all

LOW VOLUME ROAD - 10% ALLOWABLE CRACKING

PREDICTED PERFORMANCE OF EXISTING PAVEMENT

DATE (YEAR)	AGE (YEARS)	TRAFFIC (ESAL $\times 10^5$)	ROUGHNESS (QI)	CRACKING (% AREA)	RAVELLING (% AREA)
1986	0.0	0	50	0	0
	0.5	0.74	52	0	11
1987	1.0	1.50	53	0	21
	1.5	2.27	54	0	32 (*)

(*) - % RAVELLING HIGHER THAN MAXIMUM ALLOWABLE

18 PHYSICALLY FEASIBLE ALTERNATIVES EXAMINED

18 ECONOMICALLY FEASIBLE ALTERNATIVES FOUND

5 LEAST COST ALTERNATIVES SELECTED

SET OF THE FIVE BEST STRATEGIES, SORTED BY TOTAL COSTS

NO.	TOTAL COST (CZ\$/KM)	OVERLAY TYPE	DATE	COST (CZ\$/KM)
1	135,431	ASPHALT CONCRETE (7.5 CM)	1987	123,455
		DOUBLE SURFACE TREATMENT	1997	10,330
		SLURRY SEAL	2005	1,647
2	137,077	ASPHALT CONCRETE (7.5 CM)	1987	123,455
		DOUBLE SURFACE TREATMENT	1997	10,330
		SINGLE SURFACE TREATMENT	2005	3,293
3	138,266	ASPHALT CONCRETE (7.5 CM)	1987	123,455
		DOUBLE SURFACE TREATMENT	1997	10,330
		DOUBLE SURFACE TREATMENT	2005	4,482
4	141,331	ASPHALT CONCRETE (7.5 CM)	1987	123,455
		DOUBLE SURFACE TREATMENT	1997	10,330
		ASPHALT CONCRETE (3 CM)	2005	7,547
5	146,991	ASPHALT CONCRETE (7.5 CM)	1987	123,455
		DOUBLE SURFACE TREATMENT	1997	10,330
		ASPHALT CONCRETE (5.3 CM)	2005	13,207

FIGURE 2 STEP2 output for sample problem.

have the same recommended strategy for most of the analysis period. For instance, a 75-mm AC overlay after 1.5 yrs has a life of 10 yrs. This is followed by a double-surface treatment that extends the life 8 more years. The alternatives only vary in the final treatment that is recommended close to the end of the analysis period.

PAVEMENT MANAGEMENT APPLICATIONS

This design method was primarily intended to satisfy the needs of project-level investigation and the rehabilitation design of road sections, particularly relatively short, homogeneous subsections that were identified on the basis of relatively uniform pavement structure, structural response, traffic, and condition. It satisfies the desirable objectives of project-level pavement management, in terms of providing a means for optimizing the effectiveness of future rehabilitation programs for road sections. In doing so, it makes use of obtainable data on pavement characteristics that are obtained relatively easily, a set of compatible performance prediction models that are derived

from a lengthy period of experimental observation of in-service roads, and a set of design criteria that are normally determined by highway agency policy.

The inference space for the performance models covers a wide range of traffic levels, including low volumes, in a tropical to subtropical environment. It covers relatively simple pavement and surfacing types and rehabilitation treatments, including those that commonly prevail in developing countries and in large parts of the road networks in the warmer regions of developed countries. The performance models can be considered suitable for application in network-level pavement management in such regions.

The design approach that was implemented in the STEP2 program provides the ability to more easily investigate "what if" questions, such as the effects of relative trends in unit prices, trends in traffic growth, or different levels of design policy or budget constraints. The ability to readily investigate the sensitivity of the design outcome to particular design inputs is recognized as a valuable contribution to effective decision making and administration in the planning and design of road networks. These capabilities should be included in pavement management practices at both the network and project level.

