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Using Pavement Performance Data to Develop Mechanistic-Empirical Concepts for Deteriorated and Rehabilitated Pavements

U.S. Department of Transportation
Federal Highway Administration

Research and Development
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FOREWORD

This report presents concepts for improvement of pavement maintenance and rehabilitation strategies. The emphasis in this study was on the development of modeling tools rather than the development of specific models. The model tool box will allow each user to be able to develop models that are unique to their environment, soil type, and types of maintenance and rehabilitation used.

Charles J. Nemmers, Director
Office of Engineering and
Highway Operations
Research and Development

NOTICE

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16. Abstract

This report summarizes existing pavement condition indices, and available prediction models for each condition index. This report also identifies existing data bases, where the required variables for the prediction models have been collected. Successive chapters detail: the condition indices and their prediction models; the selected data bases (HPMS, SHRP-LTPP, Copes, FHWA Design, FHWA Rehabilitation, Texas CRCP, and FMIS) with analysis and evaluation of each; significant data elements in the SHRP-LTPP data base; data elements for future development models; current types of prediction models and modeling techniques; and a computer flow chart illustrating data requirements and the conceptual operation of models to select and design maintenance and rehabilitation alternatives.

The conclusions emphasize the development of modeling tools, rather than specific models. The proposed MODEL TOOL BOX allows each user to develop models unique to their environment, soil types, and maintenance and rehabilitation most frequently used.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

Table of Contents

Page

Table of Contents - CHAPTER 3 (continued)

Table of Contents (continued)

List of Figures

List of Figures (continued)

List of Tables

List of Tables (continued)

List of Acronyms

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
CBR	California Bearing Ratio
CE	Corps of Engineers
CMST	Cold Mix on Surface Treatment
COPES	Concrete Pavement Evaluation System
CRCP	Continuously Reinforced Concrete Pavements
DMR	Distress Maintenance Ratio
DOT	Department of Transportation
EAROMAR	Economic Analysis of Roadway Occupancy for Maintenance and Rehabilitation
ESAL	Equivalent Single Axle Load
EUAC	Equivalent Uniform Annual Cost
EXPEAR	Expert System for Pavement and Rehabilitation
FHWA	Federal Highway Administration
FMIS	Fiscal Management Information System
FWD	Falling Weight Deflectometer
GPS	General Pavement Study
HDM	Highway Design and Maintenance
HPMS	Highway Performance Monitoring System
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavements
JRCP	Jointed Reinforced Concrete Pavements
LCC	Life-Cycle Cost
LEF	Load Equivalency Factors
LTPP	Long Term Pavement Performance
M&R	Maintenance and Rehabilitation
MSEQ	Maintenance Sequence No.
MTC	Minimum Tolerable Conditions
NAPCOM	Nationwide Pavement Cost Model
NCHRP	National Cooperative Highway Research Program
NIMS	National Information Management System
NPV	Net Present Value
OPAC	Ontario Pavements Analysis of Costs
OVAC	Asphalt Overlay on Surface Treatment
PARS	Program and Financial Planning in Pavement Rehabilitation
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PDMAP	Probabilistic Distress Model for Asphaltic Pavements
PMS	Pavement Management Systems
PMV	Pavement Matrix Value
PQI	Pavement Quality Index

List of Acronyms (continued)

PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PW	Present Worth
R	Resistance
R^2	Coefficient of Determination
R&R	Reconstruction and Rehabilitation
RCI	Riding Comfort Index
R.I.	Roughness Index
RSAC	Reseal on Asphalt Concrete
RSST	Reseal on Surface Treatment
SAI	Structural Adequacy Index
SAR	Structural Adequacy Rating
SCI	Structural Adequacy Index
SEE	Standard Error of the Estimate
SHRP	Strategic Highway Research Program
SN	Structural Number
SPS	Special Pavement Study
SST	Slurry on Surface Treatment
ST	Surface Treatment
TAI	The Asphalt Institute
TRRL	Transportation and Road Research Laboratory
VCI	Visual Condition Index
VMT	Vehicle Miles Traveled
WASDOT	Washington State Department of Transportation

CHAPTER 1 INTRODUCTION

PROBLEM DESCRIPTION

As the focus of highway construction has shifted from new design and construction to maintenance and rehabilitation, a recognized need has developed for more accurate predictions of pavement performance. The inclusion of field performance data has been useful in evaluating new designs, and provides a tool which can be used readily to refine designs, and evaluate the long-term effects of specific design assumptions. This same approach has potential to assist the highway engineer with the task of monitoring pavement network, and planning the most appropriate strategies for that network. The timely application of maintenance, coupled with appropriately selected rehabilitation schemes, provides the combination that will provide a cost-effective pavement management program.

The obvious method of obtaining information about the beneficial combination of maintenance and rehabilitation is through the monitoring of the performance of various rehabilitation or maintenance strategies as they exist in the field. The development of performance data base information is gaining acceptability with the mandated pavement management program. More and more States are collecting performance data on their pavement networks. This information must be analyzed before any cost-effectiveness relationships can be developed.

The method of analysis normally uses derived models which attempt to predict the performance of the pavement in question. These models are either regression-based empirical models derived from the field data, or they use a mechanistic-based solution to generate performance parameters which are then combined or calibrated with the field data. There are a great many models currently being used by various State agencies. Many of these models predict the same quantity, usually a distress, from different data elements, typically traffic, pavement structure, materials, climate, rehabilitation or maintenance activity, etc.

Many of these models were developed for materials and conditions very dissimilar from those present in a State using a particular model. Many models predict distresses based on definitions that vary from one State to another. Very few of these models can be combined into a comprehensive unit to perform life-cycle costing for any one maintenance/ rehabilitation scheme. There is a need to know exactly what data and models are currently being used, the composition of these models, and how they either do or do not fit together, or could be made to fit together.

In recent years, the concept of pavement management has come into prominence as a tool with which to optimize pavement resource investments. Pavement management systems have been formalized to identify and define pavement maintenance and rehabilitation needs so as to achieve desired levels of pavement service. Pavement management systems have three major components which are: (1) a data base, (2) damage prediction models, and (3) a life-cycle cost (LCC) analysis model, including budget optimization. The data base typically contains information on pavement design characteristics, materials variability, the environment, and data from periodic condition evaluations. Distress or damage equations predict pavement condition as a function of pavement characteristics, traffic, and the environment to which the pavement is subjected. The LCC analyses require inputs on maintenance and rehabilitation costs.

Damage prediction models are an essential part of any comprehensive network-level pavement management system. Prediction models provide an estimate of future pavement behavior based on data available on past performance, which is an invaluable tool in project-level forecasting and network-level planning. Without prediction models an effective long-term network-level analysis is not possible.

Damage prediction models require specific inputs in many cases, and great care must be exercised to generate these input values. There are a great many data bases in use today, all of which contain various data elements of various usefulness to the application of the models, and the development of new models. It is necessary to critically examine current data bases to determine whether the data elements currently listed in each data base are in fact being collected and are actually useful in light of model requirements. Sophisticated models requiring detailed data that is not available, except for very specific locales, will indicate a need either to develop more appropriate models, or to increase the data collection program to make necessary data available. Models that require data that is not currently being collected will also require an investigation to determine if new models are required, or if increased data collection is the most effective solution to ensure that adequate models are being used without burdening agencies with extra data collection efforts.

A great many models currently are being used by various State agencies. Many of these models predict the same quantity, usually a distress, from different data elements, typically traffic, pavement structure, materials, climate, rehabilitation or maintenance activity, etc. Many of these models were developed from materials and conditions very dissimilar from those present in a State using a particular model. Many models predict distresses based on different definitions from one State to another. Very few from these models can be combined into a comprehensive unit to perform life-cycle costing for any one maintenance/rehabilitation scheme.

There are two general groupings wherein these models can fit, or be made to fit, to provide a useful framework for economical comparisons:

- Groups of models that predict the effects of selected types of maintenance and rehabilitation on pavement distress.

- Groups of models that evaluate life-cycle maintenance and rehabilitation costs.

When the models which are placed into either category are analyzed and placed on an equal footing, which allows each model to evaluate the same properties, an economic framework is obtained, providing a tool by which highway engineers and administrators can respond to various questions, including:

- What are the performance and cost implications associated with the possible rehabilitation and/or maintenance alternatives?

- What are the consequences of delaying or advancing a rehabilitation project within the programming period?

Assuredly, there are more questions which could be posed. However, they cannot be answered in a uniform manner until the models and data sources have been analyzed to illustrate similarities and differences. Applicability of various models will depend, to a large extent, primarily on the availability of data being collected. An extremely accurate but complex model which relies on extensive collection of data elements that are not available will not be used. This situation requires either the use of a simple model, or the recommendation that more detailed data collection be conducted. It is critical to determine exactly where the state of the practice is at the current moment.

There is a need to know exactly what data elements in data bases and what models are currently being used, and the composition of these models, and how they either do or do not fit together, or could be made to fit together. This need is the driving force behind this report.

RESEARCH OBJECTIVES

The objective of this research is to develop concepts that use various field data sources to improve pavement maintenance and rehabilitation strategies. These concepts will be adopted in future research that will develop the two groups of models identified above. These concepts can be developed only after a thorough study has been performed which details the available models, the indices which they use, and the data available. Once a thorough understanding of the state of the practice has been established, the concepts will allow a formal structure to be presented for utilizing these data in the pavement management format.

PROJECT APPROACH

The research discussed in this report was performed as a two-phase study for the Federal Highway Administration (FHWA) entitled ***Using Pavement Performance Data to Develop Mechanistic-Empirical Concepts for Deteriorated and Rehabilitated Pavements.*** Phase I of this project was devoted to presentation of the existing models, existing data bases and review of the data bases. The phase I results were presented in the First Interim Report in September 1991. The First Interim Report summarized existing pavement condition indices, available prediction models for each of the condition indices, and identified existing data bases where required variables for the prediction models were collected. The condition indices and their prediction models were presented in chapter 2 of the First Interim Report. A description of selected data bases was presented in chapter 3. The presented data bases were Highway Performance Monitoring System (HPMS), Strategic Highway Research Program (SHRP) - long term pavement performance (LTPP), Concrete Pavement

Evaluation System (COPES), FHWA Design, FHWA Rehabilitation, Texas Continuously Reinforced Concrete Pavements (CRCP), and Financial Management Information System (FMIS). A brief analysis and evaluation of each of the data bases was presented in chapter 4 of the First Interim Report. The first panel meeting was held after completion of this phase I.

The second part of this project examined available prediction models, the data elements required for these prediction models, and the modeling techniques. The results were presented in the Second Interim Report in October 1992.

The goals of the second part of this phase II are summarized as follows:

- Prepare a list of data elements required to verify current prediction models.
- Prepare a list of data elements for development of future models.
- Identify unavailable data elements and a typical range of values.
- Provide a list of cost data required for an economic analysis.
- Categorize prediction models according to modeling techniques.
- Develop modeling tools rather than the development of specific models.
- Develop a computer flow chart for LCC on conceptual operation of a model.
- Recommend an economic analysis procedure.

The Second Interim Report consisted of four chapters that summarize the ***Development of Concepts, Task E***, of the project entitled ***Using Pavement Performance Data to Develop Mechanistic-Empirical Concepts for Deteriorated and Rehabilitated Pavements.*** Chapter 2 described the data elements required for prediction models. Chapter 3 presented the findings on damage prediction models and modeling techniques. Chapter 4 summarized only the findings on Task E - Development of Concepts. The Second Panel meeting was held after completion of this phase II.

This Final Report is a combination of the First and Second Interim Reports and additional concepts for modeling the effects of Maintenance and Rehabilitation (M&R) activities on future pavement performance, as well as improvement of modeling efforts and procedures (Tool Box) for the development of models.

CHAPTER 2 PRESENTATION OF EXISTING MODELS

Pavement deterioration models predict future condition of the pavement in terms of design, traffic and environmental variables. These models play a vital role in evaluating future rehabilitation needs of the highway system. The broad types of pavement deterioration to be modeled include the following with some examples:

- Cracking - transverse, longitudinal, corner, reflective, alligator.
- Disintegration - joint deterioration, raveling.
- Distortion - rutting, roughness, present serviceability index.

Deterioration models or performance models fall into two categories: deterministic and probabilistic models. Deterministic models are developed for predicting the mean expected structural and functional performance of pavements such as distresses, PSR, and friction number. The probabilistic models, which include survivor curves, Markov, and semi-Markov transition processes, predict a distribution of those events.

In order to facilitate the maintenance and rehabilitation activities of a pavement network, two classes of models are required: first, models that describe the deterioration of new and reconstructed pavements; second, those that predict the performance of rehabilitated pavements. The latter group comprises two categories of models: first, those for estimating the immediate improvement after maintenance/rehabilitation; and, second, those predicting deterioration types resulting from load and/or environment. This review will discuss the models for new pavements first, then the models for rehabilitated pavements.

Depending on whether a compound measure or a single measure is selected to capture performance, another classification may be suggested: aggregate vs. disaggregate models. This classification refers simply to the ways in which the condition of the pavement is captured. Disaggregate indices represent pavement condition employing individual measures of distress. Aggregate indices portray pavement condition in terms of more general measures, usually indices of damage, condition, or serviceability. This report, however, groups models in several categories with emphasis on the measure (metric) employed to characterize the condition and/or distress in pavements. Four different groups (measures) are recognized, encompassing several indices to quantify the pavement performance (see table 1):

1. Roughness - International Roughness Index (IRI), Riding Comfort Index (RCI).
2. Structural - Deflection, Structural Adequacy Index (SAI).
3. Distress - Cracking, Disintegration.
4. Composite measure - Present Serviceability Index (PSI), Pavement Condition Index (PCI), Pavement Condition Rating (PCR), Pavement Quality Index (PQI).

Table 1. Classification of pavement prediction models based on various condition measures.

Group	**Roughness**			**Structural**			**Composite**				**Skid Resistance**
Index/ Identifications	*IRI*	*RCI*	*Units of in/mi*	*Fatigue*	*Deflection*	*Structural Adequacy Index*	*PSI*	*PCR*	*PQI*	*PCI*	
Flexible/ Rigid			TRRL, Arizona, Australia, PEN DOT								
Flexible	World Bank	Alberta		Asphalt Institute, Shell Pavement Design Manual, TRRL, Mobile Manual, Denmark, Belgium, Cost Allocation, NCHRP 1-1OB, ARE, VESYS	AASHO, Arizona DOT, Asphalt Institute, TRRL	Alberta, Minnesota	VESYS, HPMS, Idaho, Minnesota, Fernando Equation	Washington, Mississippi, PARS, Arkansas	Alberta	CERL	
Rigid, Jointed				Zero Maintenance			Iowa, HPMS, Illinois, Minnesota, Louisiana, Georgia, Utah, California, PCA, Cost Allocation	Washington, Mississippi			Cost Allocation

Table 1. Classification of pavement prediction models based on various condition measures (continued).

Group	**Roughness**			**Structural**			**Composite**				**Skid Resistance**
Index/ Identifications	*IRI*	*RCI*	*Units of in/mi*	*Fatigue*	*Deflection*	*Structural Adequacy Index*	*PSI*	*PCR*	*PQI*	*PCI*	
Composite							Iowa				

Table 1. Classification of pavement prediction models based on various condition measures (continued).

Group	**Distress-Related**									
Index/ Identifications	*Transverse Crack*	*Joint Faulting*	*Pumping*	*Joint Deterioration*	*Punch-out*	*Alligator Cracking*	*Rutting*	*Permanent Strain*	*Potholing*	*Raveling*
Flexible/ Rigid										
Flexible						World Bank	World Bank, Ohio State, Cost Allocation, SPDM, Monismith *et al.*, NCHRP 1-10B, VESYS, WATMODE	Monismith, Ogawa-Freeme, Barksdale, Michigan State, TTI	World Bank	World Bank
Rigid, Jointed	Illinois, Minnesota, Louisiana, Georgia, Utah, California, PCA, Cost Allocation	Illinois, Minnesota, Louisiana, Georgia, Utah, California, Cost Allocation	Illinois, Minnesota, Louisiana, Georgia, Utah, California, PCA, Cost Allocation	Illinois, Minnesota, Louisiana, Georgia, Utah, California, Cost Allocation						
Rigid, Continuous					Illinois, PCA					
Composite							EXPEAR			

CATEGORIES OF DETERIORATION MODELS

The first group of deterioration models (for new and rehabilitated pavements) are reviewed in this section. Both of these pavement groups start with a distress-free surface, a premise which may not be valid for pavements that have been rehabilitated.

Pavement Roughness Models

Described below are various models for roughness progression reported in the literature. For discussion purposes, those models may be grouped into five categories: first, models that emphasize structural effects; second, models that rely on time-related effects; third, models that consider the interaction between time and structural-related effects; fourth, models that rely on mechanistic parameters, for example, variance of rut depth; and fifth, models in which structure, surface condition, and time effects determine road roughness.

Models Emphasizing Structural Effects

Effects of pavement strength and traffic loading on road roughness progression were first quantified under controlled experimental conditions at the American Association of State Highway Officials (AASHO) road test.(1) With only minor contribution from distresses, road roughness played a major role in the PSI measure constituted at the road test. The AASHO performance equation expresses roughness progression in the dimensionless damage parameter, "g," as the fractional loss of serviceability with respect to a selected criterion of terminal serviceability. More about the model equation will be presented in the section dealing with composite measures (equation 19).

The explicit relation of roughness (determined by Bump Integrator) to pavement strength and traffic loading was reasserted by the findings of the Transportation Road and Research Laboratory (TRRL) study.(2) The roughness measure relationship took the following simple form:

$$R_t = R_o + s(S)\, N_t \tag{1}$$

where:

$s(S)$ = function of modified structural number.
R_o, R_t = roughness at time = 0 and t, respectively.
N_t = cumulative number of equivalent 18-kip (80 kN) standard axle loads to time t.

In the updated version of the model, known as the RTIM2 model, the strength function assumes the form of cubic parametric function.

Models Emphasizing Time-Related Effects

Other studies conducted on inservice pavements, however, have been unable to identify any structural effects of pavement strength and traffic loading and have related the roughness progression directly to time and pavement age. For example, the Arizona model is:(3)

$$\Delta R_t = a\, R_t\, \Delta t - b \tag{2}$$

where:

Δt = increment in time.
a,b = constant parameters which are environmental parameters of rainfall, elevation, freeze-thaw cycles, temperature, etc.

Analyzing roughness data covering a period of 1972 to 1981, another Arizona Study developed a time-based equation in the following form:(4)

$$R_t = C_o + C_1 t \tag{3}$$

where:

R_t = roughness of homogenous section, in/mi.
t = year since the treatment.
C_o, C_1 = regression coefficients.

Note that Arizona researchers used Mays meter for determining road roughness. An Australian study resulted in the following equation:(5)

$$R_t = R_o + at^b \tag{4}$$

where:

t = pavement age, in years.
a,b = coefficients determined for each data set.

Other studies reporting time-related roughness progression include, for example, 7 or more percent/year in Canada, 7 percent/year in Spain, 20 to 30 percent/year in Belgium which are much higher than the average of about 2 percent/year in Australia, and 2 to 8 percent/year range in Arizona.(6) The Arizona study related its range of progression rates to the environmental effects expressed through the coefficients in equation 3, and this may also explain the wider differences in the other studies.

Models with Interacting Effects

Some indication of interaction between time and structural-related effects was found by Queiroz:(7)

$$R_t = f\,(R_o, N_t, t, s) \qquad (5)$$

where:

s = one of the various pavement strength parameters used in alternative models.
N_t = the cumulative number of 18-kip (80-kN) standard axle loads to time t.

A normalized rate of deterioration related to the level of surface distress is being developed in a current TRRL study.(8) The generalized form of the equation is:

$$\frac{\Delta R_t}{R_t} = \max\,(a\ CX^{b}, c)\ \Delta t \qquad (6)$$

where:

CX = the amount and level of cracking distress.
a, b, c = constants.

A noticeable feature is that the independent variables include only time and distress, and exclude traffic loading.

Models Relying on Mechanistic Parameters

The theoretical approach to roughness progression has been indirect, in that the variance of rut depth has been correlated to roughness. Uzan and Lytton derived an explicit relation as follows:(9,10)

$$P_t = 4.436 - 1.686\ \log_{10}\ [1+350\ var(RD)] - 0.881\ RD^{2.5} - 0.031\ (C+P)^{0.5} \qquad (7)$$

where:

p_t = serviceability index at time t.
RD = mean rut depth, in.
C = cracking area, $ft^2/1000\ ft^2$.
P = patching area, $ft^2/1000\ ft^2$.
var(RD) = variance of rut depth, in^2.

In general, however, information is scant for quantifying the relationship between rut depth and variation of rut depth, and then to roughness.

Models Emphasizing Structure, Surface Condition and Time Effects

(a) A Comprehensive Component Model from Brazil-UNDP Study

Making use of a relatively large data base from the Brazil-United Nations Development Program (UNDP) study with IRI as the metric, an incremental model was developed under the auspices of the World Bank.(11) This model for predicting roughness progression has a radically different form from traditional performance and pavement design models which attribute roughness changes only to structural factors, and from correlative models which have often been unable to distinguish any causative factors other than age. The model predicts incremental roughness through three groups of components; structural, surface distress, and environment-age factors. The data and the model show that significant deterioration can occur even in the absence of structural weakness.

(b) Roughness Prediction Model from Brazil-UNDP Study

The model developed from the "expanded" data base followed the linear approximation of the component model from the Brazil-UNDP study but omitted the surface distress terms (rut depth, patching and cracking):

$$RI_t = [RI_o + 725\ (1 + SNC)^{-4.99} NE_{4t}]\ e^{0.0153\, t} \qquad \textbf{(8)}$$

where:

RI_t, RI_o = roughness at times t and t = 0 respectively, m/km IRI.
NE_{4t} = cumulative equivalent standard axle loadings until time t, million ESA/lane.
t = age of pavement since overlay or construction.
SNC = modified structural number.

As can be seen, the model utilizes traffic, strength, age and environmental parameters; however, the empirical evidence suggests that the terminal level of surface distress or some surrogate is needed to enhance the predictive accuracy to a level similar to that of the Brazil-UNDP study model.

(c) Alberta's Riding Comfort Index

The riding comfort index (RCI), a roughness measure determined by the Portland Cement Association car roadmeter, is predicted employing a recursive model. The models require only ΔAge and a starting value of RCI. The model for granular base sections follows:(12)

$$RCI = 5.99875 + 6.87009\log_e(RCI_B) - 0.16242\log_e(AGE^2 + 1) + 0.18489\,AGE\log_e(RCI_B) - 0.09260\,\Delta AGE \quad (9)$$

where:

RCI_B = previous RCI.
AGE = present age of pavement.
ΔAGE = 4 years.

Structural Measures for Performance Prediction

Pavement condition in general is described either in functional terms which relate to ride quality or in structural terms, a function of bearing capacity. The important structural measure employed in performance prediction is fatigue damage. The linear fatigue damage model used is known as Miner's hypothesis.

According to this hypothesis, fatigue failure occurs when:

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \geq 1 \quad (10)$$

where:

n_i = number of stress repetitions at the i^{th} stress level.
N_i = total number of stress repetitions at the i^{th} stress level which will produce fatigue failure.
m = number of load or stress increments used in this analysis.

A vast amount of literature exists on fatigue cracking of bituminous- and cement-bound materials and cement concrete as well. Typically, the horizontal tensile stress or strain at the bottom of the layer is assumed to be critical. The empirical relationships being used today are of the exponential form:

$$N = K\,S^{a} \quad (11)$$

where:

N = the number of loads to cause a certain deterioration at a stress or strain level "s" at the critically loaded position in the layer.
K,a = constants.

When using the maximum tensile stress or strain at the bottom of the bound layer, the relationship with performance should be based on empirical evidence (or actual experience) with existing pavements. Correlations between the results of laboratory fatigue tests and performance of existing pavements have been rather unsatisfactory. Brown, et al., suggest a factor of 100 to get from laboratory to in situ fatigue life of asphalt-bound layers, while Monismith and Witczack noted that various researchers applied shift factors in the range of 2 and 700.(13,14)

Asphalt Concrete Fatigue

Practically all of the models relate the load repetitions for fatigue cracking to horizontal tensile strain at the bottom of the bound layer and another variable such as temperature in some cases or AC stiffness in other cases. For example, The Asphalt Institute (TAI) MS-2 Manual lists the following equation:(15)

$$N = C * 18.4(4.32x10^{-3})\ (1/\epsilon)^{3.29}\ (1/E)^{0.854} \tag{12}$$

where:

N = number of 18-kip (80-kN) equivalent single axle loads for 20 percent or greater fatigue cracking.
ε = maximum tensile strain in the asphalt layer, in/in.
E = asphalt mixture dynamic modulus, PSI.
C = a correction factor equal to $C = 10^M$.

where:

$$M = 4.84 \left(\frac{V_b}{V_v + V_b} - 0.69 \right) \tag{13}$$

in which:

V_b = volume of asphalt, percent.
V_v = volume of air voids, percent.

Another "strain/ modulus based" algorithm is included in the Shell Pavement Design Manual.(16)

Procedures utilizing "strain-based" algorithms are also included in the studies conducted by the following agencies and institutions:

1. The Transportation and Road Research Laboratory in the U.K.(17)
2. Nottingham University in the U.K.(18)
3. Mobil Oil Company in the U.K.(19)
4. The National Road Directorate of Denmark.(20)

5. The Belgian Road Research Center.(21)
6. Illinois DOT/University of Illinois.(22)

Newer models were developed such as Flexpass and MICH-PAVE. A brief description of MICH-PAVE is presented below. No information was available for Flexpass at the time of submission of this Final Report.

MICH-PAVE is a nonlinear finite element program for the analysis of flexible pavements. Design information such as fatigue life and rut depth are estimated through empirical equations. These calculations are currently restricted to three pavement layers with asphalt concrete surface, base and roadbed soil, and four layers with asphalt concrete surface, base, subbase and roadbed soil. Each layer in a pavement cross section is assumed to extend infinitely in the horizontal directions, and the last layer is assumed to be infinitely deep.(23)

In the MICH-PAVE program, the pavement is represented by an axisymmetric finite element model, and the resilient modulus model together with the Mohr-Coulomb failure criterion is used to characterize the nonlinear material response of granular and cohesive soils. The resilient modulus model characterizes stress-strain properties of soils through a stress dependent modulus and a constant Poisson's ratio for granular soils and cohesive soils. Results from the nonlinear mechanistic analysis, together with other parameters, are used as input to two performance models (fatigue and rut depth) derived on the basis of field data, to predict fatigue life and rut depth of flexible pavements.(24) The models relate the fatigue life and rut depth to the number of equivalent 18-kip (80-kN) single axle loads, surface deflection, moduli and thicknesses of the layers, percent air voids in the asphalt, tensile strain at the bottom of the asphalt layer, average compressive strain in the asphalt layer, kinematic viscosity of the asphalt binder, and average annual air temperature.

The fatigue life model was empirically calibrated using actual modulus and thickness of different pavement layers. The fatigue life equation is:

$$\begin{aligned}\log(ESAL) = &- 2.416 - (2.799)[\log(SD)] + (0.00694)(TBEQ) + (0.917)[\log(MR_B)] + \\ &+ (0.154)(TAC) - (0.261)(AV) + (0.0000269)(MR_S) - \\ &(1.096)[\log(TS)] + (1.173)[\log(CS)] - (0.001)(KV)\end{aligned} \tag{14}$$

where:

ESAL = number of equivalent 18-kip (80-kN) single axle load traveling the pavement section prior to failure.
SD = surface deflection under the center of the load (in).
TBEQ = base thickness plus the equivalent thickness of the subbase (in).
MR_B = resilient modulus of the base material (lbf/in^2).
TAC = thickness of the AC layer (in).
AV = the percent air voids of the AC layer (percent).
MR_S = effective resilient modulus of the roadbed soil as defined in the AASHTO 1986 design guide (lbf/in^2).

TS = the tensile strain at the bottom of the AC layer.
CS = the average compressive strain of the AC layer.
KV = kinematic viscosity of the asphalt concrete binder (centistrokes).

The rut depth model was calibrated using field data from different pavement sections. The rut depth equation is:

$$\begin{gathered}\log(RD) = -1.6 + (0.067)(AV) - (1.4)[\log(TAC)] + (0.07)(AAT) - (0.000434)(KV) + \\ (0.15)[\log(ESAL)] - (0.4)[\log(MR_{RB})] - (0.50)[\log(MR_{B})] + (0.1)[\log(CS)] - \\ (0.7)[\log(TB_{EQ}) + (0.09)\log[50-(TAC+TB_{EQ})]\end{gathered} \tag{15}$$

where:

RD = rut depth (in).
ESAL = the number of equivalent ESAL at which the rut depth is being calculated.
AAT = average annual air temperature (F).
50-(TAC+TBEQ) = the affected depth of the roadbed soil (in), and all other variables are as before.

Although these models are considered to represent the material response under cyclic loadings, their accuracy depends upon the material constants used in the equations. The MICHPAVE program considers only the linear response of the asphalt concrete. In reality, asphalt concrete is a nonlinear viscoplastic material whose behavior depends greatly on temperature and on the applied load.

Deflection Prediction Models/Structural Adequacy Index (SAI)

Alberta DOT has developed prediction equations for deflection as measured by Benkelman Beam.(12) Subsequently, a structural adequacy index was necessary to convert deflections into a more meaningful engineering measure that would indicate directly the ability of the pavement structure to withstand traffic loadings. The SAI concept provides a means of converting the deflection to a scale of 0 to 10 (with 10 being perfect) and thus enables one to know the structural condition from a single number. The SAI model for granular base pavements is:

$$\begin{gathered}Log\ SAI = 1.22251 + 0.00332\ (SAL + 1.65)^{1.39} - 0.012538\ \bar{d} \\ -0.000157\ \bar{d}\ (SAL + 1.10)^{1.44} \\ When\ \bar{d} < 18,\quad set\ SAI = 10\end{gathered} \tag{16}$$

where:
$\bar{d}$ = mean fall rebound as measured by Benkelman Beam x 10^3.
SAL = cumulative ESAL/10^5.

A similar equation has been developed for full-depth pavement as well.

A structural adequacy rating (SAR), which ranges from 0 to 4, is the measure employed by Minnesota DOT for estimating the structural condition. SAR is an indication of how many ESAL's have gone over the pavement compared to how many it was built to handle.

VESYS

VESYS is the structural analysis subsystem in a generalized flexible design procedure designed by the FHWA.(25,26,27) In this procedure, a flexible pavement design is evaluated by determining its structural response to expected loading and environmental conditions compared to the required performance criteria. All versions of VESYS have included the following models:

- Rutting.
- Fatigue cracking.
- Roughness.

Substantial modifications have been made in the program over the last 10 years. Additions have included low temperature cracking and refined procedures to provide probabilistic capabilities to the program with enhanced solution schemes. The main thrust of the program still remains the prediction of the PSI from the AASHO road test equation using roughness, cracking and rutting. A complete discussion of the algorithm and the data required for pavement structural analysis can be seen in a later section.

Distress Measure

These models predict the propagation of distress as a function of structure, load and environment related variables. Distress prediction in three types of pavements (rigid, flexible and composite) will be reviewed in the ensuing sections.

Rigid Pavement

COPES data have been the major source for rigid pavement distress models. Separate models for five attributes (distresses) are derived by the State agencies of Illinois, Minnesota, Louisiana, Georgia, Utah, and California. Distresses for which models have been attempted are transverse cracks, transverse joint faulting, pumping, joint deterioration and PSI, the latter being a functional measure. Specific explanatory variables employed in modeling the distresses including the PSR by each of the six States are tabulated in table 2. A sample set of models for the five distresses as well as PSR, formulated for Illinois DOT, is included in table 3.