PREDICTED PERFORMANCE - STRATEGY NO 1

DATE	AGE (YEARS)	TRAFFIC (ESAL $\times 10^5$)	ROUGHNESS (QI)	CRACKING (% AREA)	RAVELLING (% AREA)	TREATMENT
1987	1.5	.0	25	0	0	AC (7.5 CM)
	2.0	.78	26	0	0	SNC = 4.78
	2.5	1.57	27	0	0	B = 40
	3.0	2.37	27	0	0	
	3.5	3.18	28	0	0	
	4.0	4.01	28	0	0	
	4.5	4.85	29	0	0	
	5.0	5.70	29	0	0	
	5.5	6.56	30	0	0	
	6.0	7.44	30	0	0	
	6.5	8.32	30	1	0	
	7.0	9.23	31	2	0	
	7.5	10.14	31	3	0	
	8.0	11.07	31	4	0	
	8.5	12.01	32	4	0	
	9.0	12.97	32	5	0	
	9.5	13.94	32	6	0	
	10.0	14.93	32	7	0	
1997	10.5	15.93	33	8	0	
	11.0	16.94	33	9	0	
	11.5	17.98	33	10 <1>	0	
	11.5	.0	33	0	0	DOUBLE ST
	12.0	1.05	33	0	0	SNC = 4.86
	12.5	2.11	34	0	0	B = 40
	13.0	3.18	34	0	0	
	13.5	4.28	34	0	0	
	14.0	5.39	34	0	0	
	14.5	6.51	35	0	0	
2005	15.0	7.66	35	0	0	
	15.5	8.82	35	0	0	
	16.0	9.99	35	0	0	
	16.5	11.19	36	0	0	
	17.0	12.40	36	0	0	
	17.5	13.63	36	0	0	
	18.0	14.88	36	0	0	
	18.5	16.15	37	0	9	
	19.0	17.43	37	0	21	
	19.5	18.74	37	0	33 <2>	
2005	19.5	0	37	0	0	SLURRY SEAL
	20.0	1.32	37	11	0	SNC = 4.86
	20.5	2.67	38	39	0	B = 40

<1> - % CRACKING HIGHER THAN MAXIMUM ALLOWABLE

<2> - % RAVELLING HIGHER THAN MAXIMUM ALLOWABLE

FIGURE 2 continued

TABLE 2 EFFECTS OF ALLOWABLE CRACKING POLICY

Allowable Cracking (%)	Optimum Rehabilitation Strategy		Life (yrs)	Total Cost Cz\$/km	Reduction in Cost (%)
	Type	Date			
10	75-mm AC overlay	1987	10	135,431	
	Double ST	1997	8		
	Slurry seal	2005	1+		
30	53-mm AC overlay	1987	12	95,251	30
	Double ST	1999	7+		
50	53-mm AC overlay	1987	17	90,269	33
	Single ST	2004	2+		

For example, when the analysis that is summarized in Figure 1 is repeated with policies of lower allowable standards of condition (allowable cracking of 30 and 50 percent), another set of optimum designs and performance results. These results are summarized in Table 2. They demonstrate that lower allowable standards, with a fixed minimum service life of a treatment, lead to lighter optimum strategies and, of course, a significantly lower cost. An agency's rehabilitation costs are directly related to its policy standards for minimum acceptable condition.

CONCLUSION

An approach to the design of rehabilitation treatments for low-volume roads has been demonstrated that results in a form of optimization of feasible strategies that are applied over an analysis period.

The method is centered on a set of pavement performance prediction models that were developed from an extensive performance data base that was compiled in Brazil. By predicting progressive deterioration of roughness, initiation and progression of cracking and ravelling, and the effects of rehabilitation treatments on pavement condition, these models allow the life-cycle performance of a range of feasible strategies to be predicted. This in turn leads to a comparison of alternative rehabilitation designs.

The design approach has been implemented on a micro-computer program that generates alternative strategies, predicts performance of each strategy compared with allowable criteria, and finally produces a set of the five best feasible strategies according to the predicted life-cycle rehabilitation cost.