Table 2. Explanatory variables to predict distresses, six States using COPES data base.[58]

State	Transverse Crack, linear ft/mi	Transverse Joint Fault, in	Pumping, Severity: 0,1,2,3	Joint Deterioration Number/Mi	Present Serviceability Index
Illinois	ESAL, Age, Joint, spacing, subbase stabilized, Slab thickness, Longitudinal steel (units: Number/mi)	ESAL, Maximum bearing stress on dowel bars	ESAL, Annual precipitation, Edge drains.	ESAL, No. of freeze-thaw cycles, Temp. difference, Joint seal damage, Incomp. material in joint (units = Number/100 joints)	ESAL, Age, Slab thickness, Longitudinal steel, Subbase stabilized.
Minnesota	ESAL, Age, Annual precipitation	ESAL, Slab thickness	ESAL, Slab thickness	ESAL, Age, D-cracking, Transverse joint damage.	ESAL, Joint spacing, D-cracking, Slab thickness
Louisiana	ESAL, Fill section.	ESAL, Joint load transfer type.	ESAL, Joint load transfer system, Subgrade soil type, Edge drains.	Age, Transvere joint, Seal damage	ESAL, Modulus of rupture/edge load stress, Cut section.
Georgia	ESAL, Age, cut section, Monthly max. temp - monthly min. temp.	ESAL, Subbase stabilized, Fill section, Edge load stress/modulus of rupture	ESAL, Age, Thornthwaite M.I. Slab thickness, Edge drains.	ESAL, Age, Joint seal damage, Unitube insert.	ESAL, Edge load stress/modulus of rupture, pump.
Utah	ESAL, Coarse-grained soil, Fill.	ESAL, Tied shoulder	ESAL	Age, Joint seal damage.	ESAL, Edge load stress/modulus of rupture, pumping.
California	ESAL, Coarse-grained soil, Edge load stress/modulus of rupture	ESAL, Slab thickness, Modulus of subgrade reaction, summer concentration of thermal efficiency	ESAL, Coarse-grained soil, Age, Annual precipitation	Age, Incompressibles.	ESAL, Pumping, Edge load stress/modulus of rupture

Table 3. COPES models for IDOT, summary of prediction models for Illinois.(56)

Model	Classification	Notes
$TC = AGE * ESAL \left[-1.5 + \frac{1.113}{H * ASTEEL} + \frac{4.587}{L} + \frac{1.129}{STAB + 1} \right]$	Single Visual "Transverse Cracks"	TC = Transverse Cracks of medium or high severity, number/mi AGE = Age of pavement, years ESAL = Equivalent 18-kip (80-kN) single-axle loads, millions ASTEEL = Area of longitudinal reinforcing steel, in^2/ft width of lane L = Joint spacing, ft STAB = 1, if stabilized subbase (asphalt or cement) or 0, if granular subbase H = Slab thickness, in

Table 3. COPES models for IDOT, summary of prediction models for Illinois (continued).(56)

Model	Classification	Notes
$Ln\ (f+1) = Ln\ (ESAL + 1)\ [-9.130\ x\ 10^{-2} + 1.394\ x\ 10^{-4} * BSTRl$	Single Visual "Transverse Joint Faulting"	F = Transverse joint faulting of adjacent slabs, in ESAL = Cumulative applied 18-kip (80-kN) equivalent single axle loads in the given lane, millions BSTRESS = Maximum bearing stress of the dowel bars as determined by Friberg's method for an 18-kip (80-kN) single axle load

Table 3. COPES models for IDOT, summary of prediction models for Illinois (continued).(56)

Model	Classification	Notes
Without -D- Cracking: $Ln\ (DETER + 1) = Ln\ (ESAL + 1) * [AGE * (4.042\ x\ 10^{-3} + 2.0$ $8.032\ x\ 10^{-3} * TEMDIF * JTSEAL * INCOMP] -$ With -D- Cracking: $Ln\ (DETER + 1) = AGE * [Ln\ (ESAL + 1) * (5.504\ x\ 10^{-3} + 2.2$ $\frac{TEMPDIF * PPTN}{DRAIN + 1} + 9.721\ x\ 10^{-4} * FTCYCLE] + 7.667\ x$	Compound Visual "Joint Deterioration"	DETER = No. of deteriorated joints per 100 joints FTCYCLE = Average number of annual freeze-thaw cycles at the pavement site JTSEAL = 0, if no, or, low joint seal damage = 1, if medium, or high severity seal damage TEMDIF = The difference between the highest average monthly temperature and the lowest average monthly temperature, °C INCOM = 0, if incompressible materials are not visible in transverse joints, and = 1, if incompressible materials are visible in transverse joints

Table 3. COPES models for IDOT, summary of prediction models for Illinois (continued).(56)

Model	Classification	Notes
$PSI = 4.58 + Ln\ (ESAL + 1)\ [AGE\ (-7.634\ x\ 10^{-2} + 3.688\ x\ 10^{-2}$ $3.113\ x\ 10^{-1} * STAB - 4.094\ x\ 10^{-3} * L]$ Damage = Loss of PSI = 4.58 - PSI	Compound "Present Serviceability Index"	PSI = Present serviceability index

Flexible Pavement Distress Models

Distress models relate pavement responses predicted by structural models (stresses, strains, deflections) to the evolution of pavement distresses (fatigue cracking, rutting and roughness).

(a) HDM Models (World Bank)(28)

Developed from a comprehensive, factorially-designed data base of inservice highways in Brazil and other sources, these models have been designed to be transferable and are incorporated in the new version of the Highway Design and Maintenance Model (HDM III) for the economic evaluation of costs and benefits over a highway network. The individual prediction relationships are also suitable for other applications such as pavement management system. The influence of pavement, traffic and environmental factors on the initiation and progression of cracking, raveling, and potholing, and the progression of rut depth and roughness are illustrated from the models.

Models are developed for the following distresses: (1) roughness (incremental), (2) fatigue (alligator) cracking, both initiation and propagation (incremental), (3) potholing, and (4) rut depth.

(b) EAROMAR-2 System(29)

The EAROMAR-2 System is a highway life-cycle cost model for use at a link or project. It employs a series of pavement distress models for flexible, rigid, and composite pavement. These models are based on past empirical pavement research and approximations to theoretical model predictions. The predictions of different categories of distress are translated in each year of the analysis into an estimate of the PSI. The specific categories of distresses simulated within EAROMAR-2 are as follows:

• Flexible pavements:	Lineal cracking, areal cracking, base failures, rutting, potholes, longitudinal roughness, and shoulder distress.
• Rigid pavements:	Lineal cracking, areal cracking, roughness, faulting joint filler stripping, spalling, blowups, pumping, and shoulder distress.
• Composite pavements:	Lineal cracking, areal cracking, rutting, roughness, potholes, and shoulder distress.

The EAROMAR-2 System is also used for rehabilitated pavements. A more detailed description of this model as well as mathematical formulation and data requirements are included in the upcoming section (Models for Rehabilitated Pavements) of this chapter.

(c) Cost Allocation Study

Completed in 1984, the FHWA research effort entitled "Pavement Damage Functions for Cost Allocation," had the primary objective to develop new damage and distress relationships specifically for the purpose of cost allocation.(30) A full range of damage equations was developed for both flexible and rigid pavements. Generally, they are functions of structural characteristics, environmental factors, traffic, subsoil characteristics, and pavement age. The program DAMAGE was written to assist in selecting the proper load equivalency factors (LEF's). LEF's are the basis for allocating damage and cost responsibilities to various vehicle classes.

(d) Cost Allocation Updates

An unpublished FHWA report was completed in September 1987 to update and enhance the deterioration models developed during the original highway cost allocation study.(31) Deterioration models were developed for both flexible and rigid pavements. Rigid pavement types included JPCP, JRCP and CRCP. The equations developed during the study were modeled using "S" shaped curves. Also, tire pressure was added to the list of independent variables considered.

Regression equations were developed to predict the serviceability loss, rut depth, and the amount of fatigue cracking for flexible pavements. For rigid pavements (JPCP and JRCP), models were developed to predict pumping, joint deterioration, faulting, roughness, slab cracking, reduction in skid resistance, and depression and swells. The CRCP model simply predicts an aggregate number of distresses per mile--punchouts, rupture, and patches. Input requirements to derive these models can be grouped as structural, environmental, and traffic (stream and growth). This study is an attempt in the use of "S" shaped curves for pavement deterioration prediction.

(e) Rutting

All of the pavement layers may contribute to rut depth development under repeated traffic loading. Only the AC surface layer is susceptible to fatigue in full-depth AC or conventional (AC surface + granular base/subbase) flexible pavements. Rut depth calculation is generally accomplished by employing material permanent strain accumulation models (AC, granular materials, cohesive soils). The log permanent strain vs log load repetitions relation appears to be the most appropriate and versatile for practical use at this time. The model is expressed as:(32)

$$Log\ \varepsilon_p = a + b\ Log\ N \tag{17}$$

or: $$\varepsilon_p = AN^b$$

where:

ε_p = permanent strain.
a & b = experimentally determined factors.
A = antilog of "a".

The permanent strain accumulation model proposed in the Ohio State studies is:(33)

$$\varepsilon_p / N = AN^m \tag{18}$$

where:

ε_p = plastic strain at N number of load repetitions.
N = number of repeated load applications.
A = experimental constant dependant on material and state of stress conditions.
m = experimental constant depending on material type.

NOTE: If the "b" term from the Log strain - Log N model is known, m is equal to b-1.

Composite Indices

Composite indices or aggregate indices represent pavement condition in terms of more general measures, usually indices of damage, condition, or serviceability. Present service ability index (PSI), pavement condition index (PCI), pavement condition rating (PCR), and pavement quality index (PQI) are among the widely used aggregate measures. Numerous other indices have been proposed for pavement evaluation. For example, New Jersey employs a compound rating with contributions of 60 percent roughness, 30 percent distress and 10 percent traffic. Designated as pavement matrix value (PMV) in New Mexico, it is a combination of distress, ride and average daily traffic (ADT). In New Mexico, 4R projects are ranked using a sufficiency rating system which is based on 70 percent condition rating. Virginia uses distress maintenance ratio (DMR) and traffic to forecast pavement performance. Distresses and ride contribute to the compound rating of North Carolina. Minnesota's PQI is a function of roughness, surface distress and structural adequacy. Alberta's scheme of PQI prediction is first: to predict RCI, visual condition index (VCI) and structural adequacy index (SCI) and, second: to combine the three measures to arrive at PQI value. PCR derived from roughness and distress determines the overall condition of pavements in Arkansas and Mississippi. The Washington PCR is derived from distress and ride; however, WASHTO employs a different mathematical form, as does the Program and

Financial Planning in Pavement Rehabilitation (PARS) model of Ontario. In South Dakota, projects are prioritized based on: condition 40 percent, geometric 20 percent, traffic 16 percent and safety 8 percent (the remaining criterion is unavailable). The final index (0 to 5) of Idaho is a weighted average of PSI and cracking index (0 to 5). Another aggregate condition index of wide use is PCI of CERL for evaluating streets and airfields.

PSI Models

Several PSI models are identified in the literature; notable among them are those of AASHO, HPMS, Idaho, Minnesota and Pennsylvania.

(a) AASHO Model

For performance prediction, the AASHO road test suggested the use of a power function:(1)

$$g = \frac{p_0 - p_t}{p_o - p_f} = (N_t / \rho)^{\beta} \tag{19}$$

where:

p_o = serviceability index (PSI) at time $t = 0$.

p_t = serviceability index at time t.

p_t = f (slope variance, mean rut depth, cracking and patching), slope variance is a measure of roughness.

p_f = terminal serviceability criterion, at which rehabilitation or reconstruction is indicated.

N_t = cumulative number of equivalent 18-kip (80-kN) standard axle loads to time t.

ρ, β = functions of axle type, axle load and pavement strength parameters, including the structural number and later (1972) a soil support parameter.

g = dimensionless damage parameter defining the functional loss of serviceability incurred prior to time t (Note that when $p_t = p_f$, $g = 1$).

The prediction model has the advantage of being adjustable for any observed PSI. However, it has the disadvantage of being dependent on another model for determining the design ESAL (in this case the AASHO design model). If an observed PSI is greater than PSIt and the corresponding observed ESAL is greater than the design ESALt, then the calculated exponent β is negative and the prediction model cannot be used.

(b) HPMS(34)

The FHWA HPMS uses PSR (PSI) prediction models, one for each of flexible and rigid pavement types. These models are based on the AASHO road test equations with some modifications. As in the case of the AASHO model, the HPMS is composed of two parts: one for determining the ESAL to the terminal PSR, and one for predicting the PSR curve.

The models involve PSR as a function of the structural number (SN) and the cumulative 18-kip (80-kN) ESAL's.

The models adjust to the current measured PSR (PSI) by estimating the cumulative ESAL prior to the base year (year of current measurement). This is done by using the following formula:

$$ESAL_p = 10^{(A + G/B)} \tag{20}$$

where:

$ESAL_p$ = cumulative ESAL prior to measured PSR.
G = $\log_{10}((5-PSR_c) / 3.5)$.
PSR_c = current PSR.

The A and B parameters vary with pavement type and can be derived from a structural number or concrete slab thickness depending upon the pavement type.

(c) PSI Model of Idaho

The Idaho model has the advantage of providing an S-shaped curve, as well as not breaking down when $PSI_c > PSI_t$ at $ESAL > ESAL_t$. Note PSI_c = current PSI;PSI_t = PSI trigger level; ESAL = current ESAL; and $ESAL_t$ = ESAL to failure (at PSI_t).

(d) Minnesota

The Minnesota Department of Transportation uses a PSR (PSI) prediction model that is a recursive model (PSR predicted as a function of itself) of the form:

$$PRS = PRS_p - J \tag{21}$$

where:

PSR = predicted PSR.
PSR_p = PSR 1 year previous.
J = factor developed by Minnesota DOT; it varies with type of pavement and traffic volume.

(e) Sigmoidal Model

Texas Transportation Institute has formulated prediction models using a sigmoidal (S-shaped) function.(35) The model has the form:

$$g = \exp - ^{(\rho / N_t)^{\beta}} \tag{22}$$

where:

g = normalized damage function.
ρ = number of ESAL or Age to g = 1 (PSI = PSIf).
N_t = number of ESAL or Age to given level of g (PSI).
β = site-specific constant.

Note that g has the same definition as in equation 19:

$$g = \frac{(PSIo - PSI)}{(PSIo - PSIf)}$$

where:

PSI = predicted PSI.
PSIo = PSI at time zero.
PSIf = final PSI level (at infinite age).

The general curve shape provided by this function is an S-shaped curve starting from PSI at age zero, and leveling off at PSI (approached asymptotically). In practice, this function provides curves that can have a great variety of shapes.

(f) PENNDOT Performance Prediction Model(36)

The PENNDOT model was developed as a result of an evaluation of the serviceability of reinforced concrete highways in Pennsylvania. Pavement PSI is related to roughness as measured by a Mays ridemeter. Models have been developed from the data base to estimate PSI as a function solely of pavement age. For example, this linear form of the equation is:

$$PSI = 4.24 - 0.0420(AGE) \tag{23}$$

where:

PSI = the mean PSI predicted for concrete pavements with joint spacing of 61.5 ft (18.75m).
age = the age of the pavement in years.

A similar equation has been developed for Interstate highways as well.(37)

(g) Virginia

Virginia DOT's prediction models make use of the familiar AASHO deterioration function:

$$g = A\ (ESAL)^{B} \tag{24}$$

where:

g = distress function denoting loss in serviceability (100-DMR).
A,B = load and design variables.
DMR = a composite distress index called maintenance rating.

Constants A and B have been determined by using two observations of DMR at two different ages of the pavement.

(h) Iowa DOT(38)

Based on the results obtained from the Demonstration Project 302, two models for rigid and composite pavements were derived. For rigid pavements:

$$\begin{gathered} PSI = 4.32 = BaseFactor + AggregateFactor \\ + JointFactor\ (LoadingFactor)\ (AC18) \end{gathered} \tag{25}$$

where:

Base Factor = effect of the base type
- 0.31 for ATB
- 0.10 for CTB
- 0.00 for granular base.

Aggregate Factor = effect of aggregate durability
- 0.27 for durability class 1
- 0.06 for durability class 2
- 0.00 for durability class 3.

Joint Factor = effect of joint or reinforcement type
- 0.08 for joints with aggregate interlock
- 0.05 for joints with dowels
- 0.00 for joints with dowels and mesh reinforcement
- 0.01 for continuously reinforced sections.

AC18 = loading in terms of 18-kip (80-kN) ESAL
- 0.0000796 for 8-in (203.2mm) rigid pavements
- 0.0000921 for 10-in (254mm) rigid pavements
- 0.0000984 for composite pavements.

(i) Washington(39)

The Washington State Department of Transportation (WSDOT) pavement management systems (PMS) data base was used to develop regression equations for three pavement surface layers: bituminous surface treatments, asphalt concrete, and portland cement concrete. The primary regression equations developed were to predict PCR which is a measure of the pavement surface distress (ranges from 100 (no distress) to below 0 (extensive distress)). The basic model included independent variables of Age, ESAL and surface course thickness (in). Sample equations for asphalt concrete (new or reconstruction) and asphalt concrete overlay respectively are as follows:

$$PCR = 100 - 3.08\,(AGE) - 1.4\ x\ 10^{-6}\,(ESAL) \tag{26}$$

and

$$PCR = 95.1 - 4.51\,(AGE) + 2.69\,(THICK) \tag{27}$$

(j) Mississippi PCR(40)

The performance indicator developed by Mississippi is designated as pavement condition rating (PCR, 0 to 100 scale), which is a composite index derived from monitoring data (roughness rating and distress rating).

The explanatory variables attempted include age, traffic volume , thickness of surfacing, structural thickness of pavement and surface deflection. The performance prediction model for flexible pavements, typical of other types of pavements, follows:

$$PCR_t = 90 - a[\exp(Age)^{b} - 1]\log\left(\frac{ESAL}{SNC^{c}}\right) \tag{28}$$

where:

Age = time in years since construction.
ESAL = yearly 18-kip (80-kN) single axle load.
SNC = modified structural number.
a,b,c = regression constants.

(k) Alberta's PQI(12)

Alberta's PQI is a function of three measures: (1) RCI, (2) VCI, and (3) SAI. The models or the individual measures are recursive (i.e. the future condition is a function of the present condition), with terms that relate to age, traffic, soil type, and structural thickness used as independent or explanatory variables. The scheme of PQI prediction is first: to predict RCI, VCI and SAI and, second: to combine the three measures to arrive at a PQI value.

(l) OPAC and PARS Models

The Ontario Pavements Analysis of Costs (OPAC) and PARS models were both developed for the Ontario Ministry of Transport and Communications.(41,42) Together these models can be used to relate pavement characteristics (age, strength) and traffic loadings to a pavement life-cycle, thickness of rehabilitation overlay, and periodic rehabilitation cost. They were developed to address asphalt concrete overlay, with rehabilitation modeled explicitly as a variable thickness of overlay. The models are, therefore, limited to those activities that can be expressed in terms of an equivalent increment to surface thickness.

The mathematical formulation employed in the OPAC model is:

$$N = A\ t^{b} \tag{29}$$

where:

N = life-cycle length in years.
t = layer thickness of rehabilitation overlay.
A,b = constants depending on the minimum level of acceptable performance.

The PARS model is similar in concept to the OPAC model. Pavement performance is predicted as a function of pavement age, traffic, and thickness of overlay:

$$Y=123+\sqrt{(x^2)} \tag{30}$$

$$Y = 95 - k\ x^{a}\ t^{-b}\ T^{c} \tag{31}$$

where:

Y = PCR or PCI on a scale of 0 to 100.
k = a coefficient.
x = time in years after a rehabilitation.
t = thickness of overlay.

95 = assumed maximum value of Y.
T = traffic loading, in AADT.
a,b, and c = the constants.

MODELS FOR REHABILITATED PAVEMENTS

Two types of models are required for a complete life-cycle analysis and maintenance effectiveness calculations. These models, respectively, are: (1) those for predicting the immediate improvement of pavement condition after rehabilitation, and (2) models for estimating deterioration due to time/traffic. These models are primarily for rehabilitated pavements; however, some of these models can be used for new pavements.

The first part of this discussion will focus on recent studies to investigate the effectiveness of maintenance and rehabilitation. Models to predict immediate improvement of pavements are rare, and a review of those models will be presented in the second part of the discussion.

Ten recent studies investigating the effectiveness of maintenance and rehabilitation are reviewed. Each study is analyzed with special emphasis on the models. Comparisons are made in their conceptional/methodological approaches, mathematical formulation, treatment of maintenance and rehabilitation (if applicable), and data requirement. Models utilizing disaggregate measures will be discussed first, followed by those using aggregate measures, examples of the latter group being PSR, PCI, etc.

NCHRP Project 14-6

One of the earliest studies on modeling maintenance effectiveness was a part of National Cooperative Highway Research Program (NCHRP) Project 14-6, a study built on work reported in NCHRP Report 223.(43) NCHRP 14-6 attempts to develop prediction procedures, guidelines, and criteria for highway agencies to use in determining alternative maintenance strategies (involving timing and practice) for highway pavements and bridges. Specifically, this study developed pavement condition predictions that allowed for different maintenance service levels and different maintenance treatments.

Developed as an integral part of this study are two programs: AGENCY and IMPACT. Program AGENCY computes maintenance workload by predicting the pavement's condition, quantifying the pavement condition threshold that generates a maintenance action, and defining the extent of the condition that will be corrected. The program permits the user to examine the consequences of different maintenance strategies for pavements. Program IMPACT calculates vehicle-operating costs during the analysis period, determines road occupancy hours for traffic closures and maintenance strategies, and computes the consequences in terms of vehicle operating costs, accidents, pollution, user comfort and time. The output of AGENCY can be used as input for IMPACT.

Concepts and/or Methodology

AGENCY program consists of a series of damage models to predict the future condition of the pavement. The damage models predict distress, and a distribution is associated with each distress and is used in concert with maintenance service levels to determine maintenance activity workload.

The distress is treated as evolutionary, i.e., one form of distress not corrected leads to another distress of a more serious nature. As an example, rigid pavement pumping creates voids under the pavement which, if uncorrected, leads to faulting, edge and transverse cracking, and finally holes in the pavement. The activities available to stop or retard this process are built into the program. The users identify the specific treatments they would use for each activity and the effectiveness of each treatment. The effectiveness takes two forms. First, the treatment may extend the serviceability of the pavement which will delay rehabilitation. Second, the treatment may only correct a local condition or hazard and not influence the overall performance of the pavement.

All distress follows some distribution; for example, joint sealants do not fail at some singular time. The material fails in some joints before others, so failures follow a distribution. As another example, where rigid pavements are faulting, the severity of faulting increases with time. The average of fault can be predicted, but the faults vary from some low value to some extreme value; again, a distribution defines this distress.

These models predict average levels of distress for given pavement types subject to specific environmental and traffic influence. They do not predict the performance or condition of a specific pavement. Rather, they predict the average performance or conditions for pavements having the same characteristics and subject to the same influences. Therefore, the conditions of a pavement representative of a group are being predicted. In addition to damage models, the program AGENCY includes distributions for predicted distress.

Effect of Maintenance and Rehabilitation

To determine the effectiveness of a given maintenance treatment, one must first address the factors affecting pavement performance. Then, the maintenance variables are added. These include (1) pavement condition at the time of treatment, (2) weather condition at the time of treatment, (3) amount of time that completed treatment is closed to traffic, and (4) traffic volume and composition.

Maintenance costs are based on the application of maintenance performance standards to the estimated quantity of maintenance work activity. The damage models predict average distress, but this must be converted to maintenance activity work-accomplishment units. The specified maintenance service level determines the magnitude and extent of distress that will be corrected.

To determine maintenance and repair costs, AGENCY predicts pavement distress, compares the distress with condition thresholds that define maintenance levels, alters the distress condition to reflect performed maintenance, adjusts the distress prediction to reflect the effect of maintenance on future pavement performance, and computes the costs and days of each maintenance activity.

Mathematical Formulation

(a) AGENCY Models for Rigid Pavements

With the exception of models for patching and for joint and crack sealant failure, AGENCY draws models from the Cost Allocation Study.(30)

A major drawback of the Cost Allocation models is that they are not linked to each other. Reduction in PSI is not linked to faulting, which is not linked to pumping. A danger with these models in an analysis that allows maintenance to change the level of some distress, without changing the level of another, is that unrealistic situations can occur. A second problem with the Cost Allocation models is that the output is deterministic. Maintenance workload is a function of the distribution of a distress. For these reasons, the Cost Allocation models were modified to some degree.

Joint and Crack Sealant model failure is based on work done by Riggins, et al. regarding pavement distress and serviceability.(44) The model for sealant is:

$$Percent\ Intact = e^{AGE*Z} \tag{32}$$

where:

Z = $-0.7/LIFE^3$.
Age = Sealant age, years.
LIFE = years until 50 percent of seals are failed.

Inputs for this model are simple, requiring only expected mean life and age.

As stated earlier, most of the models used in this program are adapted from the Cost Allocation study. The general form of the Cost Allocation models is:

$$g = (ESAL) \ / \ RHO)^{BETA} \tag{33}$$

where:

g = damage in terms of PSI.
ESAL = cumulative equivalent 18-kip (80-kN) single axle loads, millions.
RHO and BETA are specific to each type of distress, and are calculated using formulas in reference 43.

AGENCY uses the reduction in PSI for the period given starting and ending cumulative 18-kip (80 kN) single axles predicted by the cost allocation. This change is then multiplied by a factor that depends on two parameters: the user's impressions about how intact seals versus failed seals after reduction in PSI, and on condition of seals on the roadway in question. PSI is further reduced by an environmental factor based on Thornthwaite moisture index and freezing index. The final modification to PSI is also a result of faulting. The original change in PSI is related to the amount of faulting predicted by the Cost Allocation models, but the actual amount of faulting may be very different, especially due to grinding. The final form of the PSI model is:

$$\begin{gathered}\mathit{PSI} = \mathit{PSI\ last\ period} - \mathit{Factored\ predicted\ change\ in\ PSI} - \\ \mathit{Environmental\ effects} - \mathit{Effect\ of\ change\ in\ residual\ patching} - \\ \mathit{Effect\ of\ difference\ between\ predicted\ and\ actual\ faulting}\end{gathered} \tag{34}$$

The calibrated Cost Allocation pumping equations are:

$$\mathit{JRCP\ \ Pumping} = (g/\mathit{THICK}^{3})\ x\ \ln\,(\mathit{ESAL})^{2.3} \tag{35}$$

$$\mathit{JPCP\ \ Pumping} = (g/\mathit{THICK}^{4})\ x\ \ln\,(\mathit{ESAL})^{3} \tag{36}$$

where:

ESAL = cumulative 18-kip (80-kN) equivalent single axles.
THICK = slab thickness, in.

For faulting, AGENCY uses the models developed by the Cost Allocation Study which require no modifications other than to multiply the distributed change by the sealant and undersealant modifiers. This means, for faulting, change is distributed to slabs in the same way that pumping was distributed.

For cracking, the increase in cracking is distributed in the same way that pumping and faulting are distributed. The changes for each slab are modified by multipliers, depending on the state of sealants and undersealing for the slab.

There was no model for patching in the Cost Allocation report. As a result, a model was adapted from EAROMAR and calibrated with data from the Illinois Tollway.(76) -The model is:

$$\mathit{Patching} = F/(1.0 + e^{(1.0-(\mathit{AGE}-1.)/1.25)}) \tag{37}$$

$$\mathrm{F} = \mathrm{e}^{(2.0+1.75*\mathrm{PSINIT}-\mathrm{PSI10})}$$

where:

Patching = Potential square yd^2 of patching per period per lane mi.
AGE = Pavement age, years.
PSINIT = as-constructed PSI.
PSI10 = PSI predicted by Cost Allocation at age 10.

(b) AGENCY Models for Flexible pavements

Modeling flexible pavements was more difficult than those for rigid pavement. For flexible pavements, distress models from the World Bank's Highway Design Manual were selected to replace models from the Cost Allocation study.

The World Bank's Highway Design Manual (HDM) contains models for AASHTO Classes 2 and 4, raveling, potholes, mean rut depth, rut depth standard deviation, and roughness. Cracking divided into categories of "all" and "wide", raveling, and potholes are all divided into phases of initiation and progression of each distress. Tables 4 through 9 list equations used to predict initiation of all cracks for all surface types, equations to predict initiation of raveling, and equations used in calculating distress progression for all cracking, wide cracking and raveling.

Data Requirements

AGENCY is composed of two subroutines called AGENCYR (for rigid pavements) and AGENCYF (for flexible pavements). Each requires inputs of as-constructed data, environmental information, traffic, present conditions, maintenance levels, and financial data. The data requirements for the AGENCY program are as follows:

(a) For Rigid Pavements

The as-constructed inputs to RIGID depend on whether the pavement is JRPC or JPCP. Inputs for JRCP include:

- Slab thickness, in.
- CBR.
- Subbase thickness, in.
- Underdrains (0-none/1-present).
- Subbase type (0-nonstabilized/1-stabilized).
- Dowel bar dia, in.
- Slab length, ft.
- As-constructed PSI.
- Lane width, ft.

Table 4. AGENCY flexible pavement models for predicting the initiation of all (i.e., narrow) cracking in various pavement types.

Relationship Pavement Type

A: Surface treatments, granular base [1]

$$TYCRA = K_{ci}*(F_c * RELIA + CRT)$$

where

$$RELIA = 13.2*\exp\{-20.7*(1 + CQ)*YE4/SNC^2\}$$

B: All surfacings, cemented base (without stress-absorbing membrane) [1]

$$TYCRA = K_{ci}*(F_c*RELIB + CRT)$$

where

$$RELIB = 1.12*\exp(.035*HSE + .371*\ell n\ CMOD - .418\ell n*DEF - 2.87*YE4*DEF)$$

C: Asphalt concrete, granular base [1]

$$TYCRA = K_{ci}*(F_c*RELIC + CRT)$$

where

$$RELIC = 4.21*\exp(0.14*SNC - 17.1*YE4/SNC^2)$$

D: Slurry seal on surface treatment [2]

$$TYCRA = K_{ci}*[F_c*\{(0.05*KW + 0.4*KA*(1 - KW))*HSE + (1-KA)*(1 - KW)*RELIA\} + CRT]$$

E: Reseals on surface treatment [2]

$$TYCRA = K_{ci}*\{F_c*[2*KW*(1 + 0.01*HSNEW^2) + (1-KW)*RELIA] + CRT\}$$

F: Reseals on asphalt overlay, cemented base (without stress-absorbind membrane) [2]

$$TYCRA = K_{ci}*\{F_c*[(0.8*KA + 0.2*KW)*(1 + 0.1*HSE) + (1 - KA)*(1 - KW)*RELIB] + CRT\}$$

G: Asphalt overlay on asphalt concrete, granular or bituminous base [2]

$$TYCRA = K_{ci}*[F_c*\{(0.05\ KW + 0.4*KA*(1 -KW)]*\ HSE + (1 - KA)*(1 - KW)*RELIC\} + CRT]$$

H: Surface treatment reseal on asphalt concrete, granular or bituminous base [2]

$$TYCRA = K_{ci}*\{F_c*[KW*(1 + 0.01*HSNEW^2) + (1 - KW)*(1 + 0.3*HSNEW)*RELIA] + CRT\}$$

where

TYCRA = the time in years to the onset of cracks.
K_{ci} = calibration constant for crack initiation.
CRT = cracking retardation time due to maintenance, years.
CQ = surface construction quality (1 = construction faults/0 = no construction faults).
YE4 = number of equivalent standard axle loads for the year.
SNC = modified structural number.

Table 4. AGENCY flexible pavement models for predicting the initiation of all (i.e., narrow) cracking in various pavement types (continued).

HSE = thickness of the surfacing layers.
CMOD = resilient modulus of soil cement (cemented base).
DEF = mean Benkelman beam deflection under 18-kip (80-kN) load in both wheelpaths.
KW = a variable for indicating the presence of wide cracking in the old surface layers.
KA = a variable for indicating the presence of all cracking in the old surface layers.
HSNEW = thickness of most recent surface layer.

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[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgement.

Table 5. AGENCY flexible pavement models for predicting the initiation of wide cracking in various pavement types.

Relationship   Pavement type and model

A: Surface treatments, granular base [1]
$TYCRW = K_{ci}*\max(2.66 + 0.88*TYCRA, 1.16*TYCRA)$

B: All surfacings, cemented base (without stress-absorbing membrane) [1]
$TYCRW = D_{ci}*(1.46 + 0.98*TYCRA)$

C: Asphalt concrete, granular base [1]
$TYCRW = K_{ci}*(2.46 + 0.93*TYCRA)$

D: Slurry seal on surface treatment [1]
$TYCRW = K_{ci}*(0.70 + 1.65*TYCRA)$

E,H: All surface treatment reseals, granular [1] or bituminous base [2]
$TYCRW = K_{ci}*(1.85 + TYCRA)$
$TYCRW = K_{ci}*1.78*TYCRA$

G: Asphalt overlay on asphalt concrete, granular [1] or bituminous base [2]
$TYCRW = K_{ci}*(2.04 + 0.98*TYCRA)$

where

TYCRW = time to initiation of wide cracks.

---

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgement.

Table 6. AGENCY flexible pavement models for predicting the initiation and progression of raveling of various surfacing.

Relationship Pavement type and model

RAVELING INITIATION

A: Surface treatments including reseals (ST, RSST, RSAC) [1]

$TYRAV = K_{vi}*\{F_r*[10.5*exp*(-0.655*CQ - 0.156*YAX)]*RRF\}$

B: Slurry seal on surface treatment or asphalt concrete (SSST) [1]

$TYRAV = K_{vi}*\{F_r*[14.1*exp*(-0.655*CQ - 0.156*YAX)]*RRF\}$

C: Cold-mix surfacing or cold-mix overlay (CMST) [1]

$TYRAV = K_{vi}*\{F_r*[8.0*exp*(-0.655*CQ - 0.156*YAX)]*RRF\}$

D: Asphalt concrete and asphalt overlays (AC, OVAC) [2]

$TYRAV = 100$

where

TYRAV = time to initiation of raveling.
YAX = total number of axles of all types for the analysis year.
RRF = raveling retardation factor determined by maintenance.
K_{vi} = calibration constant for raveling initiation.

---

[1] **Statistically derived from Brazil-UNDP road deterioration study.**

[2] **Default relationship assuming sound specifications and construction of asphalt mixture.**

Table 7. AGENCY flexible pavement models for predicting all cracking progression in incremental time for various pavement types.

Relationship Pavement type and model

A,D: Surface treatment or slurry seal reseal, granular base [1]

$$\Delta ACRA = K_{cp}*5500*SCRA^{0.815}*SNC^{-3.21}*AGE2^{-0.621}*YE4*\Delta TCRA*CRP$$

B: Surface treatment or asphalt concrete, cemented-base (without stress-absorbing membrane) [1]

$\Delta ACRA_d = K_{cp}*RELPB$

where

$$RELPB = 2.42*SCRA^{0.591}*CMOD^{0.897}*DEF^{0.636}*YE4*\Delta TCRA*CRP$$

Table 7. AGENCY flexible pavement models for predicting all cracking progression in incremental time for various pavement types (continued).

C: Asphalt concrete, granular base [1]

$$\Delta ACRA = K_{cp}*RELPC$$

where

$$RELPC = 450*SCRA^{0.346}*SNC^{-2.27}*YE4*\Delta TCRA*CRA$$

E: Surface treatment reseal on surface treatment, granular base [2]

$$\Delta ACRA = \left\{ \begin{array}{ll} K_{cp}*(24/HSNEW)*\Delta TCRA*CRP & \text{if } ACRA_a < PCRA \\ K_{cp}*9.0*\Delta TCRA*CRP & \text{if } ACRA_a \geq PCRA \end{array} \right.$$

F: Reseals or asphalt overlay, cemented base (without stress-absorbing membrane) [2]

$$\Delta ACRA = \left\{ \begin{array}{ll} K_{cp}*8.0*\Delta TCRA*CRP & \text{if } ACRA_a < PCRA \\ K_{cp}*0.3**RELPB & \text{if } ACRA_a \geq PCRA \end{array} \right.$$

G: Asphalt overlay on asphalt concrete, granular or bituminous base [2]

$$\Delta ACRA = K_{cp}*25*SCRA^{.69}*SNC^{-1.6}*YE4*\Delta TCRA*CRP$$

H: Surface treatment reseal on asphalt concrete, granular or bituminous base [2]

$$\Delta ACRA = \left\{ \begin{array}{ll} K_{cp}*8.0*\Delta TCRA*CRP & \text{if } ACRA_a < PCRA \\ K_{cp}*0.3*RELPC & \text{if } ACRA_a \geq PCRA \end{array} \right.$$

[1] Statistically derived from Brazil-UNDP road deterioration study.

[2] Empirically developed based on Brazil-UNDP study data and judgement.

where:

$\Delta ACRA$ = crack progression.

SCRA = the minimum of ACRA or (100-ACRA).

AGE2 = surface layer age.

$\Delta TCRA$ = time to initiation of all cracks, years.

CRP = retardation of crack progression = 1-0.12*CRT.

K_{cp} = calibration constant for crack progression.

PCRA = percent of area of wide cracking before the latest reseal or overlay.

Table 8. AGENCY flexible pavement models for predicting wide cracking progression in incremental time for various pavement types.

Relationship — Pavement type and model

A: Surface treatment, granular base [1]

$$\Delta ACRW_d = K_{cp}*160*SCRW^{0.548}*DEF^{1.48}*YE4*\Delta TCRW$$

B: Surface treatment or asphalt concrete, cemented base (without stress-absorbing membrane) [1]

$$\Delta ACRW_d = K_{cp}*2.87*SCRW^{0.784}*CMOD^{0.558}*YE4*\Delta TCRW$$

C: Asphalt concrete, granular base [1]

$$\Delta ACRW_d = K_{cp}*720*SCRW^{0.281}*SNC^{-2.52}*YE4*\Delta TCRW$$

D: Slurry reseal, non-cemented base [1]

$$\Delta ACRW_d = K_{cp}*2.9*SCRW^{0.8}*\Delta TCRW$$

E, H: Surface treatment reseal, non-cemented base [2]

$$\Delta ACRW_d = K_{cp}*(120/HSNEW)*\Delta TCRW$$

F: Asphalt overlay or slurry reseal, cemented base [1]

$$\Delta ACRW_d = K_{cp}*4.5*SCRW^{.65}*\Delta TCRW$$

G: Asphalt overly, non-cemented base [1]

$$\Delta ACRW_d = K_{cp}*5.2*SCRW^{.69}*DEF^{1.4}*\Delta TCRW$$

[1] Statistically derived from Brazil-UNDP road deterioration study.

[2] Empirically developed based on Brazil-UNDP study data and judgement.

Table 9. AGENCY flexible pavement models for predicting the progression of raveling of various surfacings.

RAVELING PROGRESSION

All surface treatments, reseals, slurry seal, cold mix (ST, RSST, RSAC, SSST, CMST)[1]

$$\Delta ARAV_d = K_{vi}^{-1} * 4.42 * SRAV^{0.648} * \Delta TRAV/RRF$$

Asphalt concrete and asphalt overlays (AC, OVAC)[2]

$$\Delta ARAV_d = 0$$

[1] Statistically derived from Brazil-UNDP road deterioration study.

[2] Default relationship assuming sound specification and construction of asphalt mixture.

where

SRAV = minimum of ARAV or 100-ARAV

Inputs for JPCP include:

- Slab thickness, in.
- CBR.
- Foundation soil type (0-granular/1-present).
- Underdrains (0-none/1-present).
- Subbase type (0-nonstabilized/1-stabilized).
- Slab length, ft.
- As-constructed PSI.
- Lane width, ft.

Environmental inputs include:

- Average annual precipitation, cm.
- Freezing Index [32°F (0°C), Corps of Engineers (CE) method].
- Thornthwaite moisture index.

Plain and reinforced concrete pavements have common inputs for present condition including:

- Initial present serviceability index.
- Pumping (o none/ 1 slight/ 2 moderate/ 3 severe).
- Mean fault, in.
- Cracking, ft/mi.
- Patching, yd^2/mi.
- Sealant age, years.
- Starting year 18-kip (80-kN) equivalent axles (ESAL).
- ESAL growth, percent.

Another set of inputs addresses economic facets of the analysis. These include:

- A discount rate opportunity costs of money.
- Unit costs for each maintenance treatment.
- Optional inflation rates to handle anticipated inflation disparities for different materials.

For Flexible Pavement:

Construction inputs include:

- AC thickness, in.
- SN, structural number.
- Subgrade modulus (lbf/in^2).

Axle loading inputs include:

- ESAL starting year.
- ESAL growth.

Distress inputs include:

- As-constructed PSI.
- Initial PSI.
- Initial fatigue cracking, percent.
- Initial rutting, in.
- Initial thermal cracking, ft/mi.

Thermal cracking inputs:

- Penetration Index.
- Ring and Ball softening point, ^{0}F.
- Percent concentration of the aggregate.
- Solar Radiation, Langley/day.
- Minimum monthly temperature, ^{0}F.

Both pavement types have common inputs to address the economic analysis.

1985 FHWA Study

The contractor who performed the NCHRP Project 14-6, where the consequences of deferred maintenance were to be studied, simultaneously conducted the related 1985 FHWA Study. By using joint funds to collect field maintenance data, the contractor was able to further develop the AGENCY Models.

The 1985 study was intended "to develop deterioration rate functions that can be used to predict the damage and performance of pavement systems which have received a wide variety of alternative M&R actions."(45) Thus, models were sought to predict pavement distress and serviceability as a function of structural design and material characteristics, traffic, environmental factors and M&R treatments. These models were intended to be suitable for use by highway agencies in predicting pavement performance and deterioration, evaluating the advantages and disadvantages of different levels of M&R, and establishing acceptable maintenance service levels.

The FHWA Study employed existing models to develop new models that incorporated field maintenance data. The scope of the study entailed the different categories of distress and the maintenance and rehabilitation activities to be modeled. A data base was then developed from existing sources (e.g., State construction and maintenance records). Existing models were then reviewed for their ability to be adapted to a revised framework accounting for the effects of maintenance and rehabilitation. The models selected to predict flexible pavement distress were those from the HDM.(28) The models selected to predict rigid pavement distress were those from the Cost Allocation Study.(30)

Concepts and/or Methodology

These models encompass five distress modes: alligator and wide cracking, raveling, potholes, roughness, and rutting. Distresses are computed for seven surfaces and three bases. For example, seven types of surfaces considered are: (1) Surface treatment (ST), (2) Asphalt concrete (AC), (3) Slurry on surface treatment (SSST), (4) Reseal on surface treatment (RSST), (5) Reseal on asphalt concrete (RSAC), (6) Cold mix on surface treatment (CMST), and (7) Asphalt overlay or slurry seal on asphalt concrete, and asphalt overlay on surface treatment (OVAC). The types of bases modeled are granular, cemented, and bituminous base.

The concepts used to predict distresses, for example, cracking and potholes, are illustrated in figure 1. Distresses are estimated in two phases: (1) an initiation phase, which is the period before surface distress appears, and (2) a progression phase, during which the extent or severity of distress increases. From the different combinations of surface type, base type, and initiation vs progression phases, a total of 40 separate prediction models for distress have been developed.

Effect of Maintenance and Rehabilitation

Maintenance and rehabilitation activities are classified according to frequency and impact as shown in table 10. Frequency is defined as the number of applications or uses of an activity during the analysis period. Impact is measured as a change in pavement condition and strength. Routine maintenance is specified as either scheduled, condition responsive, or preventive. Scheduled maintenance is modeled as a correction of a fixed amount of damage (e.g., m^2/km of pavement repaired), or as a fixed interval between activities (e.g., every so many years). Condition responsive maintenance is modeled by introducing critical threshold levels of condition. Finally, the effect of preventive treatments is simulated by use of distress retardation factors. After the simulated performance of each activity, surface distresses that have been tallied by the models are nullified and the pavement condition updated. The effects of rehabilitation are modeled as a reclassification of surface type warranting the use of appropriate deterioration prediction relationships.

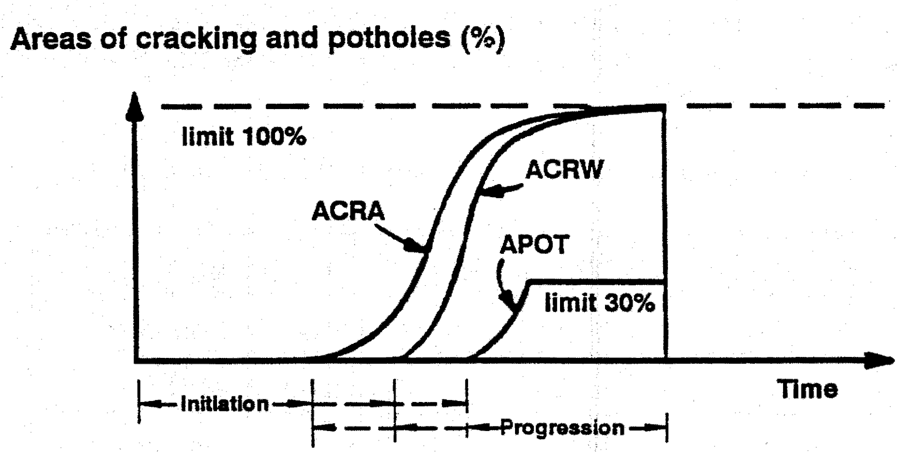


Figure 1. Area of cracking and potholes estimated in road deterioration and maintenance model.

Mathematical Formulation

The pavement condition after maintenance and rehabilitation is updated in the 1985 FHWA models using the general formulation below:

$$Condition_{J+1} = Condition_J + \Delta(Condition) \qquad (38)$$

where:

$Condition_J$ = the prediction of pavement condition in year J.
Δ(Condition) = the change in pavement condition between years J and J+1.

Estimates of work outputs for maintenance and rehabilitation are computed and applied to unit costs to predict M&R expenditures over the pavement's life-cycle. This general formulation is implemented for different types of pavements, and maintenance and rehabilitation activities, through the 40 individual deterioration models discussed earlier.

Data Requirements

Five main categories of data are required as inputs to the FHWA models. These include (1) Pavement characteristics, (2) Pavement history, (3) Pavement condition, (4) Environment, and (5) Geometry.

EAROMAR-2 System

The EAROMAR-2 System is a highway life-cycle cost model for use at a link or project level.(29) Besides predicting pavement-related costs due to maintenance and rehabilitation, EAROMAR-2 also includes simulations of traffic speed, volume/capacity, and congestion as related to highway design. Furthermore, estimates of maintenance and rehabilitation costs explicitly include the additional congestion due to the establishment of a work zone on the highway. Interactions between the structural and the operational aspects of highway performance are simulated in the model.

Table 10. Classification of M&R activities, 1985 FHWA Study.(45)

Classification		Frequency	Impact
(a)	Routine	Annual	No change in condition
(b)	Patching	Annual	Change in condition
(c)	Preventive Treatment	Periodic	Change of life, no change in condition or strength
(d)	Resealing	Periodic	Change in condition, minor change in strength
(e)	Overlay	Periodic	Change in condition, change in strength
(f)	Reconstruction	Infrequent	Change in all parameters

Concepts and/or Methodology

The EAROMAR-2 System employs a series of pavement distress models for flexible, rigid, and composite pavements. These models are based on past empirical pavement research and approximations to theoretical model predictions. The predictions of different categories of distress are translated in each year of the analysis into an estimate of the PSI. These measures of pavement condition and serviceability not only form the basis of determining requirements for maintenance and rehabilitation, but also influence the estimates of annual highway user costs. The specific categories of distress simulated within EAROMAR-2 are as follows:

- Flexible pavements: Lineal cracking, areal cracking, base failures, rutting, potholes, longitudinal roughness and shoulder distress.
- Rigid pavements: Lineal cracking, areal cracking, roughness, faulting, joint filler stripping, spalling, blowups, pumping and shoulder distress.

- Composite pavements: Lineal cracking, areal cracking, rutting, roughness, potholes and shoulder distress.

The simulation of maintenance and rehabilitation in the EAROMAR-2 System follows the precepts of the demand-responsive approach. Predictions of pavement condition by the models described above are compared with policy specifications input by the analysis governing allowable pavement conditions or thresholds at which maintenance or rehabilitation are to be performed. Specific activities of maintenance and rehabilitation considered are as follows:

- Flexible pavements: Crack filling, patching, deep patching or base repair, seal coating, overlay.
- Rigid pavements: Crack filling, patching, joint filler, replacement, slab replacement, mudjacking, overlay.
- Composite pavements: Crack filling, patching, seal coating, overlay.

Effect of Maintenance and Rehabilitation

EAROMAR-2 simulates mechanisms by which routine maintenance purportedly reduces the rate of deterioration. The primary mechanism studied in this way is the reduction in water infiltration due to sealing or patching of joints and cracks. A secondary effect that is considered is the reduction of roughness, rutting, or spalling due to the patching. Thus, the basic approach is somewhat different from that adopted in the FHWA Study which treated maintenance effectiveness more as a statistical correction to pavement condition or deterioration, rather than modeling the specific mechanism involved.

Mathematical Formulation

The basic approach adopted in this study is similar to that cited in the FHWA models:

$$\begin{gathered}\textit{Cumulative Damage}\ (t) = \textit{Net Cumulative Damage}\ (t-1) + \textit{Incremental} \\ \textit{Damage Occurrence}\ (t) - \textit{Damage Repaired} \\ (\textit{by Maintenance, Overlay, or Other Rehabilitation})\ (t)\end{gathered} \tag{39}$$

Routine maintenance may play either a corrective or a preventive role with respect to pavement damage. The corrective role is represented by the equation above, and would apply, for example, to activities such as the patching of potholes or spalls. The preventive role is also treated in EAROMAR-2, primarily with respect to sealing the pavement surface and filling cracks and joints. These activities, as discussed above, preclude water infiltration into the foundation layers that would otherwise weaken the pavement structure and promote earlier deterioration.

Data Requirements

The data requirements for EAROMAR-2 fall into the following categories:

- Route characteristics: Geometry and capacity, pavement characteristics, environmental zones, administrative sections, initial construction costs.
- Travel demand: Traffic volume, composition, and vehicle characteristics and costs.
- Pavement characteristics: Structural, materials, and drainage properties, construction and loading history, current surface condition.
- Environmental conditions: Seasonal temperature, rainfall, freezing index, AASHTO regional factor, and subgrade soil classification.
- M&R policies: Specifications governing when M&R are to be accomplished for each activity, and to what extent or degree of improvement or repair.
- Maintenance descriptions: Labor, equipment, and material use, production rates, and unit costs for each maintenance activity.
- User consequences: Unit vehicle operating costs, value of travel time, accident rates and unit costs, pollution emission data.
- Economic data: Discount rate, inflation rates.

Many of these data categories are optional, in that they can be defined to different levels of detail as needed by the user.

PAVER Pavement Management System

PAVER is a pavement management system developed by the U.S. Army Corps of Engineers for use by military installations, cities, and counties.(46) It encompasses the following management tools: PCI, scheduling of inspections, predictions of network condition, determination of maintenance and rehabilitation needs, economic analyses, and budget planning. Maintenance and rehabilitation needs and priorities are assigned based on inspection results, the resulting PCI, and other information such as traffic loading. Finally, maintenance and rehabilitation alternatives are analyzed and ranked using life-cycle cost analysis.

Concepts and/or Methodology

The current PCI is computed from the combination of distress types, severity, and extent obtained from inspection results. Employing this, the condition history of each pavement section is updated. These stored histories may then be used to assess the rate of deterioration of a pavement section.

The PAVER System provides the user with many important capabilities: data storage and retrieval, data base administration, pavement network definition, pavement condition rating, project prioritization, inspection scheduling, determination of present and future network condition, identification of M&R needs, performance of economic analysis, budget planning, and report generation.

Effect of Maintenance and Rehabilitation

Maintenance and rehabilitation strategies are recommended based on the rate of deterioration of pavement conditions (in PCI) over short-term and long-term periods. Figure 2 shows an example of long-term rate for asphalt concrete pavements. The observed distress is also attributed to its likely cause, e.g.: load, climate associated distress, etc. Relevant M&R activities are selected depending upon the respective percentages of deterioration attributable to each cause. Previous M&R policies are then examined for suitability and effectiveness and updated based upon the analysis described above.

PAVER enables the user to identify the effects of performing no major repairs on the pavement network, to determine life-cycle cost for various M&R alternative, and to determine a rational, objective basis for evaluating pavement condition and M&R needs and priorities.

Mathematical Formulation

The PAVER System utilizes the family concept, for PCI prediction.(47) This model uses mathematical techniques to fit a curve to the data. The general equation is the following:

$$PCI = 100 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 \tag{40}$$

where:

PCI = Pavement Condition Index.
X = AGE, years.
a1, a2, a3, a4 = coefficients.

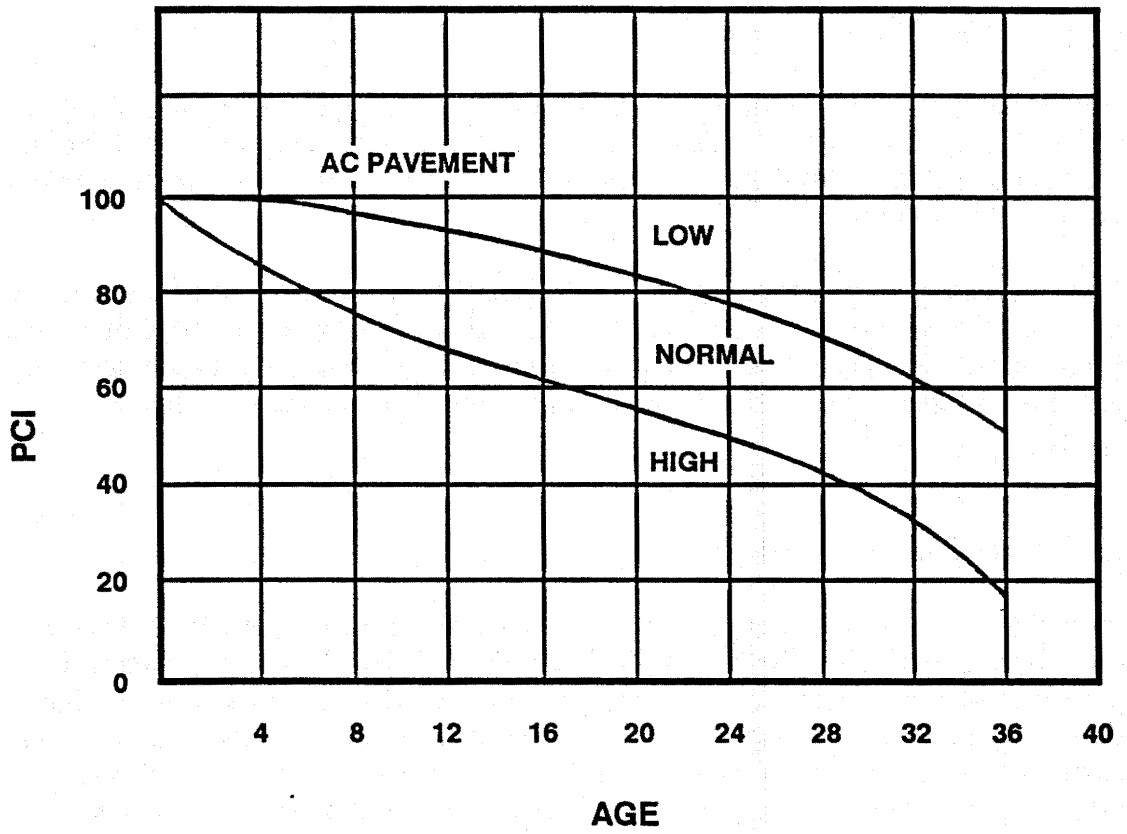


Figure 2. Long-term rate for asphalt concrete pavements.

The concept developed as part of PAVER consists of the following procedures:

- Pavement Family Grouping. The information is retrieved based on the user-specified definition of a pavement family. A pavement family is defined as a group of pavement section with similar deterioration characteristics (Branch Use, Pavement Rank, Surface Type, Zone, Section Category, Last Construction Date and PCI). The user's ability to set family definitions that may be unique for a particular location permits models to be developed specifically for that location.

- Filter Procedure. The data is filtered to eliminate obvious errors based on user modifiable guidelines (figure 3).

- Outlier Analysis. The filtered data is analyzed and statistical outliers are removed based on a user modifiable confidence level (figure 4).

- Family Condition Prediction. A best-fit curve applies to the remaining data using a constrained least squares method. This curve is constrained in that it is not allowed to have a positive slope since the PCI cannot increase with age. This best-fit curve for the family analysis extends only as far as the available data. The processed data is fitted with a fourth-degree constrained least square curve which is the pavement PCI prediction model (figure 5).

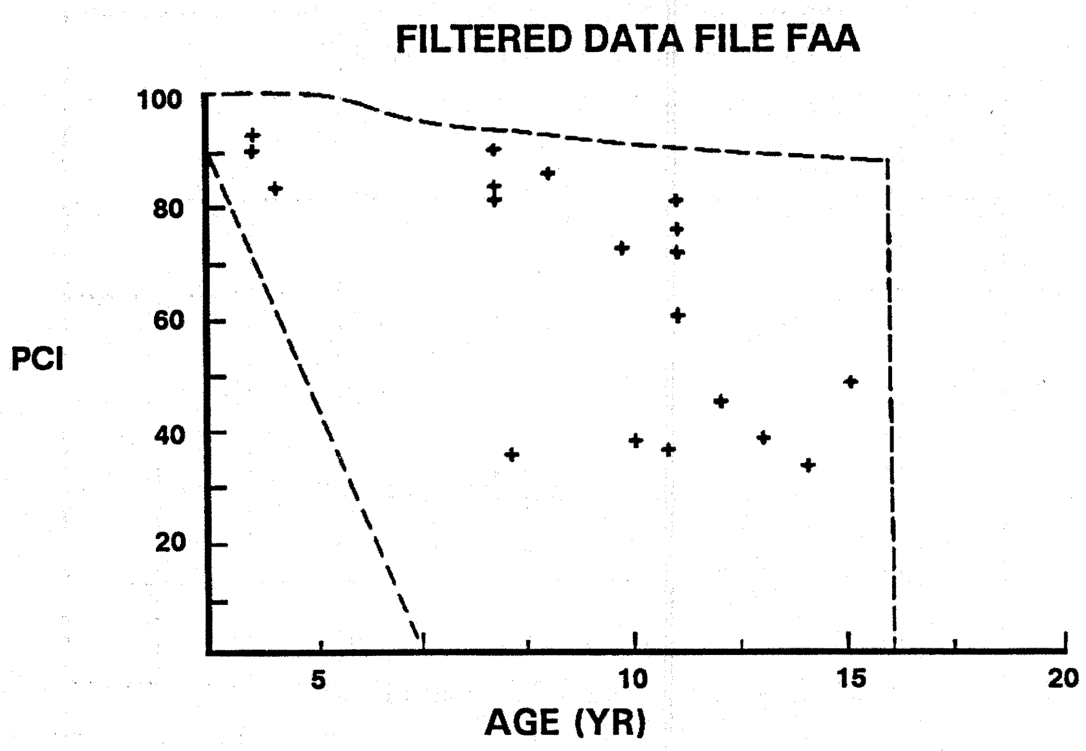
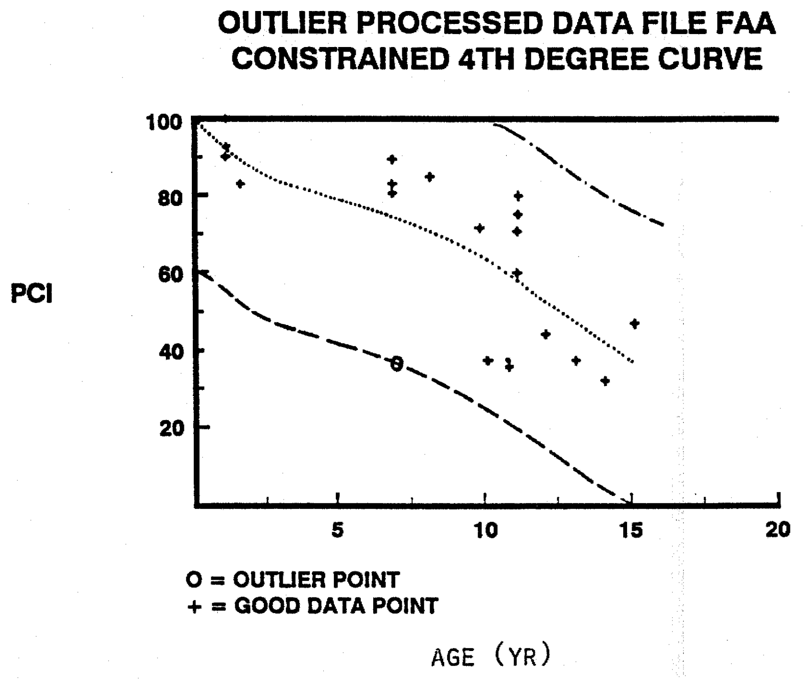


Figure 3. Sample output from the filter procedure.

- Pavement Section Condition Prediction. PCI prediction at the section level uses the family prediction model curve. The prediction function for a pavement family represents the average behavior of all of the sections of that family. The prediction for each section is done by taking its position relative to the family prediction curve. It is assumed that the deterioration of all pavements in a family is similar and is a function of only their present condition, regardless of age. A section prediction curve is drawn through the latest PCI/age point for the pavement section being investigated, parallel to the family prediction curve as shown in figure 5.

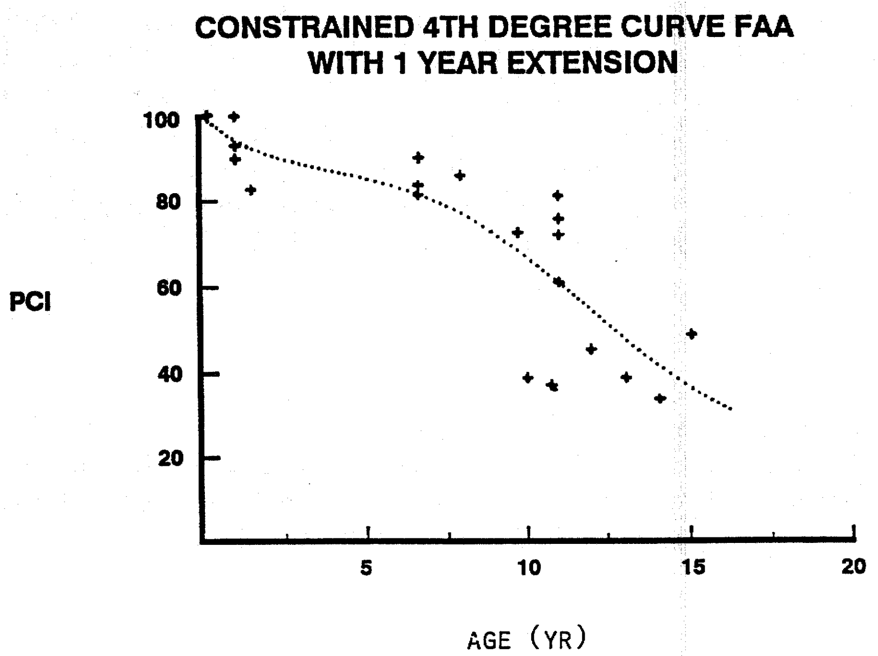
Data Requirements

The basic two variables used in the model development are PCI and Age. However, the key to the family concept is to group similar pavements to form families and thus eliminate the necessity to account for many of the other variables. For example, pavements can be grouped based on type of use, functional classification, surface type, etc.