This design approach can therefore be used as a project-level pavement management tool that is compatible with the needs of low-volume road links in tropical and subtropical environments. In addition to producing optimum designs, it can also be effectively used to conduct a sensitivity analysis of the effects of critical input variables. The performance models can also be applied to the pavement management of low-volume road networks.

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SYMBOLS, ABBREVIATIONS, AND UNITS

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| QI | Quarter-Car Index measure or prediction of roughness (counts/km). |
| A | Age of pavement since original construction, or since subsequent AC overlay or slurry seal, in years. |
| N | Cumulative number of applications of equivalent standard (8.2-ton) axle loads, corresponding to age A. |
| SNC | Modified structural number for the existing pavement. |
| B | Benkelman beam maximum deflection for the existing pavement (0.01 mm). |

DQI	Initial QI offset term, calculated at the start of the analysis period or after an overlay.	AICR	Age since the last overlay when cracks first appeared in years.
SNCa	Modified structural number for a pavement with an AC overlay.	CRb	Extent of cracking present before overlay or slurry seal (percent of area).
Ba	Equilibrium Benkelman beam deflection after an AC overlay (0.01 mm).	AANC	Average annual traffic in the period between overlaying and appearance of the first crack (ESAL/yr).
QIIA	Predicted QI immediately after an AC overlay.	RA	Predicted extent of ravelling at age A for a surface treated pavement (percent of surface area).
QIb	QI value immediately before an overlay.	AIR	Age of surface treatment when ravelling appeared in years.
H	Overlay thickness in cm.	CF	Construction quality indicator for surface treatments. Here it is assumed that CF equals 1 for a single-surface treatment; CF equals 0 for a double-surface treatment.
CR	Predicted extent of Class 2 or worse cracking at age A, for a pavement with AC surface (original or overlaid) or slurry seal surface (percent of pavement surface area).	AAHV	Average annual heavy vehicle traffic in the period between surface treatment and the onset of ravelling (100,000 ESAL/yr).
DCR	Cracking offset term, calculated to ensure that predicted cracking conforms with the initial value at the start of analysis, or to ensure that CR equals 0 before the onset of cracking.		

The Maintenance and Design System: A Management Aid for Unpaved Road Networks

A. T. VISSER AND P. C. CURTAYNE

The Maintenance and Design System (MDS) is a model that was developed to determine the effects of alternative maintenance budgets on the vehicle operating costs of a network of unpaved roads. It also is used to identify those roads for which an upgrade to a bituminous standard would be economically justified. It can be used in the framework of a management system to assess a desirable level of funding and the way resources should be allocated. It also indicates the distribution of work needed over the network in physical terms. This application is illustrated by means of a case study in which assumptions inherent in the model are indicated and recommendations are made for further research. Although a need clearly exists for improving the accuracy and scope of the MDS, the fact that it provides an orderly framework for collecting and evaluating the characteristics and needs of unpaved networks is in itself significant. Discrepancies between the system's outputs and practice can be corrected with experience for each region in

which it is applied. Maintenance operations can then be effectively controlled and budget requests can routinely be supported on economic grounds.

In many countries the majority of low-volume roads are unpaved and account for substantial proportions of the maintenance budget. The financial and operational management of this maintenance has traditionally been informal, and has largely been based on historical precedent. The lack of quantitative expressions that relate maintenance needs to local circumstances meant that managers had to rely on the experience and judgment of regional operators to apply appropriate maintenance routines. Decisions to pave gravel roads have similarly often been ad hoc and based on a general traffic volume criterion or a political objective.

The use of the Maintenance and Design System (MDS) model has proved to be a valuable aid in assessing the level and distribution of maintenance needs of unpaved road networks and in programming projects to upgrade roads to a paved standard (1, 2). This model is based on relationships that describe the behavior of unpaved roads that were derived from