EQN.: .1000000E+3 - .8244550E+01 + .1438487E+01 X^2 - .1367257E+00 X^3 + .3962556E-02 X^4

Figure 4. Sample output from the outlier procedure.



EQN.: .1000000E+3 - .6391411E+01 X + .136807E+01 X^2 - .1516525E+0X 3 + .4647153E-02 X 4

Figure 5. Pavement family condition curve extrapolated 1 year.

PAVER is capable of inventorying all surfaced areas that provide an access way for ground and/or air traffic. Depending on the management demands on the system and the scale of implementation, the inventory could consist of a limited amount of data (including pavement identification, results from one pavement condition survey, date of construction and/or last major repair, and surface type) or a wide range of information built on historical data and various destructive and/or nondestructive test results.

At the simplest level of implementation, four items of information must be provided to obtain any benefit at the network level. These items are:

1. Network definition. An inventory of the branches and sections as defined by the agency.
2. PCI. Each pavement section stored in the data base must have the results of a PCI inspection entered so that a current condition rating is available.
3. Last construction date. To predict pavement condition accurately, the last date when the pavement was considered to have been in perfect condition must be stored. In general, this date is typically the date of the last major M&R work or the date of initial construction.
4. Maintenance policy and priority scheme. To use PAVER for effective network-level management, at least one maintenance policy and priority scheme is developed. PAVER generates a report that applies the distress maintenance policy to the distress identified in the last condition survey in order to develop a distress M&R plan.

Indiana Study

Fwa and Sinha have related pavement maintenance to performance using an aggregate approach to represent pavement condition over time.(48) While this methodology is based upon the concept of pavement serviceability conceived at the AASHO road test, the concept of a modified index of pavement performance, PSI-ESAL loss, has been introduced in adopting serviceability to study maintenance effectiveness. A procedure for allocating pavement maintenance and rehabilitation costs is developed from this analytical framework of pavement performance.

Concepts and/or Methodology

The basic concepts and methodology employed in this approach were originally developed for Indiana's cost allocation study. The major items considered in the development of this aggregate approach encompass the following relationships:

- The relationship between pavement performance and routine maintenance requirements.

- The effect of maintenance on subsequent pavement performance.
- The influence of pavement characteristics, climate, and environment on the effectiveness of pavement maintenance work.

Mathematical Formulation

The concept of PSI-ESAL loss for measuring pavement condition is defined as the area between the pavement performance curve and the no-loss line, a horizontal line extending from the intercept of initial PSI. The performance equations to predict this loss are similar to the original AASHO road test results, but focus solely on pavement roughness as the independent variable rather than the several measures of distress (cracking, rutting, etc.) studied at the AASHO road test.

Effect of Routine Maintenance

The effect of routine maintenance on pavement performance is visualized as a shift in the PSI-ESAL loss curve. The average annual expenditure per lane-mile for each analysis period is used as an indication representing the level of maintenance employed. The maintenance effectiveness is quantified for each activity by a ratio of the PSI-ESAL loss to the expenditure. For Indiana flexible pavements, the effectiveness index (PSI-ESAL loss/dollar/year/lane-mile) varies from 2 to 22.

Arizona Overlay Design Procedure

A rational overlay design method for flexible pavements has been developed in this study.(49) Deflection response with Falling Weight Deflectometer (FWD) is employed not only to characterize the existing pavement, but also to determine non-linear load-deflection response providing data for a plastic deformation model. Three different deterioration models (roughness, fatigue and plastic deformation) form the foundation for the prediction model. The method is incorporated in a microcomputer program which is also capable of analyzing the economics of rehabilitation alternatives: overlay only, milling plus overlay, milling plus recycling plus overlay, and reconstruction.

Concepts and/or Methodology

The overlay design procedure is initiated with the collection and evaluation of input data which include FWD deflections, structural data, traffic, environment and costs of various items of work. Three critical performance parameters determine the overlay design: roughness, fatigue cracking and permanent deformation. For overlay design alternative, different overlay thickness can be specified. Besides overlay, feasibility of other strategies such as recycling, milling and asphalt-rubber can be investigated, for which an annual cost-based economic analysis algorithm is also included in the design methodology.

Effect of Maintenance and Rehabilitation

Effectiveness of overlay on pavement roughness is formulated by analyzing several projects whose roughness before and after the overlay were known. This analysis produced a relationship between the change in roughness and the roughness prior to overlay. An equation for roughness change in Interstate highways is:

$$\Delta R = -61.76 + 0.948\, R_b \tag{41}$$

where:

ΔR = roughness before overlay -- roughness after overlay.
R_b = roughness before overlay.

Rate of change in roughness with time was also investigated in the Arizona study. For want of a better relationship, a linear increase in roughness was adopted for predicting the life of overlays. The average change in roughness per year (in/mi), as measured with the Mays meter, are 6.7 (105.7 mm/km) for Interstate, 5.1 (80.5 mm/km) for U.S. routes, and 5.8 (91.5 mm/km) for State highways.

Mathematical Formulation

The overlay design method of Arizona can perform analysis for:

- Overlay design.
- Remaining life analysis.
- Life of a user specified overlay.
- Economic analysis.

As discussed before, the overlay option is based on the three criteria: roughness, fatigue and plastic deformation. Based on roughness criteria, the life of an overlay can be estimated using Mays meter roughness data:

$$N = (R_b - R_L + \Delta R)/C \tag{42}$$

where:

N = life of overlay in years.
R_L = limiting criteria for roughness.
R_b = roughness before overlay.
ΔR = predicted change in roughness due to overlay.
C = slope of roughness versus time relationship.

The fatigue component of the overlay design is based on a model of the usual form:

$$N = 10^{-6.03} \left(\frac{1}{\epsilon_{ac}} \right)^{3.84} \tag{43}$$

where:

N = number of ESAL applications until fatigue failure.
ϵ_{ac} = tensile strain at the bottom of the AC layer due to a standard wheel load (in/in).

The feature of the design procedure related to plastic deformation is that it is based firmly on the results of a field test, the FWD. If a section is particularly vulnerable to plastic deformations, as evidenced by the FWD, the section will receive a thicker overlay for protection. The remaining life analysis, the second option, relies on two failure criteria only: roughness and fatigue. If any of the failure conditions has been reached, the pavement needs to be overlaid.

The third option of the program permits the estimation of life of a user specified overlay. The procedure followed is similar to that used for determining the remaining life.

Included as a fourth option is provision for economic analysis determining equivalent uniform annual cost. Even though only four rehabilitation alternatives are available (as of 1988), many more can be included with little extra effort.

Data Requirements

Very basic to the rehabilitation design/analysis is a thorough evaluation of the existing pavement characteristics for which FWD deflection data are required. The pavement structure data, roughness and condition data are essential as well. Approximately 16 different cost items for each rehabilitation strategy are made available in the program to conduct economic analysis, thus helping the highway engineer decide which alternative to use.

Life-Cycle Cost Study

This study developed life-cycle costing procedures for highway pavements, encompassing both agency costs and road user costs as affected by pavement (re)construction, maintenance and rehabilitation.(50) These procedures have been implemented within a microcomputer based Pavement LCC Program that simulates pavement performance and costs through its service life. Patterned after the 1985 FHWA study, it incorporates several new aspects, e.g.: emphasis on the role of pavement policy at the network level, and the flexibility needed to test different types and combinations of pavement policies, and more refined analytic treatment of routine maintenance and rehabilitation.

Concepts and/or Methodology

The approach adopted in the LCC research was to derive a more general aggregate model by applying the knowledge already built in to disaggregate models of pavement deterioration.(44) The PCI-based framework of the PAVER system was selected as the framework for measuring pavement condition.(46) The concept of "deduct" points to account for distress manifestations, and "add" points for maintenance and rehabilitation was consistent with the approach used to account for the effects of M&R in life-cycle costing. To satisfy the requirement for prediction models, however, the approach adopted was to use existing disaggregate models of pavement deterioration (including the effects of maintenance and rehabilitation) to derive a PCI-based aggregate model suitable for life-cycle costing.

The type of distresses modeled were those that were corrected by the maintenance and rehabilitation activities being considered. These distresses include: (1) alligator cracking (both all-cracking and wide cracking), (2) raveling, and (3) rutting. The distress manifestations modeled for rigid pavements include: (1) pumping, (2) faulting, (3) cracking, and (4) deterioration of joint and crack sealants. The pavement damage estimated from the damage models was then converted to a PCI-value.

After a thorough study of a list of prevalent maintenance activities, 11 activities were selected. On the premise that maintenance effectiveness can be represented by either a change in rate of deterioration or an improvement in pavement condition, three activities (surface rejuvenation, slurry seal, and fog seal) were chosen to be represented as changes to the slope of the deterioration curve. Two activities (resealing and surface treatment) were modeled as minor rehabilitations. One activity (overlay) was selected as an activity resulting in a major change in PCI. Other activities might change the degree to which the curve is affected, but not the essential behavior. In fact, after this initial set of activities was investigated, three additional activities (crack filling, patching, and hot recycling) were also investigated. Results were similar in trend to those described below. A similar approach applies to rigid pavements as well.

Effect of Maintenance and Rehabilitation

An analytic perspective in defining preventive maintenance and also in distinguishing maintenance from rehabilitation is provided in this study. Maintenance (whether scheduled or emergency, routine or periodic, preventive or corrective) comprises those activities which can be represented mathematically by corrections to the deterioration function. This approach provides a very general and flexible structure within which different mixes and interpretations of maintenance activities may be simulated. It also distinguishes routine maintenance from rehabilitation (represented analytically as shown in figures 6 and 7) as a matter of the degree of improvement in pavement condition.

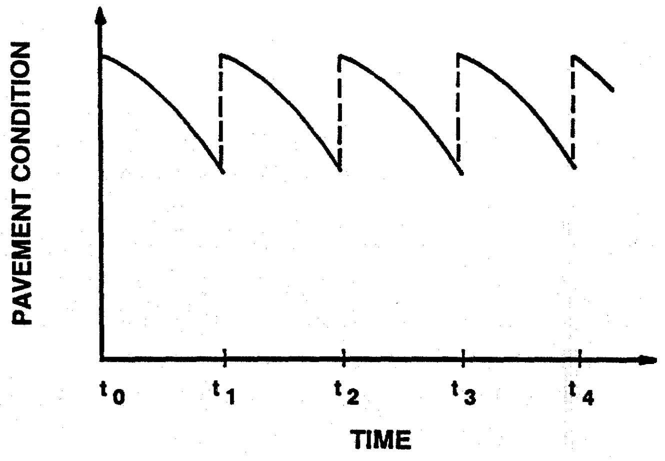


Figure 6. Analytic representation of pavement rehabilitation.

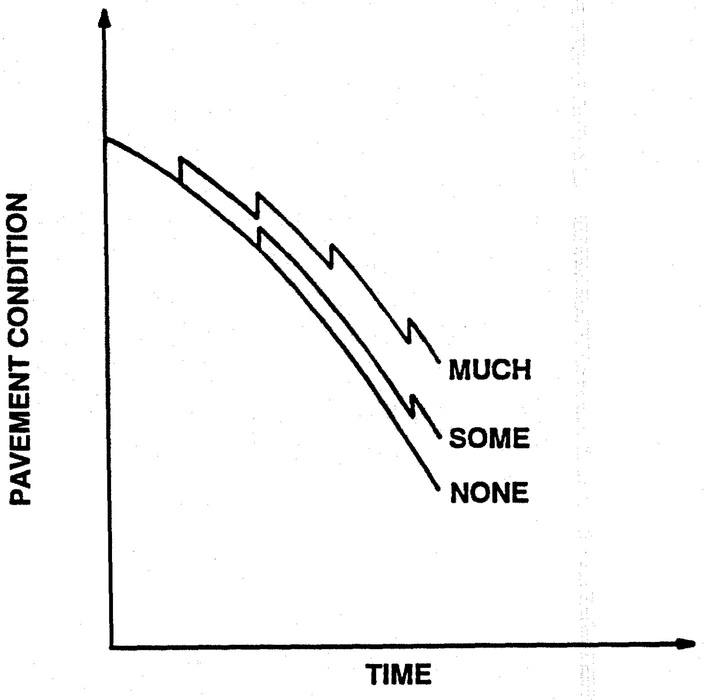


Figure 7. Analytic representation of pavement routine maintenance.

Mathematical Formulation

A recursive type equation was proposed to account for the routine maintenance effects, as well as rehabilitation:

$$PCIt = PCI_{t-1} - \Delta\ PCI_t + Add\_PCI_t \qquad (44)$$
$$PCI_t \leq PCI_o$$

where:

PCI_t = pavement condition resulting at the end of year t.
PCI_{t-1} = pavement condition at the conclusion of year t-1.
ΔPCI_t = incremental change in pavement condition in year t due to two effects (see equation 44).
Add_PCI_t = increase in pavement condition due to any rehabilitation or reconstruction in year t.
PCI_O = initial condition of the pavement when newly constructed.

A correction to reflect routine maintenance is needed in ΔPCI_t, in accordance with the following equation:

$$DELTAPCI_t = PCI\_loss_t - PCI\_correct\_by\_maint._t \qquad (45)$$

where:

ΔPCI_t = net (negative) adjustment in Pavement Condition Index in year t, due to the incremental increase in pavement condition and any correction due to routine maintenance performed in year t.
PCI_loss = incremental loss in PCI due to pavement deterioration, computed using equation 46.
$PCI\_correct\_by\_maint_t$ = adjustment in PCI due to routine maintenance, computed using equation 47.

The first component of the incremental change in pavement condition, ΔPCI_t, is the deterioration due to traffic loads and environment. The functional form selected is as follows:

$$PCI\_loss_t = K_1(T(A))^a\ S^b\ A^c - K_1\ (T(A-1))^a\ S^b\ (A-1)^c \qquad (46)$$

where:

K_1 = a coefficient that can be calibrated to local conditions.
T(A) = cumulative number of equivalent single axle loads (in millions) at pavement age A.
A = age of pavement in year t, measured in years since the time of last (re)construction or rehabilitation.

S = measure of structural capacity of the pavement: for flexible pavements, it is the structural number of the pavement, corrected for subgrade and environmental conditions; for rigid pavements, it is the slab thickness, in inches.

a,b,c = coefficients that can be calibrated to different types of pavements and materials properties, and other local conditions.

(47)

where:

maint_level(t) = maintenance relative level of effort in year t expressed on a scale of 0 to 10, with 0 denoting no maintenance to be performed, and 10 denoting the achievement of full maintenance effectiveness, as input by the Program user.
effectiveness = effectiveness of routine maintenance at different levels of pavement PCI (where PCI here denotes the pavement condition before performing maintenance), as input by the Program analyst.

Note that the treatment of rehabilitation within the LCC program is different from that of routine maintenance. The amount of expected PCI improvement is input directly by the program user, which is denoted as Add_PCI_t in equation 44.

Users of the program may limit the amount of improvement within a range of 25 to 50 PCI add points, or may specify that a rehabilitation or reconstruction will automatically restore the PCI of a pavement to its constructed value (PCI_O).

Data Requirements

The data categories required to perform life-cycle cost analysis, as in the previous investigations, include historical as well as monitoring data. Distress data collected in accordance with the PAVER manual serve to calculate the current PCI rating of the pavement. In addition, cost data pertaining to various maintenance/rehabilitation activities are required as well.

Data elements for computing the maintenance/rehabilitation effectiveness are rather subjective, and a list of them follows:

- Increase in PCI due to any rehabilitation or reconstruction.
- Input for maintenance relative level (a number from zero to 10).
- Effectiveness of routine maintenance.
- Coefficients (total four) to be used in equation 46, for each type of pavement.

Finally, in a demand responsive rehabilitation policy, the threshold PCI signalling the need for M&R action is another input required for the LCC analysis.

VESYS

VESYS is the structural analysis subsystem in a generalized flexible pavement analysis procedure designed by the FHWA.(25,26) In this procedure, a flexible pavement design is evaluated by determining its structural response to expected loading and environmental conditions, and comparing such a response to the required performance criteria. Ideally, such a general evaluation would involve individual checks for adequacy of distress predictions with respect to a series of independent mechanistic models, each requiring a number of input parameters. All versions of VESYS have included the following models:

- Rutting.
- Fatigue cracking.
- Roughness.

The program is designed in modular form so that new, revised, or additional models may be incorporated into it as they are developed, with relatively few modifications to the general structure of the program. Substantial modifications have been made over the last 10 years. Additions have included low temperature cracking, and refined procedures to provide probabilistic capabilities to the program with enhanced solution schemes. The main thrust of the program still remains the prediction of the PSI from the AASHO road test equation using roughness, cracking and rutting.

Concepts and/or Methodology

VESYS program computes primary responses, namely stress and deflection, and then uses these primary responses to calculate the distresses of rutting, roughness and cracking damage. The damage predictions are then used in the AASHO PSI equation to predict the serviceability of the pavement. The structural analysis is performed in four separate but interactive modules, namely:

- Primary response to static loading.
- General response to a Haversian pulse loading.
- Damage prediction (rutting, cracking, and roughness).
- Performance evaluation in terms of the PSI.

VESYS offers a closed form probabilistic solution to the linear, visco-elastic boundary values problem posed by a pavement structure.

Effect of Maintenance and Rehabilitation

VESYS model is a pavement performance analysis system; therefore, it is not particularly suited for investigating the effects of maintenance and/or rehabilitation. Being primarily a mechanistic-empirical model, rehabilitation actions can be simulated as construction projects increase the structure of the pavement. This approach may not be suitable for modeling maintenance activities, however.

Mathematical Formulation

VESYS is primarily a flexible pavement analysis program. The structural analysis in VESYS is performed in four separate but interactive modules, namely:

- Primary response to static loading.
- General response to a Haversian pulse loading.
- Damage prediction (i.e., rutting, cracking and roughness).
- Performance evaluation in terms of the PSI.

Stresses, strains and displacements (seven in total) constitute the response components calculated by the primary response models. Employing mechanistic-empirical concepts, distress components are computed and are accumulated over the life of the system, according to laws formulated on the basis of observations regarding the distress behavior of the various materials used. The output of the damage prediction module, describing the extent of the three primary distresses (i.e. rutting, cracking and roughness), are passed to the performance evaluation module, which determines the corresponding PSI.

The computations in this module result in the mean and variance of the PSI, as well as an estimate of the pavement reliability and the expected life of the pavement. "Pavement reliability" at any time is simply the probability that its current PSI is greater than a prescribed failure PSI value. The "expected life" of the pavement is the time required for the reliability to fall below a user-defined minimum tolerance value. All computations assume that the distribution of PSI is Gaussian.

Data Requirements

(a) Material Properties

This input data category includes linear, visco-elastic or elastic material properties for each layer which are assumed to be isotropic and locally homogeneous. These properties may also be dependent on the stress and temperature regimes developing in each layer. In the probabilistic approach, variations of these properties with time can be accounted for, by providing means and variances of the creep compliances (i.e. inverse moduli) for visco-elastic materials and elastic materials, or resilient moduli for elastic materials.

Material properties to be provided are numerous. They include:

- Resilient Modulus, fatigue and permanent deformation characteristics of the bituminous concrete layers.
- Stress-Strain and permanent deformation parameters for the unstabilized crushed stone subbase layers.
- Resilient Modulus and permanent deformation of the subgrade.

(b) Traffic Distribution

Parameters describing traffic, such as load distribution amplitude, and duration (i.e. vehicle speed), as well as the number of applied load repetitions, are assumed to be random in nature with respect to both space and time. Thus, they are represented by their corresponding means and variances.

(c) Environmental Variables

Only the two most important variables are considered, i.e., the mean temperature of bituminous layers, and the subgrade moisture content. The effect of these parameters can be accommodated for each incremental analysis period, e.g., for every month. This requires that the user provide the rutting, fatigue and stiffness properties of the pertinent layers corresponding to each environmental regime (i.e., temperature and moisture content). It is noted that unit weight and moisture content often influence the moduli of the base and subbase, in addition to that of the subgrade.

EXPEAR: Expert System for Concrete Pavement Evaluation and Rehabilitation

The Expert System for Pavement and Rehabilitation (EXPEAR) was originally developed by the University of Illinois for the FHWA, and is currently being further developed for the Illinois Department of Transportation. EXPEAR is an advisory system to assist the practicing engineer in evaluating a specific pavement section and selecting rehabilitation alternatives.

An EXPEAR program currently exists for each of the three pavement types: JPCP, JRCP, and CRCP. Programs for AC-overlaid pavements and other AC pavements are under development. The current version of the system is EXPEAR 1.4, which includes the capabilities to delay rehabilitation for up to 5 years and to perform life-cycle cost analysis of rehabilitation alternatives.

Project-level evaluation using EXPEAR begins with the collection of some basic design, construction, traffic, and climatic data for the project in question, and a visual condition survey. In the office, the design and condition data are entered into EXPEAR by the engineer using a full-screen editor. The program extrapolates the overall condition of the project from the distress data for one or more sample units.

EXPEAR evaluates the project in several key problem areas related to specific aspects of performance for the pavement type. For example, the problem areas for JPCP and JRCP are structural adequacy, roughness, drainage, joint deterioration, foundation movement, skid resistance, joint sealant condition, joint construction, concrete durability, load transfer, loss of support, and shoulders. The evaluation is performed using decision trees which compare the pavement's condition to predefined critical levels for key design and distress variables. EXPEAR produces a summary of the deficiencies found and, by interacting with the engineer, formulates a rehabilitation strategy which will correct all of the deficiencies.

Concepts and/or Methodology

The "Pavement Rehabilitation" phase of the EXPEAR program is relevant to the present study. In two distinct steps, the EXPEAR program recommends one or more appropriate rehabilitation techniques. The program determines the most appropriate main rehabilitation approach for each traffic lane. These include reconstruction (including recycling), resurfacing (with concrete or asphalt), or restoration. Once an approach is selected for each traffic lane and shoulder, the engineer proceeds to develop the detailed rehabilitation alternative by selecting a feasible set of individual rehabilitation techniques to correct the deficiencies present. By simulating each of these actions, EXPEAR recommends one or more appropriate rehabilitation techniques. A set of decision trees has been utilized to guide the rehabilitation strategy development process. Another feature of significance is the prediction of rehabilitation strategy performance. The future performance is predicted in terms of key distress types for 20 years into the future. The JRCP and JPCP EXPEAR programs include prediction models for the following key distresses for the various rehabilitation approaches:

- Reconstruction:
  Faulting, Cracking, Pumping, Joint deterioration, PSR.
- Bonded PCC overlay and Unbonded PCC overlay:
  Faulting, Cracking, Joint deterioration.
- AC structural overlay, AC nonstructural overlay, AC overlay/crack & seat, and AC overlay/saw & seal:
  Reflective Cracking, Rutting.
- Restoration:
  Faulting: - with grinding, - without grinding, Full-depth repair faulting, Cracking, Pumping, Joint deterioration, PSR.

EXPEAR 1.4 also performs the cost analysis of the rehabilitation strategies. The program uses the computed repair quantities and determines the rehabilitation alternative's life from the performance predictions. Unit costs for all of the rehabilitation techniques involved in the strategy being considered are made available in the program. EXPEAR computes the present cost and the equivalent annual cost of each technique over the entire project length and summarizes the total present annual cost of the strategy being examined. After developing several different rehabilitation strategies, the costs and performance characteristics of each of these alternatives can be compared and the one that fits the existing constraints and available funding can be identified.

EXPEAR Outputs

EXPEAR produces a summary of the project's data file, the evaluation results, recommendations for physical testing, predictions of the pavement's future condition without rehabilitation, and rehabilitation techniques, performance predictions, and cost calculations for as many rehabilitation strategies as the engineer wishes to investigate.

NAPCOM

Nationwide Pavement Cost Model (NAPCOM) is a computer-based simulation and analysis program that models the entire United States roadway network, excluding local roads.

Concepts and/or Methodology

NAPCOM produces three primary reports on the nationwide network:(51)

- Monetary need for maintaining, rehabilitating, and reconstructing the nationwide network.
- Trends in overall pavement condition over time, encompassing serviceability and distress.
- Allocation of costs to specific user groups (i.e. vehicle types and loading configurations).

The system criteria for NAPCOM was divided into five main categories. These are:

1. Overall Program Development Criteria.
2. Criteria for Modeling the Nationwide Pavement Network.
3. Criteria for Vehicle Simulation.
4. Pavement Damage Model Criteria.
5. Cost Modeling and Economic Criteria.

A more detailed list of the system development criteria is presented in table 11.

Table 11. Summary of system development criteria for NAPCOM.(51)

I. ***Overall Program Development Criteria***

A. Program Output
B. Program Input Requirements and Default
C. Ease of Use
D. Execution Time
E. Compatible with "The Status of the National Highway: Condition and Performance
F. Model Documentation and Verification
G. Available Level of Effort

II. ***Criteria for Modeling the Pavement Network***

A. Available Data Sources
B. Size Modeling Tradeoffs
C. Network Subdivision

III. ***Criteria for Vehicle Simulation***

A. Vehicle Classification
B. Vehicle Weight Groups
C. Axle Load Shifting
D. Mixed Traffic Reduction (i.e., LEF's)

IV. ***Pavement Damage Model Criteria***

A. Distresses to be considered
B. Degree of sophistication/data intensity
C. Environmental Effects
D. Load Equivalency Factors to Use
E. Empirical versus Mechanistic
F. Effect of Maintenance on Deterioration

V. ***Cost Modeling and Economic Criteria***

A. Cost to be considered
B. Rehabilitation Budget Constraints
C. Discounted Cash Flow Model Parameters

Effects of Maintenance and Rehabilitation

The ability to define rehabilitation and maintenance costs for the Nation is also built into NAPCOM. All costs are defined for each State and functional class through the use of "costs-factors." These factors are set up for flexible pavement reconstruction/rehabilitation, rigid pavement reconstruction/rehabilitation, and maintenance. It also considers different nationwide maintenance polices. The three available levels of maintenance are normal (current typical practice), low (deferred), and high (preventive). By selecting a different maintenance level, the user can change maintenance costs versus pavement age curve, as well as modify the deterioration rate associated with each distress model.

Maintenance costs are calculated with a set of user-defined curves based upon the age of the pavement (i.e., time in years since last reconstruction or overlay), the specified level of maintenance (normal, low or high), and functional class. Maintenance costs are not triggered; they systematically accrue every year on a section-by-section basis.

NAPCOM also has the ability to consider constrained or unconstrained annual reconstruction and rehabilitation (R&R) budgets. In the case of constrained R&R budgets, the actual annual budget limit is set by the user.

Mathematical Formulation

NAPCOM monitors the deterioration of several different types of distress to identify the need for pavement rehabilitation and reconstruction. For flexible pavements, these "triggering" types of distress include serviceability, cracking, and rutting; for rigid pavements, they include serviceability and cracking. Thus, any time rehabilitation (particularly overlay) or reconstruction is identified by NAPCOM, some type of design model is called upon to determine the structural requirements. The models that were chosen for structural design in NAPCOM are essentially those recommended in the latest AASHTO Guide for Design of Pavement Structures.

Four major categories of pavement repair have been incorporated into NAPCOM. They are Reconstruction; Rehabilitation (Asphalt Concrete Overlay); Surface Treatment and PCC Grinding; and Maintenance. The pavement performance and distress indicators that are modeled within NAPCOM are serviceability, cracking, rutting, and loss of skid resistance for flexible pavements; serviceability, cracking and faulting for rigid JPCP pavements. Table 12 lists the sources for each of the prediction relationships. All of the models were implemented without change except for converting "damage values" (numbers from zero to one where one is failure) to units of distress. For example, the original skid equation from the Cost Allocation Study predicted a value of zero to one where one is failure. For NAPCOM, the equation was arranged to predict a skid number by multiplying the damage by the defined failure skid number.

In integrating the diverse damage models within NAPCOM framework, several assumptions were made for input to the models. The assumptions made within each model are discussed in the reference 51.

Table 12. NAPCOM pavement performance/damage models.(51)

Pavement Performance/Distress		Original Model Source
For Flexible:	Serviceability	AASHTO Algorithm (86-8)
	Cracking	HDM-III (87-8, 85-6, 86-1)
	Rutting	HDM-III (87-8, 85-6, 86-1)
	Skid Resistance	FHWA Cost Allocation Study (84-2)
For Rigid:	Serviceability	AASHTO Algorithm (86-8)
	Cracking	FHWA Cost Allocation Study (84-2, 85-5, 86-1)
	Faulting	FHWA Cost Allocation Study (84-2, 85-5, 86-1)

Data Requirements

The primary data base that drives NAPCOM is the 1987 HPMS.(52) The HPMS fields that are included in NAPCOM on a section by section basis are State, functional class, section length/expansion factor, number/width of lanes, surface type, structural capacity (structural number for flexible pavements and slab thickness for rigid pavements), and current pavement conditions in terms of serviceability.

A supplemental HPMS data base was created to fill in those key missing data items that were needed on a section-by-section basis. The data items are pavement age, initial serviceability at last construction/rehabilitation, and soil strength values (modulus of subgrade reaction for rigid pavements and resilient modulus for flexible pavements). These three inputs were needed for virtually all pavement performance/damage prediction relationships.

The number of 18-kip (80-kN) ESAL's is calculated using vehicle miles traveled (VMT) data, section lengths, and AASHTO load equivalency factors. The load equivalency data base was developed for 20 vehicle classes along with a reasonable range of LEF's. Traffic growth is handled through a small data set in which the user defines the annual percentage increase in VMT for each State and functional class.

Environmental data is supplied to NAPCOM for each State. The pavement performance/distress prediction relationships that are environmentally sensitive use this information. The environmental data elements are: concentration of summer thermal efficiency, freezing index, Thornthwaite moisture index, average monthly temperature range, and average annual precipitation.

STATISTICAL MODELS FOR OVERLAY LIFE PREDICTION

Yet another class of models, instead of predicting the pavement condition as a function of time, simply project the life-cycle of overlay. These models are developed from pavement performance data gathered over a period of time from inservice pavements. Two models of this class will be described herein.

Based on the statistical evaluation of overlay performance, Hajek et al. developed performance prediction models that could be used for life-cycle economic analysis.(53) The duration of overlay life-cycle for a predetermined terminal serviceability was estimated as a function of overlay thickness, traffic (number of equivalent single axles), maintenance patching, and the life-cycle duration of the initial pavement. The latter variable was included to characterize the strength of the underlying support structure. Maintenance patching was included to quantify the effect of pavement maintenance on overlay performance. The following model predicts the overlay life-cycle:

$$AFT55 = 1.32\ BEF55^{0.33}\ THOV^{0.47}\ ESAL^{-0.097}\ 1.14^{PATCH} \qquad (48)$$

where:

AFT55 = duration of overlay life-cycle corresponding to the terminal PCR level of 55 (years).
BEF55 = duration of initial pavement structure life-cycle corresponding to the terminal PCR level of 55 (years).
THOV = thickness of overlay (mm).
ESAL = number of equivalent single axle loads per day calculated using equation 49.

$$ESAL = (AADT83 * TRUCK * TRUCKF * LDF) \ / \ 200 \qquad (49)$$

where:

AADT83 = 1983 Annual Average Daily Traffic.
TRUCK = truck percentage.
TRUCKF = truck factor.
LDF = lane factor.

PATCH = n indicator (dummy) variable to account for presence of patching during the initial cycle. PATCH was set to 0 for no or a limited amount of patching and to 1 for all other cases.

Employing field performance data on some 500 mi (805 km) of roads with overlay, George, et.al. derived an equation to predict AC overlay life.(54) Similar to the Ontario equation, it is of the form:

$$OVL = a\ (BEFL)^{b}\ (THOV)^{c} \tag{50}$$

where:

OVL = overlay life, years.
BEFL = age of the original pavement, years.
THOV = thickness of the overlay, in inches.
a, b, c = coefficients.

MODELS TO PREDICT PAVEMENT CONDITION IMMEDIATELY AFTER MAINTENANCE OR REHABILITATION

Just as important as a deterioration model is another type to predict immediate improvement in pavement condition (referred to as condition jump), following maintenance or rehabilitation. There is hardly any agreement as to what extent pavement condition is improved as a result of M&R action. A tacit assumption made by several researchers is that, for any type of rehabilitation (minor or major), the pavement condition reverts back to its original as-constructed state. This result is contradicted by field observations which show that condition improvement is proportional to various factors, including the pavement condition before overlay. A brief discussion of these models follows:

In a roughness-based maintenance management system developed for Indiana Department of Highways, Colucci-Rios and Sinha developed a functional relation to estimate the percent reduction of roughness as a function of overlay thickness.(55)

$$\%RED = 61.35\ T^{0.35} \tag{51}$$

where:

%Red = percentage reduction in roughness.
T = overlay thickness, in.

A recent Arizona study made use of three forms of pavement (flexible) deterioration: roughness, fatigue, and plastic deformation.(48) Regression models were developed for both immediate improvement in pavement roughness after placing an overlay, and also for the roughness progression with time. For Interstate highways:

$$\Delta R = 61.76 + 0.948 R_B \tag{52}$$

where:

ΔR = improvement in roughness due to overlay.
R_B = roughness before overlay, in/mi determined using Mays meter.

Note that thickness of overlay is not considered a factor in the model.

Estimating immediate effect on PCR by a treatment was the subject of a study in Ontario.(52) The results, graphed in figure 8, conclusively show that "PCR Jump" is a function of PCR before overlay and, to a lesser degree, lift thickness.

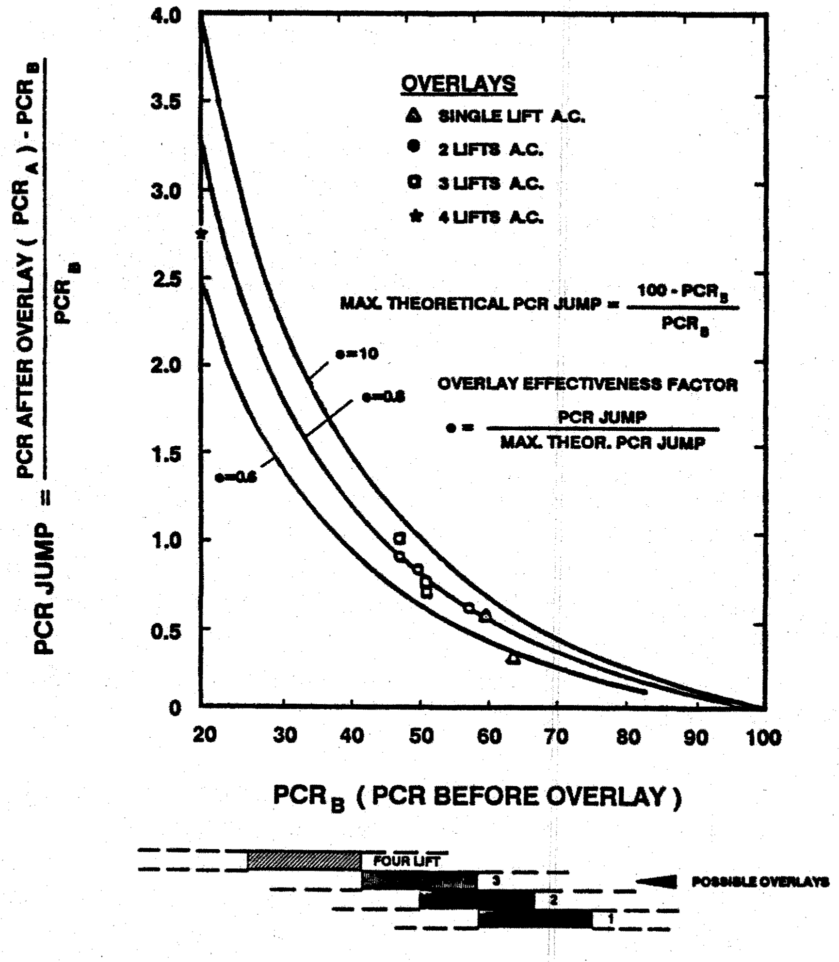


Figure 8. Effectiveness of overlay in restoring ride quality, as per study in Ontario.(48)

Feasibility of Selected Models in Life-Cycle Cost Analysis

Among the several deterioration models for rehabilitated pavements, five models are critically reviewed as to their suitability/adaptability in the proposed LCC analysis. As can be seen in table 13, they exhibit significant differences in their conceptual format and methodology as well.

Table 13. LCC analysis models to study maintenance effectiveness.

Model	Conceptual Format/Methodology
VESYS [25,26]	Mechanistic - empirical
Arizona Study [49]	Deflection based mechanistic-empirical
LCC of FHWA [50]	HDM models and subjective adjustment factors
EXPEAR [62] (Rigid Pavement)	Regression models from new and rehabilitated pavements
NAPCOM [51]	Regression Models for rehabilitated pavements (to analyze potential long-term life-cycle pavement cost associated with Federal truck and weight policy options and related highway cost allocation procedures.)

VESYS in LCC Analysis

The VESYS model, by calculating and combining predominant damages, predicts performance of a flexible pavement system, expressed in terms of the PSI. The model as such has the potential for evaluating the deterioration of a rehabilitated pavement, provided the existing pavement including the programmed treatment can be structurally characterized. Required specifically for each layer are linear visco-elastic or elastic material properties. Nondestructive testing, such as deflection tests, in conjunction with back calculation procedure could be utilized for characterizing the existing layers.

The damage models, mainstay of VESYS, need to be so modified that they can be adapted to rehabilitated pavements which are a "composite" structure of damaged as well as undamaged layers. In previous overlay design studies, instead of modifying the damage equation, an equivalent thickness concept has been proposed to transform the cracked layer to an uncracked layer of reduced thickness. Unfortunately, the thickness equivalency concept is only approximate at best. Routine maintenance activities like crack sealing, slurry seal, etc., are not amenable to modeling by the equivalency concept because they are hardly of any structural value to the pavement.

Furthermore, that the VESYS model cannot predict immediate improvement of a pavement after maintenance/rehabilitation is another serious drawback that deters its use in life-cycle cost analysis.

Arizona Overlay Design Procedure

The prediction model for forecasting overlay life appears to be the weakest link in the life-cycle algorithm. That the Arizona study does not evaluate effectiveness of "maintenance" treatment is yet another drawback of the method.

The basic methodology of utilizing surface deflection for designing overlays, predicting future performance and/or studying wheel load effects, has been adopted by various agencies.(46) California DOT recently proposed an extension and adaptation of their AC overlay design procedure to new pavement design. They utilize a "tolerable deflection -ESAL" relationship for design, as other agencies also do, for example: The Asphalt Institute, Roads and Transportation Association of Canada, Minnesota DOT, and Illinois DOT. Extensive studies conducted at the TRRL have indicated that performance [number of 18-kip (80-kN) axle loads to failure] is related to the early life surface deflection. Undoubtedly, deflection-performance relations offer significant potential for flexible pavement analysis and design as well as overlay thickness design. Since deflection response of a pavement represents both structural and distress-related aspects of the entire pavement, a surface deflection based approach for overlay design life is appealing and very useable. Moreover, deflection criteria indirectly consider both pavement rutting and AC fatigue distress modes. Considering all of the major factors that can potentially influence flexible pavement responses and performance, perhaps a deflection-based approach represents the degree of refinement that can be justified at this time.

LCC Models of FHWA

It is the adaptability of the two prediction models that is of interest in this review. The models utilized in the LCC study are (1) a procedure to correct the pavement condition as a consequence of an M&R action, and (2) a model to predict subsequent deterioration of the rehabilitated pavement with time and traffic. The "add PCI" concept utilized in the LCC model is ad hoc and warrants further investigation to formalize this procedure. How much improvement in condition can be expected of a rehabilitation action is not clear, nor are the causal factors responsible for improvement well documented. A recent Arizona study reports that pavement roughness improvement is independent of the overlay thickness (equation 48), whereas equation 51 derived from the Indiana study, predicts roughness improvement to be a function of overlay thickness.(48) The Ontario study concluded that the PCR jump is a function of the PCR before overlay.(52) In light of these conflicting results, a systematic study of the causal factors and, in turn, model(s) to predict immediate improvement, should be given top priority. In as much as prediction of immediate improvement, if any, as a result of routine maintenance activities is very much subjective in the FHWA study, effort should be directed in this area as well.

A cursory inspection of the deterioration model (equation 45) reveals that it calls for several (four in total) regression coefficients for utilizing the model. The regression coefficients should be calibrated to different types of pavements and material properties, and other local conditions.

EXPEAR

Since the focus of the present study is to formalize prediction models for rehabilitated pavements, a large number of predictive models in EXPEAR for concrete pavements with rehabilitation warrant special consideration. These models, developed from data collected on 161 rehabilitated concrete pavements in 24 States, provide a clear insight into various causal factors influencing the performance of rehabilitated jointed concrete pavements. Even though EXPEAR includes models for a number of key distresses for the various rehabilitation approaches, it is deficient in models for immediate improvement (jump) of performance.

The cost analysis in EXPEAR is a simple and approximate procedure, the primary purpose of which is to facilitate rapid generation and comparison of rehabilitation alternatives. Nevertheless, the general concept adopted in EXPEAR deserves close attention in the conceptual model building phase of the present study.

NAPCOM

NAPCOM is a policy analysis tool that can be used to analyze potential long-term life-cycle pavement costs associated with Federal truck size and weight policy and related highway cost allocation procedures. The life-cycle pavement costs associated with truck size and weight policy were computed for the nationwide network. The costs considered were essentially maintenance and rehabilitation/reconstruction. User costs and vehicle operating costs were not considered. The effects of rehabilitation/reconstruction budget limitations were handled by the system. Costs need to be discounted and summarized in terms of net present value (NPV), and in terms of the projected annual "needs" for the network.

Overall, the cost modeling and economic criteria for NAPCOM were well established, with the important exception of a model for maintenance costs as a function of pavement age. A traditional life-cycle approach was used to discount the cost associated with projected maintenance and rehabilitation requirements for the entire Nation network.

Output of the model indicates pavement improvement costs, including reconstructed pavement costs and changes in nationwide pavement condition, for a user defined analysis in annual intervals.

SUMMARY

This chapter critically reviews predictive models for road deterioration and maintenance. Two classes of models are reviewed: They are (1) models for new or reconstructed pavements, and (2) models for pavements receiving maintenance and/or rehabilitation. Yet another class of models reviewed predict the immediate improvement in pavement condition, especially following a rehabilitation action.

Deterioration models have been discussed and categorized in four groups (table 1) highlighting the measures employed for evaluating the road condition. Judging from the sheer number, flexible pavement models are more plentiful than the rigid pavement counterpart. Another observation is that disaggregate indices, distress for example, have been preferred in rigid pavement deterioration modeling, as opposed to composite (aggregate) indices for flexible pavements.

For the most part, the present deterioration prediction models have been statistically-estimated from field data and structured on mechanistic principles of pavement behavior. The methodologies used are empirical, developing parametric models by statistical regression of time-series data which had been collected in studies of inservice roads. Only a handful of investigations, for example, World Bank studies, comprised a statistically designed factorial sample of inservice roads with differing structural and traffic characteristics. A majority of the models predicted the absolute value of pavement measure employing the explanatory variables of structural, traffic and environmental factors.

The latter part of the chapter reviews models for quantifying the effect of maintenance and rehabilitation. One approach utilized is to account for major repairs (rehabilitation actions, such as overlay) by measurable changes in the current condition of the pavement and to represent the routine maintenance rather as an adjustment in the slope of the deterioration curve. A few equations that predict the immediate improvement resulting from rehabilitation action are reviewed. Another approach to accomplish this objective is to apply adjustment factors, mostly subjective, to account for the different levels of effort and policies for different M&R activities. The resemblance of deterioration models for rehabilitated pavement to those for new ones is apparent in that both types are regression models developed from careful observations of inservice pavements.

Also presented in this chapter is a discussion as to the feasibility of utilizing the concepts and/or models of recent investigations to investigate maintenance effectiveness. The models discussed are: (1) VESYS of FHWA, (2) Rational Characterization of Pavement Structures Using Deflection Analysis, an Arizona Study, (3) Life-Cycle Cost Evaluation of Pavement Construction, Maintenance, and 4R Projects from FHWA, (4) EXPEAR, a study by the University of Illinois, and (5) NAPCOM.

CHAPTER 3 PRESENTATION OF EXISTING DATA BASES

The major emphasis of State agencies in recent years has been on the establishment of PMS. This is in response to FHWA requirements that PMS programs be initiated, and is a recognition of the benefits that can be derived from these procedures. The deterioration models which were discussed in previous chapters represent one end use for the material being collected by the various agencies. These models require specific inputs in many cases, and great care must be exercised to generate these input values. There are a great many data bases in use today, all of which contain various data elements of various usefulness to the application of the models and the development of new models.

It is necessary to critically examine current data bases to determine whether the data elements currently listed in each data base are in fact being collected, and are actually useful in light of the model requirements detailed in the previous chapters. Sophisticated models requiring detailed data that is not available except for very specific locales will indicate a need to either develop more appropriate models, or increase the data collection program to make the necessary data available. Models that require data that is not currently being collected will also require an investigation to determine if new models are required, or if increased data collection is the most effective solution to ensure that adequate models are being used without burdening agencies with extra data collection.

This chapter presents data bases that are currently available and being used. This presentation will not include all State agency data bases, but the more general data bases that have been used in current studies. Each data base will be presented to illustrate the breadth of data allowed for in the data base, and discussed as to suitability of data elements available. A critical review of each data base will be provided to address the suitability of data as to current model requirements.

CURRENT DATA BASES

The data bases investigated for this report include:

- HPMS.
- SHRP LTPP.
- COPES.
- FHWA Design.
- FHWA Rehabilitation.
- Texas CRCP.
- FMIS.

Each data base will be discussed and its data elements illustrated to demonstrate the extent of information available to judge the suitability of each data source in model development.

HPMS

The HPMS data base contains the following tables for data collection and storage:

- Type of surface summary.
- Concrete joint spacing.
- Load transfer devices.
- Structural number.
- Slab thickness.
- Type of base summary.
- Type of subgrade summary.
- Measured roughness.
- Overlay or pavement thickness.
- Type of improvement summary.
- Type of shoulder summary.

The Highway Performance Monitoring System Analytical Process is described in reference 56. This report demonstrates the sensitivity of the HPMS analytical process to selected sample section data elements and to minimum tolerable conditions (MTC) used in the analysis of collected data. It also clearly shows the data elements which are available.

The HPMS analytical process is a system of computer programs which analyze the data collected in the data base. These data are used to estimate highway needs over an analysis period. This study demonstrated the degree to which specific data affect the results of the analysis and the degree to which MTC's affect the needs and improvement estimated by the analysis.

The data elements used in this analysis are:

- Structure, either SN or D.
- Pavement condition.
- Pavement deterioration rate.

Figure 9 graphically illustrates the sensitivity of the HPMS analytical process to the selected data elements. It shows the ratio of the magnitude of the percent change in the item analyzed. The items analyzed were placed into three basic categories based on their effects on the model:

1. These items have a one-time effect in the analysis period. They generate immediate needs which, when once corrected, no longer generate additional needs, and include:
    - Lane width.
    - Right shoulder width.
    - Left shoulder width.
    - Widening feasibility.

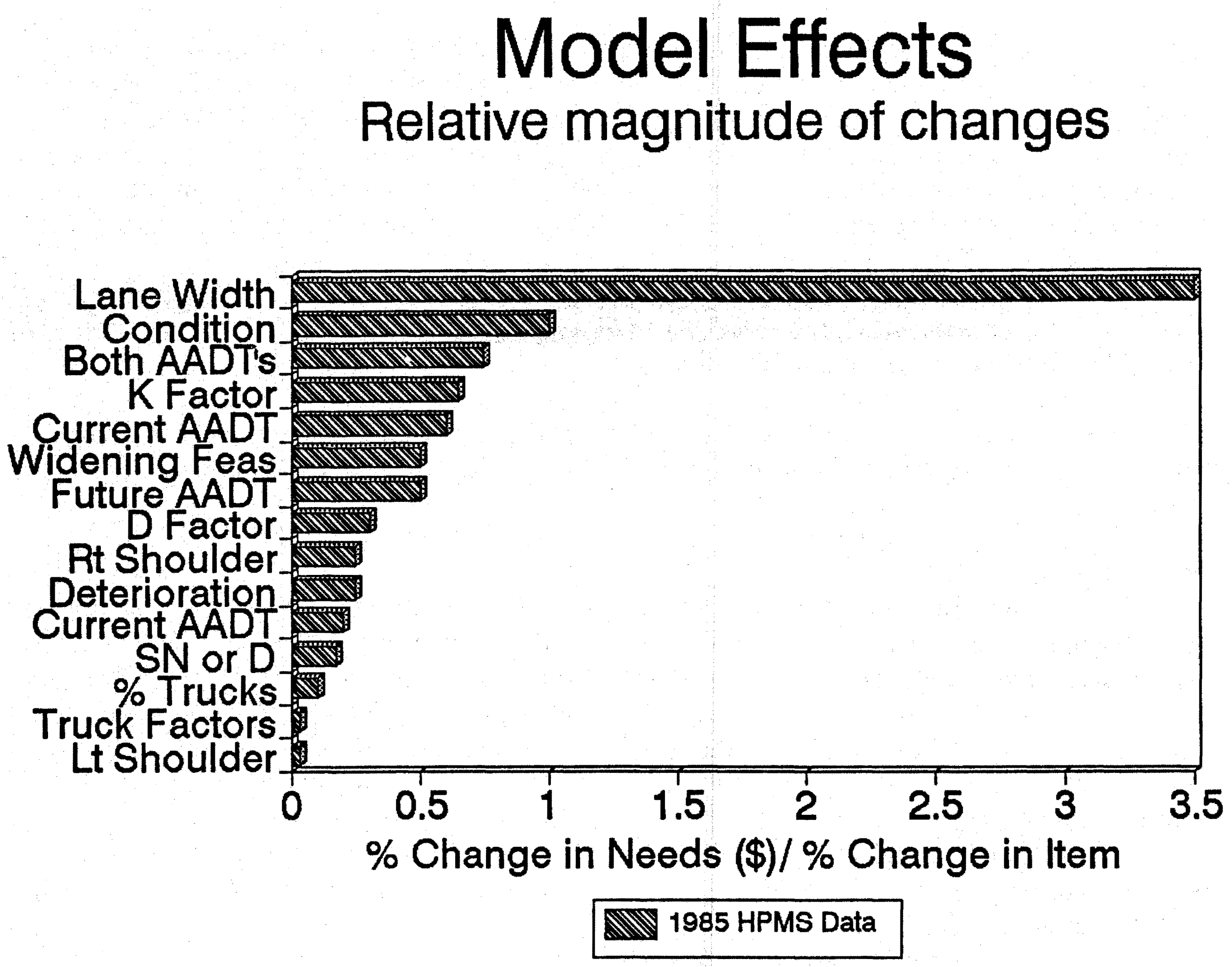


Figure 9. Sensitivity of the HPMS analytical process to the selected data element.

2. These items affect capacity continuously throughout the analysis period:

- Combination of both current and future AADT.
- k factor.
- Future AADT.
- Directional factor.
- Current AADT.

3. These items affect the pavement continuously throughout the analysis period:

- Pavement condition.
- Pavement deterioration rate.
- SN or D.
- Relative truck growth.
- Percent trucks.
- Truck ESAL factors.

The data in category 1 generally had the greatest effect on needs generated by the process, but the influence of these items would decrease over a longer period of time. The items in category 2 had more influence on needs than did those in category 3. This is due to the higher cost of capacity related improvements generated by items in category 2 compared to resurfacing related improvements generated by those in category 3. Generally for the traffic related items in category 2, the effects of changes were greater in urban areas than in rural areas.

Sensitivity to Minimum Tolerable Conditions (MTC)

The sensitivity of changes to the MTC can be divided into two categories of MTC's, major and minor. The major MTC's identify specific deficiencies resulting in additional improvements:

- Operating speed.
- Volume/capacity ratio.
- Lane width.
- Pavement condition.

The Minor MTC's resulted in a different type of improvement:

- Shoulder type.
- Right shoulder width.
- Surface type.
- Horizontal alignment.
- Vertical alignment.

The sensitivity of the results of the analytical process to the MTC's is discussed in terms of needs (costs of improvements), because they showed greater change than miles of improvements. Figure 10 shows the sensitivity of the needs to changes in the major MTC's of approximately 10 percent. In the rural analysis the largest changes were the result of lane width and pavement condition. In the urban analysis, the largest changes were the results of increasing and decreasing the MTC's for pavement condition, lane width and volume/capacity ratio.

Figure 11 shows the sensitivity of the costs of improvements to changes in the minor MTC's by one category number or 2 ft (.61 m) for shoulder width. Moderate changes occurred when the quality of vertical and horizontal alignment (rural areas only) and rural shoulder type were increased. In the urban analysis, the largest changes were the results of decreasing the MTC for shoulder width.

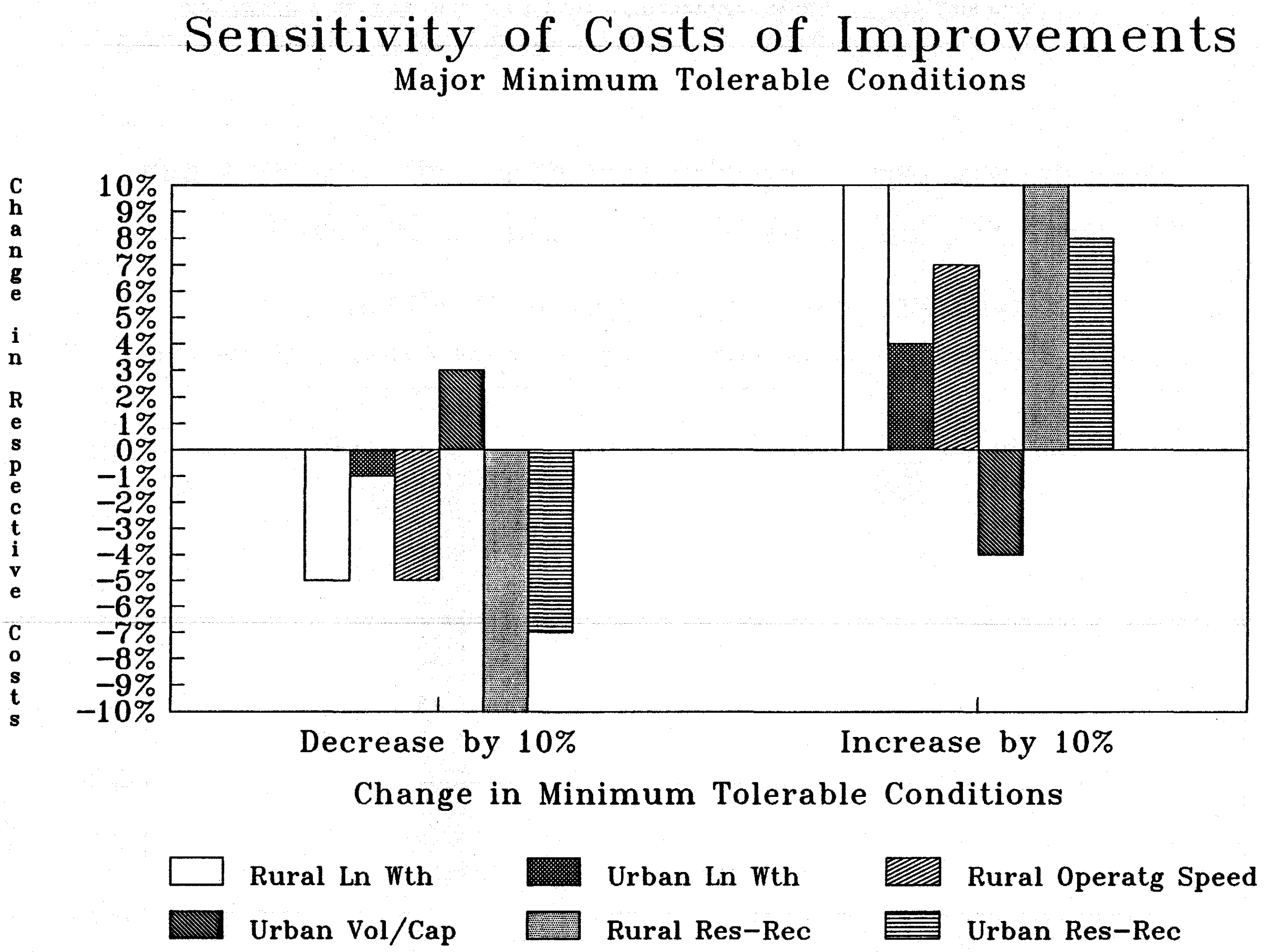


Figure 10. Sensitivity of the needs to changes in the major MTC's of approximately 10 percent, HPMS data base.

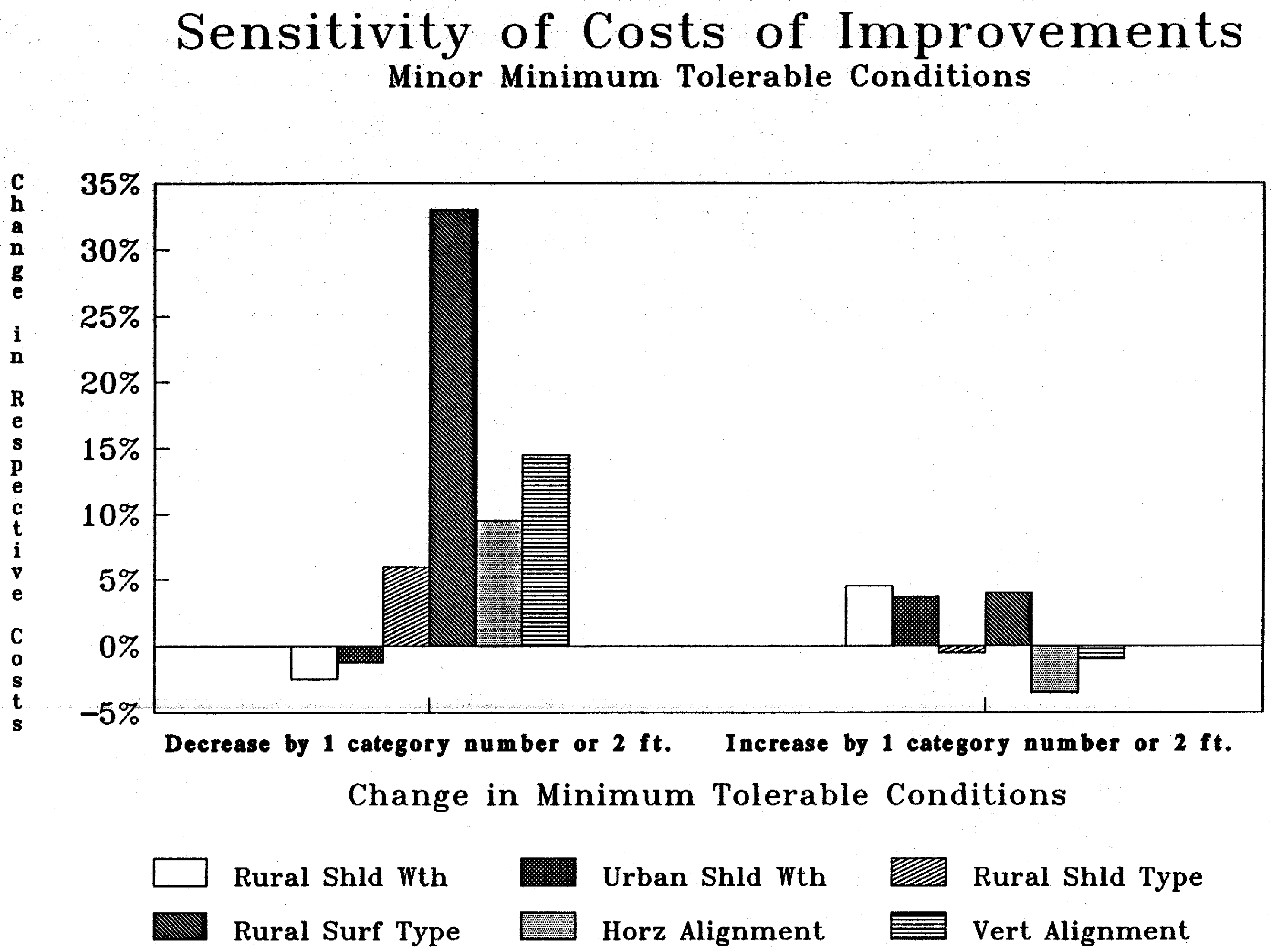


Figure 11. Sensitivity of the costs of improvements to changes in the minor MTC's by one category number or 2 ft (.61 m) from shoulder width, HPMS data base.

SHRP LTPP

The SHRP LTPP data base represents the most comprehensive data base to date. It is set up for both flexible and rigid pavements. It incorporates a section for general pavement studies (GPS), and special pavement studies (SPS). There are over 117 data elements included for each pavement. The general data elements are included on individual sheets and include the following:

- Project and section identification.
- Geometric, shoulder and drainage information.
- Layer descriptions for all layers.
- Age and major improvements.
- Portland cement concrete joint data.
- Portland cement concrete reinforcing steel data.
- Portland cement concrete mixture data.
- Portland cement concrete strength data.
- Plant mix aggregate properties.
- Plant mix asphalt cement properties.
- Original asphalt cement properties.
- Laboratory-aged asphalt cement properties.
- Original mixture properties.
- Plant mix asphalt bound layer construction data.
- Base/subbase material data.
- Subgrade data.
- Deflection data.
- Environmental data.
- Stiffness values for all layers including subgrade.
- Complete distress survey data.

There are many individual data elements that are entered in conjunction with the general data requirements of each sheet listed here which make up the over 117 elements required for a complete description. The data base has been structured to contain pavement sections from throughout the United States with a statistical significance that will allow for model development for new pavement design and for maintenance effectiveness.

The data elements and measurement techniques specified for the SHRP LTPP data base are very similar to the data elements in the COPES data base which will be described in a subsequent section. This data collection procedure is very comprehensive. The data base is presently receiving its first data elements, and little or no information is available to date. It represents the best of all existing data bases as it is derived from the work performed on COPES and the FHWA Design and Rehabilitation data bases. It will contain data on flexible and rigid pavements. It also will include new design, maintenance sections, and rehabilitation. The data will include material tests and deflection data to present the most detailed set of data available when it is completed.

COPES Data Base

The COPES data base was established from a nationwide survey of jointed concrete pavements, with the goal of establishing field performance criteria that could be used to evaluate the design and performance of concrete pavements in the field.(57,58) This is a comprehensive data base containing design and performance (distress) data from all climatic regions in the United States. The data has been used to formulate performance prediction regression equations which predict the deterioration of the original pavement in each climatic region. The following data are present in the data base:

Climatic Data

•	FTCYCLE	Average number of annual freeze-thaw cycles at the pavement site.
•	TEMDIF	The difference between the highest average monthly temperature and the lowest average monthly temperature, °C.
•	DMOIST	Thornthwaite moisture index (a positive value indicates excess moisture over the year).
•	SCTE	Summer concentration of thermal efficiency (higher values of SCTE means less winter potential evapotranspiration and more likely low temperature moisture damage).
•	ANNPPTN	Total average annual precipitation at the pavement site, cm., SUMPREC - ANNPPTN.

Drainage Data

•	DRAIN	0, if underdrains are present 1, if no underdrains are present.
•	PPTN	0, if no longitudinal underdrains 1, if longitudinal underdrains are present.

Traffic Data

•	ESAL	Cumulative 18-kip (80 kN) equivalent single axle loads, millions.

Slab Data

•	AGE	Age of pavement since construction, years.
•	H	Slab thickness, in.
•	L	Joint spacing, ft.
•	ASTEEL	Area of longitudinal reinforcing steel, in^2/ft width of lane.
•	RATIO	MR/STRESS.
•	MR	Modulus of rupture of the concrete slab, (lbf/in^2)
•	STRESS	Westergaards edge stress computed from a 9000-lb (4087-kg) wheel load placed at the outer edge of the slab. STRESS is a function of slab thickness and the subgrade support (k).

Subbase Data

•	STAB	1, if stabilized subbase (asphalt or cement). 0, if granular subbase.
•	BASETYPE	0, if cement stabilized base. 1, if cement stabilized base, and = 1, if granular or bituminous stabilized base.

Subgrade Data

•	SOILCRS	Subgrade soil type 0 if fine-grained soil (A4 to A7) 1 if coarse-grained soil (A1 to A3).
•	CUT	0, if majority of the section is at grade or in fill 1, if majority of the section is in cut.
•	FILL	0, if majority of section is at grade or in cut 1, if majority of the section is in cut.
•	KVALUE	Effective modulus of subgrade reaction (measured at top of base), PI.

Joint Data

•	BSTRESS	Maximum bearing stress of the dowel bars as determined by Friberg's method for an 18 kip (80 kN) single axle load.
•	INCOMP	0, if incompressible materials are not visible in transverse joints 1, if incompressible materials are visible in transverse joints.
•	JLTS	Joint load transfer system type, = 0 if star lugs exist, and, = 1 if dowel bars exist.
•	UNITUBE	0, if no unitube inserts were used, and = 1, if unitube inserts were used.
•	SKEWNESS	Skewness of joints, ft/lane.

Shoulder Data

•	EDGESUP	1, if tied PCC shoulder, or = 0, if AC shoulder.

Distress Data

•	*PUMP	severity of pumping visible on the pavement surface 0, if no pumping, 1, if low severity, 2, if medium severity, and 3, if high severity.
•	FAULT	average transverse joint faulting, in.
•	*DETER	number of deteriorated joints/mi.
•	*CRACKS	linear ft of deteriorated cracks/mi.
•	*TC	Transverse cracks of medium or high severity, no/mi.
•	DCRACK	0, if no "D" cracking and = 1, if "D" cracking is present.

•	JTSEAL	Transverse joints seal damage, = 0, if none or low severity and, = 1 if medium or high severity.

NOTICE: (*) This mark indicates that PUMP, FAULT, DETER, CRACKS, AND TC models are computed from the given data.

Serviceability Data

- *PSI Present Serviceability Index.
- *PSR Present Serviceability Rating.

NOTICE: (*) This mark indicates that PSI and PSR models are computed from the other given data.

Design Data - COPES

Project and Uniform Section Identification

- Type of highway.
- Number of uniform section in project.
- Number of lanes in uniform section.
- Type of original concrete slab.

Environmental Data

- Average monthly temperature, °C.
- Average maximum daily temperature, °C.
- Average minimum daily temperature, °C.
- Average monthly precipitation, cm of water.
- Latitude (Degrees).
- Freezing Index [32 °F (0 °C) - CE Method].
- Average number of annual freeze - thaw cycles.
- Elevation (ft above sea level).
- Average annual deicing salt ($CaCL_2$) application (ton/lane mile/year).

Slab Structural Design

- Slab thickness, in.
- Lane width, ft.
- Date slab construction completed, month/year.
- Date opened to traffic, month/year.

Joint Data

- Average contraction joint spacing, ft.
- Built-in expansion joint spacing, ft.

- Skewness of joint in ft/lane.
- Transverse contradiction joint load - transfer system (dowels, no mechanical load transfer device, other).
- Dowel dia, in.
- Dowel spacing, in.
- Dowel length, in.
- Dowel coating.
- Method used to install dowels.
- Method used to form transverse joints (sawed, plastic inserts, metal inserts).
- Joint sealant type used in transverse joints (as built).
- Transverse joint sealant reservoir (as built).
- Type of longitudinal joint (between lanes).
- Tie bar dia, in.
- Tie bar length, in.
- Tie bar spacing, in.
- Type of shoulder - traffic lane joint.
- Shoulder-traffic lane joint tie bar diameter in inches (for concrete shoulder).
- Shoulder-traffic lane joint tie bar length in inches (for concrete shoulder).
- Shoulder-traffic lane joint tie bar spacing in inches (for concrete shoulder).

Reinforcing Steel Data

- Type of reinforcing.
- Transverse bar dia, in.
- Transverse bar spacing, in.
- Longitudinal bar dia, in.
- Longitudinal bar spacing, in.
- Yield strength of reinforcing, ksi.
- Depth to reinforcement from slab surface, in.
- Method used to place rebar.
- Length of steel lap at construction joint, in (CRCP only).

Concrete Data

- Mix design (#1 yd^3).
- Strength (28-day modulus of rupture based on 3rd point loading) (lbf/in^2)
- Slump, in.
- Type cement used.
- Alkali content of cement, percent.
- Entrained air, percent.
- Additives other than air - entrainers.
- Maximum size of coarse aggregate, in.
- Type of coarse aggregate.
- Source of coarse aggregate.
- Type of fine aggregate.
- Source of fine aggregate.
- Type of aggregate durability test used.

- Result of durability test in the previous item.
- Type of paver used.
- Method used to cure concrete.
- Method used to finish concrete.
- Geologic classification of coarse crushed stone concrete aggregate.

Base Data

- Type of base.
- Stabilized base layer thickness, in.
- Type strength test used for stabilized base layer.
- Result of strength test in the previous item.
- Percent material passing no. 200 sieve (for granular base only).
- Nonstabilized (granular) base layer thickness, in.
- Type strength test used for nonstabilized base layer thickness.
- Result of strength test in the previous item.

Subgrade Data

- AASHTO soil classification.
- Strength test used on subgrade.
- Test result from the previous item.
- Test used to predict swell potential.
- Test value from the previous item.
- Test used to predict frost susceptibility.
- Test value from the previous item.
- Optimum laboratory dry density, (lbf/in^2).
- Optimum laboratory moisture content (percent).
- Test used to measure dry density.
- Mean measured dry density in situ (percent optimum).
- Mean measured moisture content in situ (percent optimum).
- Plasticity index.
- Liquid limit.

Shoulder Data

- Shoulder surface type.
- Shoulder base type.
- Shoulder width in ft.
- Shoulder surface thickness, in.
- Shoulder base thickness, in.

Drainage Data

- Subsurface drainage type.
- Dia of longitudinal drain pipes, in.
- Subsurface drainage location.

Roughness, Skid, and PSI Data - COPES

- Calculated PSI from roughness/distress measurements.
- Inspection date (day/month/year).
- Skid number (S.N.) (Wet).
- Inspection date (day/month/year) for S.N.
- Experiment used to measure S.N. (left and right lanes).
    - Trailer (locked wheel with ASTM E274 standard tire).
    - Mu meter.
    - Other.
- Roughness Index (R.I.).
- Inspection date (day/month/year) for R.I.
- Equipment used to measure R.I. (left and right lanes).
    - BPR Roughometer, in/mi.
    - May's Ride meter, in/mi.
    - PCA Roughometer, in^2/mi.
    - Profilograph, in/mi.
    - GM profilometer.
    - Other.

Axle Load Data - COPES

- Single axle load.
- Tandem axle load.
- Average no. of axles per truck (single and tandem).

Traffic Volume Data - COPES

- Year (year).
- One way ADT.
- One way ADTT.
- One way lane distribution (Trucks) = - left lane.
  - right lane.
- One way load distribution factor.

Maintenance Data - COPES

- Year (year).
- Maintenance sequence no. (MSEQ).
- Work type.
- Location on pavement.
- Maintenance material.
- Work quantity.
- Thickness, in.

Field Data - COPES
Construction Project Reference Data

- Construction project locations.
- Construction project length, mi.
- Highway no.
- Direction of survey.

Maintenance Material Types

- Preformed joint fillers.
- Hot-poured joint and crack sealer.
- Cold-poured joint and crack sealer.
- Portland cement concrete (JPCP).
- Portland cement concrete (JRCP).
- Portland cement concrete (CRCP).
- Portland cement concrete prestressed.
- Portland cement concrete fibrous.
- Asphalt concrete.
- Cold mix bituminous material.
- Sand asphalt.
- Surface treatment single layer.
- Surface treatment double layer.
- Surface treatment three or more layers.
- Sand seal.
- Slurry seal.
- Fog seal.
- Prime coat.
- Tack coat.
- Dust layering.
- Treated or stabilized materials.
- Cement grout.
- Aggregate (gravel, crushed stone or slag).
- Sand.
- Longitudinal drains.
- Transverse drains.
- Drainage blankets.
- Well system.
- Drainage blankets with longitudinal drains.
- Other.

Maintenance and Rehabilitation Work

- Crack sealing, ft.
- Transverse joint sealing, ft.
- Lane-shoulder longitudinal joint sealing, ft.
- Full depth transverse joint repair patch, ft^2.

- Full depth slab patching other than joint, ft^2.
- Slab replacement, ft^2.
- Longitudinal subdrainage, ft.
- Shoulder replacement, yd^2.
- Overlay, ft^2.
- Grinding surface, ft^2.
- Grooving surface, ft^2.
- Pothole repair, ft^2.
- Seal coat, yd^2.
- Pressure grout to fill voids (no. of holes).
- Slab tacking depressions (no. of depressions).
- Asphalt undersealing (no. of holes).
- Spreading of sand or aggregate, yd^2.
- Reconstruction (removal and replacement), yd^2.
- Other.

Test Types

- Resistance (R) Value.
- California Bearing Ratio (CBR).
- Unconfined compressive strength.
- Repetitive static place load test.
- Vane shear test.
- Triaxial compression test.
- Penetration test of concrete.
- Compressive strength of bituminous mix.
- Marshall stability test.
- Resistance of deformation and cohesion of bituminous materials - Hveem Apparatus.
- Resistance to plastic flow by means of the Hubbard-field apparatus.
- Dynamic modulus of asphalt mix.
- Penetration test of bituminous mixture.
- Flexural strength of concrete using beam with third-point loading.
- Splitting tensile strength.
- Compressive strength of concrete.
- Static modulus of elasticity.
- Resistance of concrete to freezing and thawing.
- Test for compressive strength of soil - cement.
- Test for flexural strength of soil - cement.
- Wetting and drying test of soil - cement.
- Freezing and thawing test of soil - cement.
- Fly ash and other pozzolans for use with lime.
- Determination of the strength of soil - lime - mix.
- Determining expansive soils and remedial actions.
- Soil - aggregate subbase, base and surface courses.
- Classification of soils and soil aggregate mixtures for highway construction purposes.
- Terms relating to subgrade, soil aggregate and fill materials.

- Potential volume change of cement aggregate combinations.
- Evaluation of frost resistance of coarse aggregate in air - entrained concrete by critical solution procedures.
- Other.

Base Types

- No base (slab placed directly on subgrade).
- Gravel (uncrushed).
- Crashed stone or gravel or slag.
- Sand.
- Soil aggregate (predominantly soil).
- Bituminous treated soil-aggregate.
- Bituminous aggregate mixture (plant mix).
- Asphalt concrete hot mix.
- Open graded asphalt treated.
- Thin asphalt concrete layer over granular material.
- Soil cement.
- Cement - aggregate mixture (gravel and crushed stone).
- Cement - aggregate mixture over granular material.
- Lean concrete mixture.
- Recycled concrete mixture.
- Lime soil.
- Pozzolanic - aggregate mixture.
- Other.

Aggregate Durability Test Types

- Abrasion of stone and slag by use of the Deval machine.
- Abrasion of gravel by use of Deval machine.
- Specific gravity and absorption of fine aggregate.
- Specific gravity and absorption of coarse aggregate.
- Resistance to abrasion of small size coarse aggregate by use of Los Angeles Machine.
- Soundness of aggregates by freezing and thawing.
- Soundness of aggregates by use of sodium sulfate or magnesium sulfate.
- Resistance to abrasion of large size by use of Los Angeles machine.
- Potential volume change of cement - aggregate combinations.
- Scratch Hardness of coarse aggregate particles.
- Evaluation of frost resistance of coarse aggregates in air-entrained concrete
- Critical dilution procedures.
- Concrete aggregates.
- Potential alkali reactivity of cement aggregate combinations.
- Potential reactivity of aggregates.
- Test for clay lumps and friable particles in aggregates.
- Recommended practice for petrographic examination of aggregates for concrete.

Cement Additives

- Retarding admixture.
- Water-reducing admixture.
- Accelerating admixture.
- Fly ash.
- Coloring admixtures.
- Dampproofing agents.
- Water-reducing and retarding admixture.
- Water-reducing and accelerating admixture.
- Others.

Enclosed are the distress types included in COPES field data collection, "Distresses":

Jointed Plain Concrete and Jointed Reinforced Concrete

- Blow up.
- Corner break.
- Depression.
- "D" cracking.
- Faulting - Transverse Joints and cracks.
- Joint load transfer deterioration.
- Joint seal damage.
- Lane/shoulder dropoff.
- Lane/shoulder joint separation.
- Longitudinal cracking.
- Longitudinal joint faulting.
- Patch deterioration - including replaced slabs.
- Patch adjacent slab deterioration.
- Popouts.
- Pumping and water bleeding.
- Reactive Aggregate distress.
- Scaling and map cracking.
- Spalling (joint crack).
- Spalling (corner).
- Swell.
- Transverse and diagonal cracks.

Continuously Reinforced Concrete

- Asphalt patch deterioration.
- Blow up.
- Concrete patch deterioration.
- Construction joint deterioration.
- Depression.
- "D" cracking.
- Edge punchout.

- Lane/shoulder dropoff.
- Lane/shoulder joint separation.
- Localized distress.
- Longitudinal cracks.
- Longitudinal joint faulting.
- Patch adjacent slab deterioration.
- Popouts.
- Pumping and water bleeding.
- Reactive aggregate distress.
- Scaling and map cracking.
- Spalling.
- Swell.
- Transverse cracking.

FHWA Design

The data included in this data base were collected as part of a nationwide survey of jointed concrete pavements to provide data to be used in an investigation of innovative design concepts for new and rehabilitated pavements.(59) The data collected was in several areas, including:

- Design and construction.
- Condition survey.
- Drainage survey.
- Field testing.
- Weigh-in-motion.

Projects were surveyed in Minnesota, Arizona, California, Michigan, New York, Pennsylvania, Ohio, New Jersey, North Carolina, Ontario, and Florida. Design features evaluated included slab thickness, base type, joint spacing, reinforcement design, joint orientation, transverse joint load transfer, dowel bar coatings, longitudinal joint design, transverse joint sealant, tied PCC shoulders/widened lanes, and subdrainage. Predictive equations for each item were prepared.

Each project was identified with a project name, year constructed, and a project identification. The first sequence of data were for the slab design data including:

- Slab thickness (design and core).
- Joint spacing.
- Percent steel.
- Skewed joint indicator.
- Load transfer dia and coating.
- Elastic modulus from deflection testing.
- Modulus of rupture from cores.

The next sequence deals with the granular materials in the base, subbase and subgrade, including:

- Base type.
- Thickness from design and core.
- Estimated permeability.
- Dynamic modulus of subgrade reaction, k_{eff}.
- Subbase type.
- Thickness from design and core.
- Estimated permeability.
- AASHTO classification of subgrade.
- Outer shoulder type.
- Surface thickness.
- Base thickness.

Detailed information was collected on the joints including:

- Calculated joint opening.
- Joint seal shape factor.
- Joint sealant type, age, and condition.
- Depth of longitudinal joint.

Outer lane deflection data was collected that included:

- High, low, and average middle slab deflection.
- Corner deflections.
- Load transfer efficiency.
- Load transfer across shoulder.
- Percent corners with voids.

Outer and inner lane performance data included:

- Average PSR, panel rating.
- Mays meter roughness, in/in.
- Faulting before grinding.
- Average faulting.
- Deteriorated transverse cracks per mi.
- Longitudinal cracking ft/mi.
- Pumping.
- Percent joints spalled.
- Materials durability distress.

Traffic information included the following:

- Original design traffic, $ESAL_s$ (millions), ADT.
- Age.

- Estimates at survey time, percent trucks, ADT.
- Inner and outer lane ESAL$_{18}$, 1987, and at survey date inner and outer lanes.

While primarily being directed toward refining the design of new concrete pavements, several rehabilitation projects were included. These data were used to develop performance equations for jointed concrete pavements following various rehabilitation strategies. In particular, the following rehabilitation strategies were included in the data base:

- Grinding.
- Saw and seal overlay.
- Crack and seat overlay.
- Concrete overlays.

This project also included a comprehensive evaluation of existing computer models that had potential use in describing the behavior of the pavements. The models evaluated include ILLI-SLAB, JSLAB, WESLIQUID, WESLAYER, H51ES, CRCP-2, JCS-1,RISC, CMS, BERM, and PMARP. These programs have the applicability in the mechanistic portion of the model development.

FHWA Rehabilitation

This project evaluated rehabilitation strategies for jointed concrete pavements with the goal of developing improved design procedures for the rehabilitation strategies.(60,61,62) Projects were surveyed throughout the United States to provide information on the following rehabilitation strategies:

- Bonded and unbonded concrete overlays.
- Crack and seat overlay.
- Grinding.
- Full-depth repair.

The elements in this data base are very similar to the COPES information. They are broken into general areas for each rehabilitation strategy evaluated. The rehabilitation areas include overlay, full-depth patching, crack and seat overlay. Each of these areas included collection data in the following:

- Project field.
- Traffic.
- Environmental variables.
- Pavement condition variables.
- Slab distress variables.
- Joint distress variables.
- Additional distress variables related to PCC repairs.
- Original pavement design and construction variables.
- Joints and reinforcing.
- Subgrade, shoulder and drainage.

- Full-depth repair design and construction variables (general, design. considerations, and construction considerations).
- PCC overlay variables (pre-overlay repair information).
- Crack and seat variables (distress in the asphalt overlay).

The data in this project were used to prepare sophisticated regression equations indicating the impact of various design variables on the performance of the rehabilitation. These performance equations were used in the program EXPEAR, an expert guidance program dealing with rehabilitation strategies and planning. The program assists the engineer in structuring an approach to analyzing the pavement and entering the data that has been collected, and provides predictions of distress developing in the pavement before and after application of the rehabilitation strategy. Cost data are used in the analysis.

Texas CRCP

This data base provides a comprehensive list of information on Texas CRCP.(63) The report includes details of data collection techniques, and it presents instructions for accessing the data, both in the form of "hands-on" examples for the casual user and as detailed information about the design and structure of the data base.

Contents of the CRCP Data Base

The data available in the Texas CRCP Data Base are:

- Structural capacity.
- Riding quality.
- Skid resistance.
- Distress manifestations.
- Information on environment.
- Traffic.
- Materials.

Condition Survey Data

(a) 1974 Condition Survey

The 1974 Condition Survey was made from a car traveling on the shoulder at 5 mi/h (8 km/h), over survey section 0.2 mi (.32 km) in length. The present serviceability index (PSR) was rated from a ride at 50 mi/h (80.5 km/h) in the right lane.

The data consists of:

- Transverse cracks: Estimated percent of pavement area with transverse cracks spaced at least 18 in (461.5 mm) from the neighboring cracks.
- Localized cracks: Estimated percent of pavement area with Y-shaped cracks that link two closely spaced neighboring cracks of the type described in (1).

- Spalling: Estimated percent of cracks with spalling, recorded separately for minor and severe spalling into four percentile categories: 1 to 5, 6 to 20, 21 to 50, and 51 to 100.
- Pumping: Estimated percent of section subject to pumping recorded separately for both minor and severe pumping into four percentile categories: 1 to 5, 6 to 20, 21 to 50, and 51 to 100.
- Punchouts: Estimated length of the road that is subject to minor and severe punchouts recorded into four length categories (in ft): 1 to 3, 4 to 9, 10 to 19, and 20 or greater.
- Patches: Estimated area of the road that has patches recorded separately for AC and portland cement concrete (PCC) patches for the following area categories (in ft^2): 1 to 15, 16 to 120, 121 to 240, and 241 and greater. The condition of the patch was not recorded.
- Shoulder Condition: Subjective description made by driver.
- PSR: Subjective rating of riding quality.

(b) 1978 Condition Survey

The 1978 Condition Survey was made from a car traveling on the shoulder at 5 mi/h (8 km/h). The data consists of:

- Transverse Crack Spacing: crack spacing measured in one (1) 300 ft (91.4m) sample of the road per project.
- Spalling: number of spalled cracks.
- Pumping: the criterion is identical to that for 1974.
- Punchouts: number of punchouts, punchouts shorter than 20 ft (6 m) and longer than 20 ft (6 m).
- Patches: number of patches (AC and PCC separately).

The following formula is used to convert 1974/1978 spalling data to percentage of spalled cracks:

$$PSPL + (NSPL) * CSPC) / 1056 \tag{53}$$

where:

PSPL = percent spalling in a 0.2-mi (.32-km) section.
NSPL = number of spalled cracks in a 0.2-mi (.32-km) section.
CSPC = mean crack spacing for the project.

(c) 1980 Condition Survey

The 1980 Condition Survey was made from a car traveling on the shoulder at 5 mi/h (8 km/h). The data consists of:

- Spalling.
- Number of cracks.
- Pumping: a yes/no occurrence without distinction between minor and severe pumping.
- Punchouts: number of punchouts.
- Patches: number of patches.

(d) 1982 Condition Survey

The 1982 survey used the 1980 procedure.

(e) 1984 Condition Survey

The 1984 Condition Survey was made from a car traveling on the shoulder at 15 mi/h (24 km/h), instead of at 5 mi/h (8 km/h). The length of the survey sections was increased to 0.4 mi (.64 km). The data consists of:

- Spalling: number of severely spalled cracks or joints.
- Punchouts: number of severe punchouts.
- Patches: number of patches in the right-most lane counted separately for AC and PCC patches.

(f) 1987 Condition Survey

In the 1987 Condition Survey, the raters walked on the shoulder. For non-overlaid sections, the data consists of:

- Number of cracks: number of cracks counted on every 200-ft (61-m) survey subsection.
- Crack Spacing.
- Punchouts: number of punchouts.
- Patches: number and size of patches of each material (AC or PCC).

For the overlaid sections, the data consists of:

- Number of Cracks: number of reflected cracks.
- Crack spacing.
- Bond Failures: recorded for each 200-ft (61-m) subsection as a yes/no occurrence.
- Patches: identical to the data for the non-overlaid case.

For both overlaid and non-overlaid sections, the condition of the shoulder was also described by the raters.

(g) The Diagnostic Data

In the summer of 1988, a survey was conducted to collect data for structural evaluation, instead of distress data. This survey was termed a "diagnostic survey," which consisted of:

- Deflections, research with the FWD.
- Crack width, measured with a microscope.
- Pavement temperature.
- Rut depth, in some districts.

(h) Data from Sources Other than Field Survey

Examples for this type of data are traffic, rainfall and pavement thickness. The following non-diagnostic variables have also been included in the data base:

- Drainage coefficients.
- Traffic data.
- Design criteria: slab thickness, subbase type, coarse aggregate type, subgrade grading type.
- Environmental Data: average annual rainfall, average lowest annual temperature.
- Road bed soil type: This type of data is recorded as a binary variable (yes/no) which stands for the presence (Y) or absence (N) of swelling characteristics.
- Pavement age.

PURPOSE OF DATA BASE

The purpose of a data base is to establish a repository of information that will have use at some time in an analysis of a pavement. To date, the majority of data base usage has been in a network level management scheme where the performance over time is monitored in a rough manner to provide budgetary information for planning. The use of a data base for project level evaluations becomes much more detailed, requiring the development of models from the data base. Historically, these models have been limited to the limits of pavements surveyed. These physical, climatic, and performance limitations meant that the models did not have true nationwide implications. Additionally, the data base itself quite often did not contain the significant variables for a particular model which an expert researcher might deem highly related to the development of the dependent variable, typically distress.

Because of these limitations, a majority of data bases in service today do not contain the necessary information to be able to support development of numerous models, but may be limited to investigation of only models similar to the ones previously developed from the data base. The potential for developing new models requires the postulation of model forms and contents which can then be compared with the contents of each data base on an individual basis. A discussion of this will be presented in the next chapter.

SUMMARY

The data bases presented here represent the nationwide availability of data relative to pavement performance, and performance of different rehabilitation strategies. While individual State data bases may provide much more specific information relative to developing models for an individual State, they will not provide general data relative to the conceptual development of generalized models. It is foreseeable that, in the future, individual State data collection efforts would be revised to include specific elements deemed appropriate by this study.

CHAPTER 4 DATA BASE REVIEW

The purpose of a data base is to provide the data elements that are significant in describing the performance of the pavements from which the data has been collected. If the data have been collected in sufficient quantity and it covers the appropriate variables of the pavement, the data can be used to accurately predict the performance of numerous pavements. The purpose of this project is to develop concepts for new or improved models. To do this, it is necessary to ascertain the suitability of existing data bases for use in developing new models and/or improving existing models that may have applicability to rehabilitation. To accomplish this, the data bases containing the pavement performance information must relate specifically to rehabilitation. In the past, most data bases have been prepared from one of two general directions. First, they have been formulated in a very general manner to maintain a wide-ranging set of information that provides a general view of the pavement, and focus primarily on expenditures for the pavement system, and for management purposes not requiring a detailed description of the pavement's performance. The second approach has dealt with the assemblage of detailed data bases collecting a significant amount of precise data describing design, construction, and performance of the pavement structure, with the resultant use of this data being the investigation of design elements in the pavements being studied. These two approaches are clearly seen in the data bases described in the previous chapter. To be effective in evaluating maintenance and rehabilitation, the data base must contain elements pertinent to the rehabilitation techniques being evaluated. These elements are contained in the models presented in chapter 2. If these existing data bases are to be useful in investigating the potential for developing new models, elements which may be required for the development of new models, or the improvement of existing, must also be present. If data is not available, there must be some justification for any recommendation for collecting new data.

This chapter will discuss the suitability of current data bases to support investigations for the improvement of the existing models discussed in chapter 2. A discussion of these data bases and their ability to provide relevant data for models will be discussed. The models described previously can be broken into the two general areas for data bases discussed here, namely new pavements and rehabilitated pavements.

The performance and deterioration models presented earlier have differing levels of importance in pavement modeling. They also have differing levels of acceptability for future developments and refinements. Both of these items relate directly to the availability of data required to operate the particular model being investigated. Improvements to existing models, or development of completely new models, is also highly dependent on the data available, and the quality of that data.

The acceptability, or lack thereof, arises from the models' requirements of data elements for the predictions. The two major types of data that were recognized in the model evaluation include inventory data and monitoring data, as explained in chapter 3. The data bases presented previously contain these data elements to a different extent. The extent of data present in each data base relates directly to the intended use of the data base at the time the models were developed. The lack of material test properties or deflection data indicate that the developers of a particular data base did not deem the particular data as relevant to the models, or the funding did not allow for collection of that particular data element. This specificity of each data base makes its use for general development of newer, more general damage models problematic and limits the use of a data base for development without compromising the validity of the existing models.

DATA BASE EVALUATION CRITERIA

The suitability of any data base is indicated by the number of critical variables that are contained within the data base. Critical variables are those that are required for a particular model or form of model that have a significant impact on the performance being predicted by that model. An example of this has been done for the GPS-1 experiment of the SHRP LTPP data base. While for new design performance, it indicates what will be required for the development of rehabilitation models and data base evaluation. In this study, several researchers rated the significance of every variable in the data base relative to the distress that would be modeled. Alligator cracking, for example, produced the following results:

- 38 data elements would be significant to predicting alligator cracking.
- 13 data elements were significant, but will not be available in sufficient numbers to be used in the predictive model.
- 6 variables with correlations to other variables were not included in analysis.
- 2 deflection data elements are not to be used.
- 17 data elements remained for use in the analysis (38-13-6-2).
- 11 unavailable data elements could be correlated with other variables for possible use.

Thus, for alligator cracking, 17 elements could be used, whereas the researchers felt that some 38 would correlate or influence the development of alligator cracking. Large discrepancies between important data elements and collected data elements could indicate areas where the predicted models developed may allow for significant improvement.

Table 14 illustrates the variables deemed important for alligator cracking. Many of these variables would also be deemed important for model development for rehabilitation, such as an asphalt concrete overlay which would be subject to alligator cracking under traffic. The overlay would require even more data relevant to the properties of the existing pavement at the time of overlay placement, any remaining life in the old pavement, stiffness values, etc. Project level models will be much more specific than the models for new pavements, which relate more to network level analysis.

Table 14. Variables deemed important for alligator cracking.

A. C. Surface Thickness - Critical Lab Value
Unbound Base Thickness - Critical Lab Value
Unbound Subbase Thickness - Critical Lab Value
Surface Stiffness - Critical Lab Value
Unbound Base Stiffness - Critical Lab Value
Subbase Stiffness - Critical Lab Value
Subgrade Stiffness - Critical Lab Value
Age of Pavement - Critical Inventory Value
Cumulative 18-kip (80-kN) ESAL - Critical Traffic Value
Gradation of Combined Aggregates - Critical Lab Value
Original Asphalt Cement Viscosity - Important, Correlated
Asphalt Content - Critical Lab Value
Percent Air Voids - Critical Lab and Inventory
Asphalt Concrete Percent Compaction - Unavailable
No. Days Max. Temp. Above 90 °F (32 ^{0}C)- Monitoring Environmental
No. Days Min. Temp. Below 32 °F (0 ^{0}C)- Environmental Correlated
No. of Freeze-Thaw Cycles/Year - Environmental Correlated
Asphalt Grade - Important, Correlated
Viscosity - Important, Correlated
Penetration - Important, Correlated
Type of Asphalt Modifiers - Critical Inventory
Quantity of Asphalt Modifiers - Critical Inventory
Aged Viscosity - Unavailable
Aged Penetration - Unavailable
Marshall Stability - Blows- Important Correlated
Marshall Stability - Flow - Important Correlated
Lay Down Temperature - Unavailable
Percent Compaction - AC - Unavailable
CBR - Base - Important Correlated
R Value - Base - Important Correlated
CBR - Subgrade - Unavailable
R Value - Subgrade - Unavailable
Measured Deflections - Critical Monitoring data
Depth to Rigid Layer - Available at mid point of Test Section
Type of Environment - Critical Environmental
Monthly Average Temp. - Critical Correlated
Average Max. Daily by Month - Critical Correlated
Average Min. Daily by Month - Critical Correlated

It is difficult, if not impossible, to evaluate a data base for models that have not been developed. At best, only approximations can be made when using carefully structured experimental plans to formulate the data base. Models requiring more variables may be less effective when applied to any particular data base. The data elements required for current prediction models are included in chapter 5 of this report.

EXISTING DATA BASES

A discussion of these data bases and their suitability to provide relevant data for models is discussed in this section.

HPMS

The HPMS data base contains the most general data of all sets. This data is useful for the more general models which do not require detailed distress information. General roughness and ride data are available and represent a broad category of pavements throughout the United States. For this reason, the data in the HPMS is useful for validation of models and extending their applicability through inclusion of data from a wide variety of climates.

COPES

The COPES data base represents the first attempt at collecting data that would be useful in validating the design parameters of a jointed concrete pavement, and the data base has been put to this task in FHWA projects. The data in this data base remains useful today even though it is becoming outdated. It contains sufficient distress data to be useful in expanding models and updating their formats. The data base is lacking in structural modeling of the pavements, which will limit its usefulness with the mechanistic procedures required to extend the range of existing models.

FHWA Rehabilitation and Design

These data bases contain the most current data available, relevant to concrete pavement performance, design, and select rehabilitation strategies. The information covers design, traffic, performance, and structural behavior. They contain data most applicable to the broadest number of different models presented in chapter 2, and provide a high level of potential for application on models other than those specifically developed with these data bases. These, like the COPES data base, are somewhat limited in pavement type and location, and do not reflect new designs which may be constructed today, such as the Illinois hinged joint concrete pavement. The predictions for these pavements cannot be made with these data bases. The rehabilitation strategies, even though very thoroughly investigated, are somewhat limited and do not include maintenance activities.

Texas CRCP

This data base represents the only available information on CRCP performance. It is very limited in that it only included pavements in Texas. This limits the climate and soil types which are critical for CRCP performance. The usefulness of some information may be limited because of the different survey procedures used in different years.

SHRP LTPP

The SHRP LTPP data base represents the most comprehensive collection of data as represented by these data bases. It includes specific data elements related to portland cement concrete and asphalt concrete newly constructed pavements, and specific maintenance procedures. The collection procedure ensures accurate field distress data, complete inventory data, monitoring data, environmental data, traffic and truck data, and material properties. The data elements represent the most complete set of data for the widest possible number of pavement types, and will provide data similar to those contained in the other data bases discussed here. This data base provides an excellent supplement to the others for the development of new models. The other data bases would be limited insofar as the pavement types, but would allow the models to be examined and evaluated for acceptability and indication of different elements which may be required.

SUMMARY

The models presented in this report were all derived from specific data sources or from a mechanistic based analysis of a pavement system. The data in the data bases presented here is sufficiently detailed to provide a base for further analysis of the models to validate their applicability under many different conditions, and to propose modifications to the existing models which could extend their usefulness.

Not all data bases will be directly applicable for all models, but the information that is available is suitable to use in validating the forms of new models for the same pavements and forming a base for expansion of capabilities of the existing models, should potential model forms investigated in the next phase of this project indicate this can be done.

A lack of information is currently evident for specific distresses in the flexible pavements. This comes from the difficulty in obtaining meaningful material properties. The useful distress models prepared from data bases to date have dealt primarily with concrete pavements with the flexible pavement data being most often used in developing composite models. Because of the inability to develop realistic distress models, the development of data bases for flexible pavements has not been pursued to the same degree as concrete pavement data bases. The SHRP LTPP data base program will provide flexible data of sufficient quality to overcome this shortcoming, but this data will not be available for some time. At present there are no data bases that can be used to model flexible pavement performance, and the mechanistic procedures for rutting and fatigue appear to represent the best compromise in modifying the performance models and extending the usefulness of existing data.

There is no reason to consider any of the data bases incapable of being used to evaluate new model forms. The contents of the data base will provide more or less quality in the models, depending on the precise contents. The final quality of the model may not be desirable for a predictive model, but may be perfectly acceptable from the standpoint of demonstrating the applicability of a particular new form of model. A more complete data base would be desirable to substantiate the overall predictive validity of the model with more general applicability, but for the purpose of this project, which is to investigate model forms, the data bases here are adequate.

CHAPTER 5 DATA ELEMENTS IN PREDICTION MODELS

Prediction models have differing levels of importance in pavement management. They also have differing levels of acceptability for future developments and refinements. Both of these items relate directly to the availability of data required to operate the particular model being investigated. Improvements to existing models, or development of completely new models are also highly dependent on the data available and the quality of that data.

The SHRP-LTPP data base was chosen as it was sufficiently detailed to provide a base for further analysis of the models to validate their applicability under many different conditions, and to propose modifications to the existing models which could extend their usefulness.

The SHRP Pavement Maintenance Effectiveness Program (Contract H-101) and the Pavement Maintenance Field Data collection (Contract H-102) studies were required to provide the data base for model development. It is important to clarify that these contracts are not completed yet. However, some of the preliminary results on data collection, draft reports, and technical memorandums were obtained from the parties involved in these contracts.

The SHRP H-101 Contract is assessing the effectiveness of six specific preventive maintenance treatments by testing them on inservice State highways. Treatments for both asphalt and concrete pavements are being evaluated. For asphalt (flexible) pavements, the project is assessing chip seals, thin overlays, slurry seals, and crack sealing. For concrete (rigid) pavements, joint and crack sealing, and undersealing are being assessed. The effectiveness of a treatment is affected by how and when it is applied, climate, traffic and a number of other variables. The goal of SHRP H-101 Contract is to determine which treatment is best for use at a particular site, and how and when it should be applied.

The State agencies cooperated by providing more than 100 test sites to represent a range of traffic, environment (climate and soil), and pavement conditions. In most cases, the test sites are contiguous with the test sites for SHRP's LTPP, GPS program. The SHRP H-101 Contract is planned as part of the SHRP's SPS program (flexible pavements as SPS-3 experiments and rigid pavements as SPS-4 experiments). These test sections are being monitored using distress surveys (manual and photographic), profile measurements, and structural evaluation with the falling weight deflectometer. The data are entered into the National Pavement Performance Data Base at the Transportation Research Board along with the data from the SHRP-LTPP experiments.

The Pavement Maintenance Field Data Collection (Contract H-102) is a project given to the SHRP's regional engineering contractors, to supervise the contractors that are used in SHRP's Long-Term Pavement Performance program in monitoring the test sections built for the Contract H-101. The SHRP Contract H-101 (Preventive Maintenance Cost-Effectiveness evaluation project) is not completed yet.

DATA ELEMENTS REQUIRED FOR CURRENT PREDICTION MODELS

The list of data elements required for the current prediction models has been prepared for the models presented in chapter 2. Table 15 summarizes the data elements involved in each model with required inputs and expected data collected by SHRP-LTPP. Sets of variables and discussions have been included, that were believed to be significant to the prediction models. Deficiencies of the SHRP-LTPP data base are noted where appropriate.

The data elements involved in each of these newer models, required inputs, and expected data collected by SHRP-LTPP, are also shown in table 15. This summary table cannot capture all of the aspects of the models, but it can serve as an excellent index when searching for a specific relationship. The following examples were extracted from table 15:

Example No. 1:

Group:	Roughness, emphasizing time related effects.
Prediction Model:	Arizona Study.
Required Input Basic:	Time and Initial Roughness.
Data Base Collected by SHRP LTPP GPS Program:	Pavement age and roughness.
Deficiencies:	It is difficult to find information on initial roughness.

Example No. 2:

Group:	Deflection Prediction Models/SAI.
Prediction Model:	Alberta DOT (SAI model for granular base pavements).
Required Input Basic:	Deflection measured by Benkelman beam and ESAL.
Data Base Collected by SHRP LTPP GPS Program:	ESAL.
Deficiencies:	Only Falling Weight Deflectometers are to be used for SHRP-LTPP GPS Program.

Table 15. List of data elements required for current prediction models.

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
For Roughness:					
Emphasizing Structural Effects:	AASHO Road Test	SN, ESAL's, Initial Roughness.	Initial roughness, ESAL, SN, Soil Support, mean rut depth, cracking, and patching.	Distress Survey, Traffic, Subgrade data, roughness.	Agencies other than SHRP will record calculated PSI from correlations between roughness and Present Serviceability Ratings.
Emphasizing Structural Effects:	TRRL Study (1975)	SN, ESAL's, Initial Roughness.	Modified SN, Layer Thickness, materials, drainage coeff., initial Roughness, ESAL.	Layer thickness, material properties, and Deflections, ESAL, Roughness.	It is difficult to find initial Roughness.
Emphasizing Time-related Effects:	Arizona Models	Time, Pavement Age, initial Roughness and environmental parameters.	Pavement age, initial roughness, environmental parameters such as rainfall, elevation, freeze-thaw, temperatures, etc.	Environmental data, pavement age, and roughness.	It is difficult to find initial Roughness.
	Arizona Study	Time, initial Roughness.	Time and initial roughness.	Pavement age and roughness.	It is difficult to find initial roughness.
	Australian, 1972	Pavement Age, and initial roughness.	Age and initial roughness.	Pavement age and roughness.	It is difficult to find initial Roughness.
Models with Interacting Effects:	Queiroz	Pavement Strength parameters, Traffic and initial roughness.	Cumulative number of 18-kip (80-kN) axle load, time and Initial Roughness.	Roughness index, ESAL and material properties.	
Models relying in Mechanistic Parameters:	Uzan and Lytton, 1982	Rut Depth, variance of rut depth, and distress.	Mean rut depth, cracking area, patching area and variance of rut depth.	Distress survey.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
Models Emphasizing Structure, Surface Condition and Time Effects:	Brazil-UNDP (IRI-World Bank)	Structural factors, Surface Distress and environment-age factors and traffic.	Pavement type, layer thickness, age, surface distress, traffic and environmental parameters.	All of the required inputs.	Only for Flexible pavements.
	Brazil-UNDP Study (from expanded data base)	Same as above but omitting the surface distress terms.	ESAL, modified SN, but omitting rut depth, patching and cracking. Age of pavement since overlay or construction.	All of the required inputs but modified SN.	
	Alberta's Riding Comfort Index	Previous Riding Comfort Index (RCI), and age of pavement.	Previous RCI and present age of the pavement.	Age of the pavement.	RCI is not collected by SHRP.
Structural Measures for Performance Prediction:					
Asphalt Concrete Fatigue	Asphalt Institute (TAI) MS-15	ESAL, AC dynamic modulus, Strain, Asphalt Characteristics.	ESAL for 20-years, Strain in the asphalt layer, % of AC and % of air voids.	All of the required inputs.	
	MICH-PAVE (non-linear finite element for flexible pavement, 1989)	Traffic, layer thickness, material properties, environmental conditions.	ESAL, surface deflections, layer thickness, resilient moduli, annual air temperature, kinematic viscosity, air voids of AC layer, stress and strain of the AC layer.	ESAL, material properties, environmental conditions, surface deflections, distress surveys, layer thickness.	Only for flexible pavements.

Table 15. List of data elements required for current prediction models (continued).

Group	***Prediction Model***	***Required Input Basic***	***Required Input Detailed***	***Database Collected by SHRP LTPP GPS Program***	***Deficiencies / Comments***
Deflection Prediction Models/Structural Adequacy Index (SAI)	Alberta DOT (SAI model for granular base pavements)	Deflection measured by Benkelman beam, ESAL.	Mean fall rebound deflection x 10^3 and Cumulative ESAL/10^5.	ESAL.	Only Falling Weight Deflectometers are to be used for SHRP-LTPP.
	VESYS (flexible design procedure designed by FHWA)	Material properties, Traffic, surface distress, and environmental variables.	Resilient Moduli, fatigue and permanent deformation, load distribution, duration and number of applied loads, mean temp. for AC layers, subgrade.	All of the required inputs.	
Distress Measure					
For Rigid Pavements:	COPES	See table 2 of Interim Report for detailed description of inputs.	Age, ESAL, environmental parameters, pavement type, layer thickness, joint load transfer, joint seal damage, material properties.	All of the required inputs.	Only rigid pavement distress models.

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
For Flexible Pavements:	HDM Models (World Bank)	Structural factors, traffic and environmental.	Pavement type, layer thickness, ESAL, environmental factors.	All of the required inputs.	
	Cost Allocation	Structural characteristics, environmental factors, traffic, subsoil characteristics, and pavement age.	Structural characteristics, environmental factors, traffic, subsoil characteristics, and pavement age.	All of the required parameters.	
	Rutting (Predicts strain in the AC layer under repeated traffic loading)	Traffic.	Strain, ESAL, layer stiffness and layer thickness.	All of the required inputs.	Only the AC layer is susceptible to fatigue in full depth AC or conventional AC/granular base.
	Rutting (Ohio State)	Traffic.	Same as above, and experimental constant depending on material type and state of stress conditions.	ESAL, material properties, layer thickness.	SHRP LTPP does not include experimental constant needed for this model.
Composite Indices:					
PSI Models	AASHO Model	Roughness, rut depth slope variance, cracking and patching.	ESAL, SN, Soil Support, mean rut depth, cracking and patching, slope variance.	All of the required inputs.	
	HPMS (FHWA Highway Performance Monitoring System)	SN and ESAL.	PSR as a function of the SN and ESAL.	Material properties, layer thicknesses and ESAL.	SHRP will not include PSR. It will calculate PSI from correlations between Roughness and PSR.
	PSI Model of State of Idaho	Traffic (ESAL).	ESAL.	ESAL.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
	State of Minnesota	PSR, Type of pavement and traffic volume.	PSR (PSI) predicted as a function of itself, PSR one year previous, pavement type and traffic volume.	Pavement type and traffic volume.	
	Sigmoidal Model (Texas Transportation Institute)	Traffic and site location.	Traffic and location of the site.	All of the required inputs.	
	PENNDOT Performance Prediction Model Performance Prediction Model	Age of the pavement.	Age of the pavement.	Age of the pavement.	
	State of Virginia	Traffic, pavement age, and distress.	Load and design variables; a composite distress index called maintenance raiding (DMR), and age of the pavement.	Age of the pavement, distress survey and traffic.	
	Iowa DOT For Rigid and Composite Pavements	Material Characteristics, ESAL, joint or reinforcement type.	Base type, aggregate durability, joint or reinforcement type, and ESAL.	Base type, aggregate durability, joint or reinforcement type, and ESAL.	
	State of Washington	Pavement age, ESAL, thickness of the overlay.	Pavement age, ESAL, thickness of the overlay.	All of the required inputs.	
	Mississippi PCR	Pavement age, ESAL, Modified SN.	Pavement age, traffic volume, thickness of surfacing, structural thickness.	All of the required inputs.	
	Alberta's PQI	PQI is a function of RCI, VCI and SAI.	Pavement age, traffic, soil type, and structural thickness.	All of the required inputs.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
	OPAC and PARS Models (Performance is predicted as a function of pavement age, traffic, and thickness of overlay)	Pavement characteristics, age, traffic, thickness of overlay, period of rehabilitation, PCI.	Pavement characteristics, age, traffic, thickness of overlay, period of rehabilitation, PCI.	All of the required inputs.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
Models for Rehabilitated Pavements					
	NCHRP Project 14-6	Pavement condition, structural factors, traffic.	Pavement condition, structural factors and traffic.	All of the required inputs.	
	1985 FHWA Study (Prediction models for alligator and wide cracking, raveling, potholes, roughness and rutting)	Pavement Characteristics, pavement history, traffic pavement condition, environment and geometry.	Pavement Characteristics, pavement history, traffic, pavement condition, environment and geometry.	All of the required inputs.	Only for flexible pavements.
	EAROMAR-2 System (Predictions of different categories of distress that are translated into PSI)	Route Characteristics, Travel demand, Pavement Characteristics, Environmental Conditions, Economic Data, M&R Polices, User consequences.	Structural, materials and drainage properties, construction and loading history, current surface condition, seasonal temperature, rainfall, freezing index, AASHTO regional factor, subgrade soil classification, inflation rates.	Material properties, traffic, environmental parameters, pavement type, layer thickness, distress survey.	
	PAVER Management System (Based on the rate of deterioration of pavement conditions, PCI, over short and long term periods)	PCI and age.	Age, pavement type, and surface distress.	All of the required inputs.	
	Indiana Study (Based on PSI-ESAL loss focus on pavement roughness)	Relationship between pavement performance and routine maintenance, pavement characteristic, effect of maintenance.	Modified index of pavement performance, PSI-ESAL loss,Climate and environmental influence on the effectiveness of pavement maintenance work.	ESAL, material properties, environmental, Roughness.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
	Arizona Overlay Design Procedure (based on deterioration models for roughness, fatigue and plastic deformation)	FWD deflections, structural data, traffic, environmental and cost of various items of work.	Roughness before overlay and after, limiting criteria for roughness, predicted change in roughness due to overlay, slope of roughness versus time relationship, tensile strain at the bottom of the AC layer due to standard wheel load and economic analysis parameters.	ESAL, material properties, roughness measurements, FWD deflections, environmental parameters.	
	Life-Cycle Cost Study (Distress modeled for flexible: Alligator crack, raveling and rutting; for rigid: pumping, faulting, cracking and deterioration of joint and crack sealants	Increase of PCI, maintenance relative level, effectiveness of routine maintenance, coefficients depending on pavement type, material properties, and local conditions.	Increase of the PCI due to any rehab. or reconstruction, PCI_t, PCI_0, PCI_{t-1}, PCI_{loss}, $PCI_{correct.\ by\ maint.}$, ESAL, age of the pavement, Structural capacity of the pavement, for flexibles: SN corrected for subgrade and environmental conditions, for rigids: slab thickness.	Layer thickness, environmental conditions, material properties, drainage, ESAL, distress surveys.	
	NAPCOM (Nationwide Pavement Cost Model, 1990)	Pavement Age, Traffic, environmental, surface type, structural capacity, serviceability.	18-kip (80-kN) calculated as VMT and LEF, functional class, surface type, structural number, initial serviceability at last construction/rehabilitation, cost, freezing index, temperature, precipitation, Thornthwaite index.	ESAL, material properties, environmental conditions, distress surveys, pavement age, layer thickness.	

Table 15. List of data elements required for current prediction models (continued).

Group	*Prediction Model*	*Required Input Basic*	*Required Input Detailed*	*Database Collected by SHRP LTPP GPS Program*	*Deficiencies / Comments*
	VESYS **(Only for flexible pavements, prediction models for Rutting, Fatigue cracking and Roughness)**	Material properties, traffic distribution, environmental variables.	•Resilient Moduli, fatigue and permanent deformation characteristics of AC layers. •Stress-Strain and permanent deformation parameters for unstabilized crushed stone subbase layers. •Resilient Moduli and permanent deformation of the subgrade. •Traffic distribution (load distribution amplitude and duration, number of applied load distribution. •Environmental variables (mean temperature of bituminous layers and the subgrade moisture content).	Material Properties, Traffic Distribution and Environmental variables.	
	EXPEAR **(For JRCP,JPCP, prediction models for Faulting, Cracking, Pumping, Joint deterioration, and for AC/PCC, Reflective cracking and Rutting)**	Basic design, construction, traffic, climatic data, and visual condition survey.	Structural adequacy, roughness, drainage, joint deterioration, foundation movement, loss transfer, loss of support, shoulder conditions.	All of the required inputs.	Only for JPCP, JRCP and CRCP. Programs for AC-overlaid pavements and other AC pavements are under development.

Table 16 (for flexible pavements) and table 17 (for rigid pavements) present a list of data elements required for current prediction models grouped by predicted distress and type of pavement. A "•" (dot) in a box indicates that the data element is available in SHRP-LTPP and used in current models.

The National Information Management System (NIMS) has 117 data elements for pavements with asphalt concrete surfaces, 128 data elements for jointed concrete pavements, and 120 data elements for continuously reinforced concrete pavements. Table 18 shows an example of the NIMS data elements for pavements with asphalt concrete surfaces. As it is clearly impractical to attempt to model pavement performance with so many independent variables, as well as hundreds of potential interactions, it was necessary to reduce the number of variables, in order to analyze performance prediction models and estimate the significance of independent variables to occurrence of specific distress. Dr. Brent Rauhut ("Early evaluation of the SHRP LTPP data and planning for sensitivity analyses," chapter 3) and several researchers rated the significance of every variable relative to distress that would be modeled. This reduction of data resulted in elements for alligator cracking, transverse cracking, rutting, roughness, friction loss and raveling and weathering for both AC and PCC.

The approach adopted by Dr. Rauhut for preliminary elimination of less significant variables was to obtain relative significance rankings from experts in pavement performance modeling. These selections required balancing relative significance, data availability, and correlations with other variables. Three levels of significance were considered. Assignments of the number "1" indicated that the rater considered the data element to be clearly significant to prediction of the distress of interest. Assignment of the number "2" indicated moderate significance, and the number "3" indicated little or no significance. The experts filled out the significance rating forms entering 1, 2, or 3 in each block representing a data element and a distress. When the significance rating forms were returned, the entries were averaged for each block to arrive at an average rating. If the average score for data element and distress combination was less than 2, that data element was considered to be significant for prediction of that distress. If the average score was exactly 2, these were retained in the significance studies in some cases, and not in others, on the basis of judgement. Data elements with scores greater than 2 were not considered further at this time.(64) This process considerably reduced the number of data elements to be dealt with. The significant data elements in the SHRP National Information Management System for pavements with asphalt concrete surfaces are shown in table 19, and for pavements with portland cement concrete surfaces are shown in table 20.

Table 16. Detailed data elements for current models grouped by predicted distress in asphalt concrete pavements.

● = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	Layer Thick.	Layer Stiff.	Age	Traffic, ESAL	Asphalt Layer Properties	Base / Subg. Properties	Moisture Content Subgrade	Subsurface Drainage Type	Type of Environment	Monthly Temp.	Freeze Index	Annual Precip.	Thornthwaite Index	Pre-Repair/ OL Distress
Roughness:														
AASHO Road Test	●	●	●	●	●		●	●	●					
TRRL Study	●	●	●	●	●									
Arizona Models			●						●					
Australian, 1972			●											
Queiroz	●	●		●	●	●								●
Uzan and Lytton, 1982														
Brazil-UNDP	●		●						●					●
Alberta's RCI			●											
VESYS	●	●		●	●	●	●	●	●	●	●	●	●	
FHWA Study	●	●		●	●	●			●					●
EAROMAR-2 System	●	●	●	●	●	●	●		●	●	●	●	●	
HDM Models (World Bank)	●		●	●					●					
NAPCOM	●	●	●			●			●	●	●	●	●	
Rutting:														
HDM Models (World Bank)	●		●	●					●					
Ohio State				●										
Cost Allocation	●	●	●	●		●			●					
NCHRP	●	●	●	●										
VESYS	●	●	●	●	●	●	●		●	●	●	●	●	

Table 16. Detailed data elements for current models grouped by predicted distress in asphalt concrete pavements (continued).

• = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	Layer Thick.	Layer Stiff.	Age	Traffic, ESAL	Asphalt Layer Properties	Base / Subg. Properties	Moisture Content Subgrade	Subsurface Drainage Type	Type of Environ-ment	Monthly Temp.	Freeze Index	Annual Precip.	Thornth-waite Index	Pre-Repair/ OL Distress
FHWA Study	•	•		•	•	•			•					•
LCC Study	•		•	•	•	•			•					•
MICH-PAVE	•	•		•	•	•				•				
NAPCOM	•	•	•			•			•	•	•	•	•	
EAROMAR-2 System	•	•	•	•	•	•	•		•	•	•	•	•	
Alligator (fatigue) Cracking:														
HDM (World Bank)	•		•	•					•					
FHWA Study	•	•		•	•	•			•					•
Asphalt Institute	•		•	•	•	•			•					
VESYS	•	•		•	•	•	•	•	•	•	•	•	•	
Cost Allocation	•	•	•	•		•			•					
EAROMAR	•	•	•	•	•	•	•		•	•	•	•	•	
NCHRP	•	•	•	•										
NAPCOM	•	•	•			•			•	•	•	•	•	
MICH-PAVE	•	•		•	•	•				•				
Arizona Models			•						•					
Potholing:														
HDM Models (WB)	•		•	•					•					
FHWA Study	•	•		•	•	•			•					•
EAROMAR-2 System	•	•	•	•	•	•	•		•	•	•	•	•	

Table 16. Detailed data elements for current models grouped by predicted distress in asphalt concrete pavements (continued).

• = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	Layer Thick.	Layer Stiff.	Age	Traffic, ESAL	Asphalt Layer Properties	Base / Subg. Properties	Moisture Content Subgrade	Subsurface Drainage Type	Type of Environment	Monthly Temp.	Freeze Index	Annual Precip.	Thornthwaite Index	Pre-Repair/ OL Distress
Raveling:														
FHWA Study	•	•		•	•	•			•					•
LCC Study	•		•	•	•	•			•					•
Skid Resistance:														
NAPCOM	•	•	•			•			•	•	•	•	•	
Shoulder Distress:														
EAROMAR-2 System	•	•	•	•	•	•	•		•	•	•	•	•	

Table 17. Detailed data elements for current models grouped by predicted distress in portland cement concrete pavements.

• = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	Layer Thick.	Layer Stiff.	Age	Traffic, ESAL	PCC Layer Properties	Base / Subg. Properties	Moisture Content Subgrade	Subsurface Drainage Type	Joint Effic.	Monthly Temp.	Shoulder Type	Annual Precip.	Air Freeze-Thaw Cycles	Pre-Repair Distress
Transverse Crack:														
COPES	•	•	•	•	•	•	•		•	•		•	•	•
LCC Study	•	•		•	•	•	•	•		•		•	•	•
EXPEAR	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Cost Allocation Study	•	•			•	•	•	•		•		•	•	
Joint Faulting:														
COPES	•	•	•	•	•	•	•		•	•		•	•	•
Cost Allocation Study	•	•			•	•	•	•		•		•	•	
EXPEAR	•	•	•	•	•	•	•	•	•	•	•	•	•	•
NAPCOM	•	•	•		•	•				•		•	•	
AASHTO	•	•	•	•	•		•	•		•		•	•	
EAROMAR	•			•	•	•		•		•		•	•	
LCC study	•	•		•	•	•	•	•		•		•	•	•
Pumping:														
Cost Allocation Study	•	•			•	•	•	•		•		•	•	
COPES	•	•	•	•	•	•	•		•	•		•	•	•
EAROMAR-2 System	•			•	•	•		•		•		•	•	
LCC Study	•	•		•	•	•	•	•		•		•	•	•
EXPEAR	•	•	•	•	•	•	•	•	•	•	•	•	•	•

Table 17. Detailed data elements for current models grouped by predicted distress in portland cement concrete pavements (continued).

• = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	Layer Thick.	Layer Stiff.	Age	Traffic, ESAL	PCC Layer Properties	Base / Subg. Properties	Moisture Content Subgrade	Subsurface Drainage Type	Joint Effic.	Monthly Temp.	Shoulder Type	Annual Precip.	Air Freeze-Thaw Cycles	Pre-Repair Distress
Joint Deterioration:														
COPES	•	•	•	•	•	•	•		•	•		•	•	•
Cost Allocation	•	•			•	•	•	•		•		•	•	•
Lineal Cracking:														
EAROMAR-2 System	•			•	•	•		•		•		•	•	
LCC Study	•	•		•	•	•	•	•		•		•	•	•
COPES	•	•	•	•	•	•	•		•	•		•	•	•
EXPEAR	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Spalling:														
EAROMAR-2 System	•			•	•	•		•		•		•	•	
Blowups:														
EAROMAR-2 System	•			•	•	•		•		•		•	•	
Serviceability:														
AASHTO	•	•	•	•	•		•	•		•		•	•	
COPES	•	•	•	•	•	•	•		•	•		•	•	•
Cost Allocation														
EAROMAR-2 System	•			•	•	•		•		•		•	•	
HPMS	•		•	•	•		•			•		•	•	•

Table 17. Detailed data elements for current models grouped by predicted distress in portland cement concrete pavements (continued).

• = Data Available in SHRP-LTPP and used in Current Models

Distress / Models	**Layer Thick.**	**Layer Stiff.**	**Age**	**Traffic, ESAL**	**PCC Layer Properties**	**Base / Subg. Properties**	**Moisture Content Subgrade**	**Subsurface Drainage Type**	**Joint Effic.**	**Monthly Temp.**	**Shoulder Type**	**Annual Precip.**	**Air Freeze-Thaw Cycles**	**Pre-Repair Distress**
Shoulder Distress:														
EAROMAR-2 System	•			•	•	•		•		•		•	•	

Table 18. Example of the 117 data elements in the SHRP National Information Management System for pavements with asphalt concrete surfaces.[(64)]

Data Elements (Significant Variables)			
No.	Description	No.	Description
	Layer Thickness		*Plant Mix Asphalt Cement Properties*
1	A.C. Overlay	25	Asphalt Grade
2	A.C. Surface	26	Source
3	Unbound Base	27	Specific Gravity
4	Unbound Subbase		*Original Asphalt Cement Properties*
5	Bound Base	28	Viscosity
6	Bound Subbase	29	Penetration
	Layer Stiffness	30	Type of Asphalt Modifiers
7	A.C. Overlay (w/temp.)	31	Quantity of Asphalt Modifiers
8	A. C. Surface (w/temp.)	32	Ductility
9	Unbound Base	33	Ring and Ball Softening Point
10	Unbound Subbase		*Lab-Aged Asphalt Cement Properties*
11	Bound Base	34	Viscosity
12	Bound Subbase	35	Ductility
13	Subgrade	36	Penetration
	Age and ESAL's	37	Ring and Ball Softening Point
14	Age of Pavement	38	Weight Loss
15	Cumulative 18-kip (80-kN) ESAL		*Original Mixture Properties*
	Plant Mix Aggregate Properties	39	Max. Spec. Gravity
16	Composition of Coarse Aggregate	40	Bulk Spec. Gravity
17	Geological Classification of Coarse Aggregate	41	Asphalt Content
18	Composition of Fine Aggregate	42	Percent Air Voids
19	Type of Mineral Filler	43	Marshall Stability - Blows
20	Aggregate Durability	44	Marshall Stability - Flow
21	Polish Value of Coarse Aggregate	45	Hveen Cohesiometer Value
22	Gradation of Combined Aggregates	46	Type of Asphalt Plant
23	Bulk Spec. Gravities	47	Type of Antistriping Agent

Table 18. Example of the 117 data elements in the SHRP National Information Management System for pavements with asphalt concrete surfaces (continued).(64)

Data Elements (Significant Variables)			
No.	Description	No.	Description
24	Effective Spec. Gravity Aggregate Combination	48	Moisture Susceptibility
49	Moisture Susceptibility	78	In Situ Dry Density
50	Mean Mixing Temperature	79	In Situ Moisture Content
51	Lay down Temperature	80	Relative Density (Cohesionless Soil)
52	Percent Compaction	81	Soil Suction
	Base/Subbase Materials Data	82	Expansion Test
53	AASHTO Soil Classification	83	Swell Pressure
54	Plasticity Index	84	% by Wt. Finer than 0.00078 in (0.02 mm).
55	Max. Lab. Dry Density	85	Av. Rate of Heave (Lab. Freeze Test)
56	Optimum Lab. Moisture Content	86	Frost Susceptibility Classification
57	Percent Compaction		***Deflection Data***
58	Gradation of Coarse Aggregate	87	Measured Deflections (normalized to stnd. temp.)
59	Gradation of Fine Aggregate	88	Depth to "Rigid" Layer
60	Type of Stabilizing Agent (Bound)		***Environmental Data***
61	Percent Stabilizing Agent	89	Type of Environment
62	Type of Admixture	90	Freeze Index
63	Quality of Admixture	91	Thornthwaite Index
64	Compressive Strength (with confining press.)	92	Annual Precipitation
65	Calcium Carbonate Content	93	Precipitation Days by Month
66	CBR	94	Precipitation Days by Year
67	R-Value	95	No. of Days with High Solar Radiation
	Subgrade Data	96	Highest Annual Solar Radiation
68	AASHTO Soil Classification	97	Lowest Annual Solar Radiation
69	CBR	98	Elevation Above Sea Level
70	R-Value	99	% Sunshine (of Possible Time)
71	% Passing # 40 Sieve	100	Average Wind Speed by Month
72	% Passing # 200 Sieve	101	Average Dew Point by Month
73	Plasticity Index		***Temperature***

Table 18. Example of the 117 data elements in the SHRP National Information Management System for pavements with asphalt concrete surfaces (continued).(64)

Data Elements (Significant Variables)			
No.	Description	No.	Description
74	Liquid Limit	102	Monthly Average
75	Max. Lab Dry Density	103	Average Max. Daily by Month
76	Optimum Lab. Moisture Content	104	Average Min. Daily by Month
77	Percent Compaction	105	No. days w/ Max. Temp greater than 90 ^{0}F (32.2^{0}C)
106	No. Days w/ Min. Temp less than 32 ^{0}F (0 ^{0}C)	*Subsurface Drainage Data*	
107	No. of Freeze-Thaw Cycles/Year	113	Type
Shoulder Data		114	Location
108	Shoulder Width	115	Dia of Long. Drain Pipes
109	Shoulder Surface Type	116	Spacing of Laterals
110	Shoulder Surface Thickness		
111	Shoulder Base Type		
112	Shoulder Base Thickness	117	No. of Lanes in Travel Direction

Table 19. Significant data elements in the SHRP National Information Management System for pavements with asphalt concrete surfaces.[64]

Significant Data Elements			
	Description	No.	Description
1	Surface Thickness	16	Subsurface Drainage
2	Base/Subbase Thickness	17	Geological Classification of Course Aggregate in HMAC
3	Surface Stiffness	18	% of Subgrade Soil Passing # 200 Sieve
4	Unbound Base/Subbase Stiffness	19	Plasticity Index of Subgrade Soil
5	Bound Base/Subbase Stiffness	20	Liquid Limit
6	Subgrade Stiffness	21	% of Subgrade Soil Finer than 0.00078 in (0.02 mm)
7	Age of Pavement	22	Type of Environment
8	Cumulative ESAL's	23	Average Max. Daily Temp. by Month
9	Asphalt Viscosity	24	Average Min. Daily Temp. by Month
10	Asphalt Content	25	Thornthwaite Index
11	Percent Air Voids	26	Freeze Index
12	HMAC Aggregate Gradation	27	No. of Days Min. Temp > 30 °F (-1 °C)
13	Percent Compaction of Base/Subbase	28	No. of Days Max. Temp > 90 °F (32.2 °C)
14	Subgrade Soil Classification	29	Number of Air Freeze-Thaw Cycles
15	In Situ Moisture Content of Subgrade	30	Annual Precipitation

Table 20. Significant data elements in the SHRP National Information Management System for pavements with portland cement concrete surfaces.[64]

Significant Data Elements			
	Description	No.	Description
1	PCC Surface Thickness	16	Subgrade % Passing # 200 Sieve
2	Base Thickness	17	Moisture Content of Subgrade
3	PCC Surface Stiffness	18	Joint Efficiency
4	Base Stiffness	19	Thornthwaite Index
5	Subgrade Stiffness	20	Annual Precipitation
6	Age of Pavement	21	Precipitation Days by Year
7	Cumulative ESAL's	22	Shoulder Type
8	Type of Coarse Aggregate for PCC	23	Subsurface Drainage Type
9	Gradation of Coarse Aggregate for PCC	24	Average Max. Daily Temp. by Month
10	PCC Compr. Strength	25	Average Min. Daily Temp. by Month
11	AASHTO Soil Class Base/Subbase	26	No. of Days Min. Temp. < 32 °F (0 °C)
12	% Compaction of Base/Subbase	27	No. of Days Max. Temp. > 90 °F (32.2 °C)
13	Coarse Aggregate Gradation of Base/Subbase	28	Air Freeze-Thaw Cycles
14	Fine Aggregate Gradation of Base/Subbase		
15	AASHTO Soil Classification of Subgrade		

COST DATA REQUIRED FOR ECONOMIC ANALYSIS

Economic analysis is a decision support tool.[65] The objective of the LCC analysis is to evaluate the economic consequence of different strategies and alternatives in terms of long-term costs. ***LCC requires a data base of performance and cost information along with prediction models to estimate the initial effect and the life of various alternatives.*** The current prediction models have been described earlier; however, the life of some treatments cannot be predicted using these models.

For any given pavement section, several different maintenance strategies could be applied. Each strategy has associated costs which will occur over a long time period. Three major components of pavement LCC are:

- Initial maintenance and rehabilitation/construction costs.
- Future maintenance and rehabilitation costs.
- Salvage value at the end of analysis period.

Salvage value represents the worth of the pavement at the end of the analysis period, which is normally 20 or more years from the beginning of the analysis period. If it can be assumed that all alternatives will have equal salvage value, this cost factor can be neglected.(66) By using the equivalent uniform annual cost calculation procedures, a salvage value is not needed as an input to compare alternatives which have unequal lives. However, it is assumed that each alternative will be repeated at the end of its life. The interest and inflation rates are used to account for the time-value of the money expended.

Maintenance and rehabilitation are terms which mean different things to different people. Maintenance engineers in various fields usually define two types of maintenance: preventive and corrective. Preventive maintenance consists of periodic inspections to determine if the subject is in satisfactory condition and periodic repairs to replace components worn to some predetermined level or which are known to fail after some period of time. Preventive maintenance is applied before pavement deterioration has become severe and corrects minor faults reducing further deterioration. It normally includes crack sealing and application of surface seals. Minor patching can be included, and thin overlays can be substituted for surface seals when the seal would not be expected to survive high traffic.

Rehabilitation includes all other uses of treatments. Rehabilitation can be thought of as responsive repair; treatments are applied to correct deterioration that has developed in the pavement. This deterioration is manifested in distress types which must be corrected to return the pavement to a condition similar to the original construction conditions. Rehabilitation is completed to restore the integrity of the pavement, while preventive maintenance is applied to preserve the integrity of the pavement.(46)

Selected treatments are used in the analysis to determine budget needs. The selected treatment and its associated cost are connected to each pavement section identified as needing maintenance or rehabilitation. Life cycle cost analysis requires estimates for the original pavement and various maintenance and rehabilitation treatments. Life estimates (or life extension) for each surface type combination without major maintenance and rehabilitation are based on prediction models which are under analysis in this project. Life estimates for rehabilitation treatments which add a new surface to the existing pavement are estimated based on the prediction models for that type of surface, i.e., AC/AC curve for an overlay is illustrated in figures 12 through 14. However, life extension for other treatments must also be estimated. These are developed from performance data which are not currently available. It was hoped to obtain such data from the SHRP H-101 contract, but at this time it was not available.

Several factors affect the pavement life extension provided by a maintenance or rehabilitation treatment. Some of them include:

- Condition at the time the treatment is applied.
- Climatic factors (the environment in which they are located).
- Traffic on the pavement.
- The structural adequacy of the pavement.
- The materials used in the treatment.
- The application procedures.

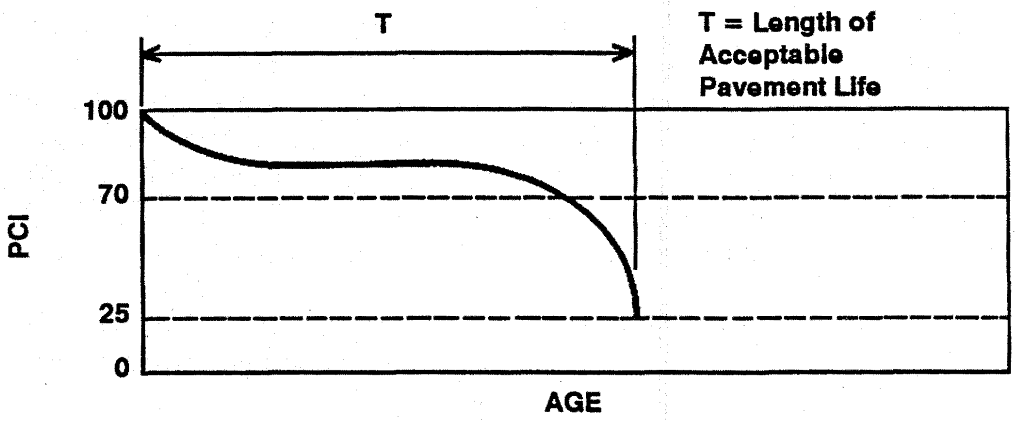


Figure 12. AC/AC curve for an overlay, life extension - acceptable life without maintenance or rehabilitation.

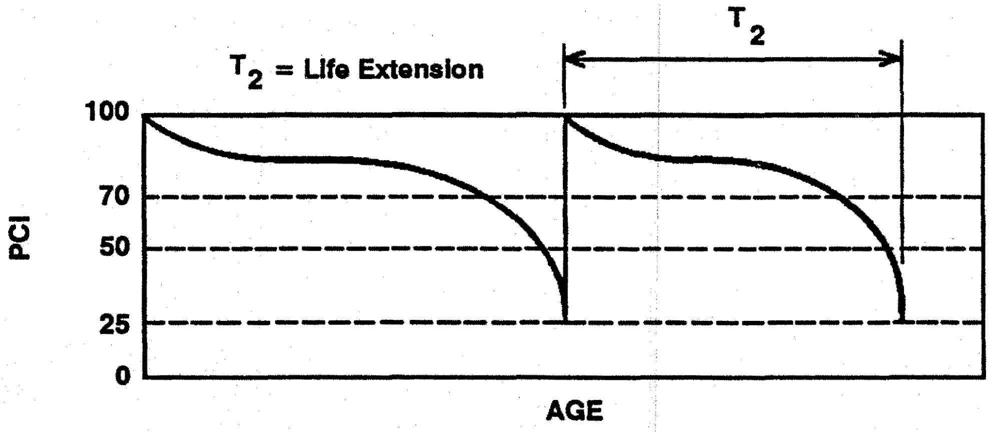


Figure 13. AC/AC curve for an overlay, life extension - life extension of rehabilitation treatment applied at or after PCI of original pavement is 25.

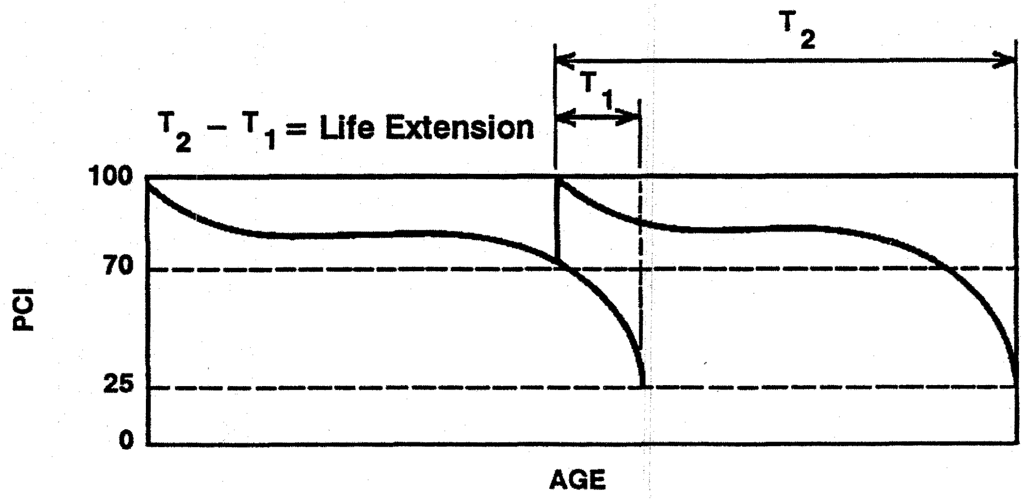


Figure 14. AC/AC curve for an overlay, life extension - life extension of acceptable maintenance.

Life extensions are for individual treatments and only represent one application. When they must be applied more than one time, their effectiveness may decrease, or it may not be feasible to repeat the treatment indefinitely. The treatments are generally most effective when combined together into long-term maintenance and rehabilitation strategies. Each strategy includes specific arrangements of maintenance and rehabilitation treatments applied over an analysis period (normally 20 to 30 years). This period must be long enough to evaluate the effect of each alternative considered in the strategy analysis.

Cost Data or components are those portions or characteristics of a model which describe ***what*** costs are to be considered, and ***how*** they are computed, and any model constraints that affect them. The following cost data have been identified:

- Costs for routine maintenance.
- Costs for rehabilitation.
- Budget constraints.
- Costs for new construction.
- Analysis period (time over which the economic analysis is to be conducted).
- Performance period (time period between the beginning of the life of an alternative and the time when major rehabilitation is next required).
- Interest rates.
- User costs.
- Salvage values.
- Methods for cost growth.

It should be recognized that life-cycle cost analyses are not precise, since reliable data for maintenance, subsequent stages of construction, salvage value, and pavement life are not always available, and it is usually necessary to apply engineering judgement to make reasonable estimates. Despite these difficulties, life-cycle cost analysis is believed to provide the best potential to obtain the greatest service from a pavement construction or rehabilitation project at the lowest possible cost.

DATA ELEMENTS FOR FUTURE DEVELOPMENT OF MODELS

Several significant problems exist in the data and its use for future development of models. Examples are incomplete data and possible errors in traffic estimates (cumulative ESAL's), and the fact that several of the dependent variables are not measured as one quantity but as two (severity and extent). The severity is usually a categorical variable (low, medium, or high) while the extent is a continuous variable.

Another example would be an asphalt concrete overlay that is subject to alligator cracking under traffic. The overlay would require even more data relevant to the properties of the existing pavement at the time of the overlay placement, any remaining life in the old pavement, stiffness values, etc.

Collineariility is one of the most serious problems in data elements for future development of models. Collinearity is a data problem that occurs when two or more variables are linear functions of each other; that is, there exists a definite correlation among these variables. For example, for a specific highway section, age and total traffic since opening are highly correlated. Because of this correlation, the coefficients on these variables may depend on the order in which they are entered into the regression equation. Collinearity also causes problems by inflating the variances such that intuitively significant variables are not significant and giving coefficients signs contrary to what is expected. Special techniques will have to be used to detect these collinearities and the effect of the outliers which may mask the collinearities.

Another characteristic of the data that will greatly influence the success of the future models will be missing items of inventory data that concern the design and construction of the pavements. There is also very little information on repairs done to a specific pavement section prior to a major rehabilitation (i.e. an AC overlay).

For future models there will be an excellent traffic data base from the monitoring equipment installed (by SHRP's contracts), while data traffic from the past will rely on estimates of past ESAL of very limited accuracy. While years of time-sequence monitoring data will be available later, at this time any prediction model will only have measurements for one point in time, or at most two. Prediction models that deal in loss of performance (roughness and friction) will depend on educated estimates for initial roughness and friction resistance.

It is difficult, if not impossible, to evaluate data elements for future models that have not been developed yet. At best, only approximations can be made when using carefully structured experimental plans to formulate the data elements in the data base for future models.

DATA ELEMENTS UNAVAILABLE

The great majority of the data are available. However, many specific data elements are missing for a number of test sections involved in SHRP LTPP. This is primarily a consequence of the development of a broad data base that would include "bins" for storing any feasible data that might be used for a number of purposes, not just performance analysis.

Some of the unavailable data are, for example, the initial values of roughness and initial values of skid resistance. As serviceability loss is the primary factor in the AASHTO design equations, it will be essential to develop reasonable estimates for initial PSI for evaluating the equations.

There are a number of data elements available for predicting alligator cracking, transverse cracking, rutting, roughness, and raveling/weathering of pavements with asphalt concrete pavement surfaces. However, only four data elements are available for studies of friction loss. There is little data on polishing or durability of the course aggregate. For pavements with portland cement concrete surfaces, there are few data elements for friction loss.

The two major types of data elements that were recognized in model evaluation include inventory data and monitoring data. The data bases reviewed previously (chapter 4) contain these data elements to a different extent. The extent of data elements presented in each data base relates directly to the intent of the data base at the time the models were developed. The lack of material test properties or deflection data indicate that the model development being conducted from a particular data base did not deem the particular data as relevant to the model, or the funding did not allow for collection of that particular data element. This specificity of each data base makes its use for general development of newer, more general damage models problematic, and limits the use of a data base for development without compromising the validity of the models currently developed.

TYPICAL RANGE OF VALUES FOR UNAVAILABLE DATA ELEMENTS

As indicated in the above section, specific data elements are missing for a number of test sections involved in SHRP LTPP. While excellent traffic will be available for future data analysts from the monitoring equipment installed, past traffic data analysis will have to rely on estimates of past ESAL of very limited accuracy. Another important item will be distress measurements which may be available for one point in time or at most two. For most distresses, an additional data point may be inferred for conditions just after construction. For example, rutting, cracking, faulting of joints may be generally taken as zero initially. As mentioned earlier, prediction models that deal in loss of performance (roughness and friction) will depend on educated estimates for initial roughness and friction resistance.

For other data elements, such as gradation of base course and fine aggregate in PCC mixtures, initial values of skid resistance and initial values of roughness, the SHRP Regional Offices are contracting the State highway agencies to find this information early in the pavement's lives, and this will be used to estimate initial values. As serviceability loss is the primary factor in the AASHTO design equations, it will be essential to develop reasonable estimates for initial PSI for evaluating the design equations.

The SHRP projects are already dealing with procedures for missing data elements. They will include reasonable estimates for some data elements without seriously affecting the results. A final list on typical range of values for unavailable data cannot be completed until the majority of the data elements are collected. For example, there is a possibility in some cases that so few sections will have experienced a distress that the number of observations will be too few to directly support meaningful prediction models.

SUMMARY

This chapter presented the data elements involved in the prediction models. The list of data elements required for current prediction models, as well as required inputs for these models and expected data to be collected by SHRP-LTPP, were discussed under this chapter. Cost data required for performing an economic analysis was also included in this chapter. Sets of variables and discussions have been included that were believed to be significant to the prediction models.

The great majority of the data is available. However, many specific data elements are missing for a number of test sections involved in SHRP LTPP. This is primarily a consequence of the development of a broad data base that would include "bins" for storing any feasible data that might be used for a number of purposes, not just performance analysis.

The SHRP projects are already dealing with procedures for missing data elements. They will include reasonable estimates for some data elements without seriously affecting the results. A final list on typical range of values for unavailable data cannot be completed until the majority of the data elements are collected.

CHAPTER 6 DAMAGE PREDICTION MODELS

The objective of the data elements analysis discussed earlier was to specify what types of data elements are available and how they will be handled to obtain relevant pavement performance parameters.

Pavement prediction models are an essential part of any comprehensive network-level pavement management system. Prediction models provide an estimate of future pavement behavior based on data available on past performance, which is an invaluable tool in project-level forecasting and network-level planning.

The subtasks related to prediction models were summarized as follows:

- Identify and categorize possible modeling techniques, i.e. s-curve, regression, polynomial etc. Identify generic modeling techniques to be evaluated.
- Categorize damage prediction models according to modeling techniques.
- Develop procedures for comparing modeling techniques.
- Develop computer flow chart of life cost on conceptual operation.
- Recommend an economic analysis procedure.

The following sections will discuss each of the subtasks listed above.

IDENTIFY AND CATEGORIZE POSSIBLE MODELING TECHNIQUES

The categories of prediction models and modeling techniques currently used are described in the following paragraphs.

Types of Models

Models are important tools available to pavement engineers that assist them in the design and analysis of pavements, and improve their understanding of pavement performance. The models can be based on theory (mechanistic), on observed performance (empirical), or a combination of the two.

Models can be broadly grouped into two categories for use in the pavement field: design and analysis.(67) Pavement design models can be classified as empirical, in which the design equation for pavement thickness is derived from field data, and mechanistic-empirical, in which pavement responses such as stresses and strain are related to the number of allowable loads until failure of the pavement occurs.

Pavement analysis models have been developed to provide behavioral information about pavement structure. The interaction of the different layers in a pavement system, the different designs that are used, the range of environmental conditions to which a pavement is exposed, and the variation in location and magnitude of applied loads define a very complex structure. The goal in the development and use of an analysis model is to have a better understanding of pavement responses to loading and environment, and to improve pavement design.

A subset of the design models is prediction models. Prediction models attempt to predict the condition of the pavement after it has been subjected to a given number of environmental and traffic loads. This prediction is usually based on models for performance that are developed from actual inservice pavements. Prediction models can incorporate mechanistic variables that are based on the properties of the pavement materials and their response to loading. It is believed that mechanistic-empirical models provide a more accurate characterization of pavement structure, and more flexibility in design and analysis than strictly empirical models.

The primary response of a mechanistic model (deflection, stress, or strain) must be related empirically to some measurable form of distress. An empirical model is an attempt to form a statistical relation between causal factors and their effects in the absence of complete understanding of the physical principles that are involved.

Pavement prediction models predict the future condition of the pavement in terms of design, traffic and environmental variables. These models play a vital role in evaluating future rehabilitation needs of the highway system. Prediction models or performance models fall also into two categories: deterministic and probabilistic.(68) The deterministic models predict a single number for the life of the pavement or its level of distress, or other measure of condition. These models include primary response, structural performance, functional performance, and damage models. The probabilistic models predict the probability distribution of pavement performance. These models include survivor curves, Markov, and semi-Markov transition processes. The following paragraphs describe each of these models briefly.

Deterministic models

(a) Primary Response Models: These models predict deflection, stress, strain, thermal stress, etc., due to applied loads and climatic conditions. These models may be either mechanistic, empirical, or mechanistic-empirical models which have been established with observed data.

(b) Structural Performance Models: These models predict individual pavement distress or composite pavement condition, such as the structural component of the PCI. These models may be empirical or mechanistic-empirical.

(c) Functional Performance Models: These models represent pavement condition in terms of more general measures of damage, condition or serviceability. For example, PSI, PQI, and the functional component of the PCI.

(d) Damage Models: These models are derived from either the structural or functional per-formance models. For example, the load equivalence factors are determined from damage models.

Probabilistic Models

(a) Survivor Curves Models: A survivor curve is a plot of probability versus time. The probability changes with time from a value of 1.0 to zero, indicating the percentage of pavement that remains in service at a particular time without requiring major maintenance or rehabilitation.

(b) Markov Models: A Markov transition matrix expresses the probability that a group of pavements of similar characteristic have for transiting from one condition state to another within a specific time interval. The Markov process describes the pavement condition probabilities before and after transition. It is the probability that a group of pavements of similar age or traffic will transition from one state of distress or serviceability index to another within a specified time period.(69)

Some of the condition indices and prediction models are more suited for network level analysis, while others are more suited for project level analysis. At the project-level management, pavement performance prediction models are used to design pavements, to perform life-cycle cost analysis, to select optimal design with least cost, and in trade off analysis. The annualized costs of new construction, maintenance, rehabilitation, and user costs are summed for a specific pavement design to determine the best time and pavement condition to perform each.

At the network-level management, pavement performance prediction models are used for inspection scheduling, life-cycle costing, benefit analysis and budget optimization.

Modeling Techniques Used in Prediction Models

As stated earlier, the models can be based on theory (mechanistic), on observed performance (empirical), or a combination of the two (mechanistic-empirical). Therefore, the modeling techniques are based on mechanistic, empirical or a combination of both. The modeling techniques currently in use for deterministic prediction models include:

- Straight-line extrapolation.
- Regression analysis (linear, multiple, special).
- Polynomial curve fitting (B-spline Model and Constrained Least Squares Model).
- Exponential (S-shaped curve).

The modeling techniques currently in use for probabilistic prediction models are:

- Probabilistic Distribution (survivor curves models).
- Markov Model.

A description of each technique is included below:

(a) Straight-Line Extrapolation is used to predict the condition of a pavement section when only one time condition survey is available. However, when sufficient data are available, it is found that the shape of the deterioration curve is generally curvilinear, rather than the straight-line. This method is only applicable to individual pavement sections and does not lead into the development of a model that can be used with other pavement sections.(70)

(b) Regression Analysis (linear, multiple, special) is used to establish empirical relationships between two or more variables. Each variable is described in terms of its mean and variance. There are several forms of regression analysis; the simplest is linear regression between two variables. The other forms are multiple. The regression analysis techniques are valid only if the predictive variables can be found that are related to pavement condition deterioration. The regression techniques are only applicable to very specific climatic conditions, materials, construction techniques, etc.

(c) Polynomial Curve Fitting (B-spline Model and Constrained Least Squares Model)

B-spline Model is based on the original mechanical splines used in drafting, and it assumes that the curve takes on a shape that minimizes its potential energy. A B-spline of degree k is a continuous function having its first k-1 derivatives continuous. Due to the complex nature of selecting the number and the position of interior knots and the possibility of the occurrence of a positive slope in the function, the B-spline technique is not deemed suitable as a pavement condition prediction modeling technique.

Constrained Least Squares Model fits a polynomial curve to the data that minimizes the squares differences between the predicted and the actual data points. At the same time the technique applies a constraint that ensures a monotonically decreasing slope of the predicted condition versus age curve.

(d) Exponential (S-shaped curve) is a logarithmic equation that follows a sigmoidal curve (S-shape). Similar to the polynomial constrained least squares, the S-shaped curve fitting technique is very useful when predicting the change in a variable (e.i., PCI) as a function of another variable (e.i., pavement age). These equations are used to indicate the normal deterioration path for a pavement section and used to project the condition of individual pavement sections from the last observed PCI to a future time.

(e) Probabilistic Distribution (survivor curves models) describes the probabilities associated with all the values of a random variable. A pavement condition measure such as the PCI or IRI can be treated as a random variable with probabilities associated with this value. The use of probability distribution in the prediction of pavement condition requires the

knowledge of the distribution law for the variable being predicted. This technique is particularly useful for individual distress prediction.

(f) Markov Model is based on determining the probabilities associated with a pavement in a given condition state either staying in that state or deteriorating to the next state after one duty cycle. A Markov transition matrix expresses the probability that a group of pavements of similar characteristics have for transition from one condition state to another within a specified time interval. The Markov model is based on the following assumptions:

- Pavement condition can be expressed in a finite number of states.
- The transition probabilities depend only on the present condition state.
- The transition process is stationary, i.e., the probability of transition from one condition state to another is independent of time.

CATEGORIZE DAMAGE PREDICTION MODELS ACCORDING TO MODELING TECHNIQUES

The categorization of the prediction models according to modeling techniques is included in table 21. This table presents all the prediction models discussed previously in chapter 2, classified and categorized according to modeling techniques.

Based on how the models were developed, they were classified either deterministic or probabilistic. A deterministic model predicts the mean value of a predicting (dependent) variable, while a probabilistic model predicts the distribution of a dependent variable. Prediction models were categorized as mechanistic, empirical or mechanistic-empirical, depending on the formulation and whether mechanistic variables were used in the model.

Lastly, there are project-specific or network models.(71) Project-specific models predict pavement attributes as functions of several key pavement factors and can be used for a variety of pavement sections within their limit, while network level models predict the average condition of a pavement group (for example, a group of 3-in (77-mm) asphalt overlays in a certain climatic condition and under a certain traffic loading).

For example, one of the models developed for network level analysis is the Arizona model. One hundred and twenty different condition states based on different roughness, cracking levels, and rate of cracking were defined, and probability transition matrices were developed for different networks, defined by climatic conditions, and traffic levels.

Some other models predict overall pavement condition as a function of major pavement parameters. Among these models are the PARS models. Another category of prediction models are site-specific models. In this type of model, which is currently in use in the State of Washington's PMS, future pavement condition is projected from past performance. Other models have also developed to predict only individual pavement distress rather than overall condition (COPES, EXPEAR, etc.).

Table 21. Modeling techniques used for current prediction models.

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
Roughness				
Emphasizing Structural Effects	AASHO Road Test	Initial roughness, ESAL, SN, Soil Support, mean rut depth, cracking, and patching.	Empirical, deterministic, functional performance model. (AASHTO'86 empirical-mechanistic)	Exponential-regression analysis.
Emphasizing Structural Effects	TRRL Study (1975)	Modified SN, Layer Thickness, materials, drainage coeff., initial Roughness, ESAL.	Empirical, deterministic, functional performance model.	Regression analysis (linear).
Emphasizing Time-related Effects	Arizona Models	Pavement age, initial roughness, environmental parameters such as rainfall, elevation, freeze-thaw, temperatures, etc.	Empirical, deterministic, functional performance model.	Regression analysis (linear).
	Arizona Study	Time and initial roughness.	Empirical, deterministic, functional performance model.	Regression analysis (linear).
	Australian, 1972	Age and initial roughness.	Empirical, deterministic, functional performance model.	Regression analysis.
Models with Interacting Effects	Queiroz	Cumulative number of 18 kip (80 kN) axle load, time and Initial Roughness.	Empirical, deterministic, functional performance model.	Regression analysis (linear).
Models relying in Mechanistic Parameters	Uzan and Lytton, 1982	Mean rut depth, cracking area, patching area and variance of rut depth.	Empirical, deterministic, functional performance model.	Regression analysis.
Models Emphasizing Structure, Surface Condition and Time Effects	Brazil-UNDP (IRI-World Bank)	Pavement type, layer thickness, age, surface distress, traffic and environmental parameters.		Equation N.A.
	Brazil-UNDP Study (From expanded data base)	ESAL, modified SN, but omitting rut depth, patching and cracking. Age of pavement since overlay or construction.	Empirical, deterministic, structural and functional models.	Regression analysis (linear approximation).
	Alberta's Riding Comfort Index	Previous RCI and present age of the pavement.	Empirical, deterministic, functional performance models.	Regression analysis (multiple).

Table 21. Modeling techniques used for current prediction models (continued).

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
Structural Measures for Performance Prediction				
Asphalt Concrete Fatigue	Asphalt Institute (TAI) MS-15	ESAL for 20-years, Strain in the asphalt layer, % of AC and % of air voids.	Mechanistic-empirical, deterministic, damage models.	Regression analysis (multiple).
	MICH-PAVE	ESAL, surface deflections, layer thickness, resilient moduli, annual air temperature, kinematic viscosity, air voids of AC layer, stress and strain of AC layer.	Mechanistic-empirical, deterministic, primary response model.	Empirical equations with mechanistic analysis.
Deflection Prediction Models/Structural Adequacy Index (SAI)	Alberta DOT (SAI model for granular base pavements)	Mean fall rebound deflection x 10^3 and Cumulative ESAL/10^5.	Mechanistic-empirical, deterministic, damage models.	Regression analysis (multiple).
	VESYS (Flexible design procedure designed by FHWA)	Resilient Moduli, fatigue and permanent deformation, load distribution, duration and number of applied loads, mean temp. for AC layers, subgrade.	Mechanistic-empirical, probabilistic, primary response model.	Regression analysis.
Distress Measure				
<u>For Rigid Pavements:</u>	COPES	Age, ESAL, environmental parameters, pavement type, layer thickness, joint load transfer, joint seal damage, material properties.	Mechanistic-empirical, deterministic, structural and functional performance models.	Regression analysis (multiple) and mechanistic analysis.
<u>For Flexible Pavements:</u>	HDM Models (World Bank)	Pavement type, layer thickness, ESAL, environmental factors.	Empirical-mechanistic, deterministic, structural and functional models.	
	Cost Allocation	Structural characteristics, environmental factors, traffic, subsoil characteristics, and pavement age.	Empirical-mechanistic, deterministic, structural performance model.	S-shaped curve.
	Rutting (Predicts strain in the AC layer under repeated traffic loading)	Strain, ESAL, layer stiffness and layer thickness.	Mechanistic, deterministic, primary response model.	Exponential-regression analysis.

Table 21. Modeling techniques used for current prediction models (continued).

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
	Rutting (Ohio State)	Same as above, and experimental constant depending on material type and state of stress conditions.	Mechanistic, deterministic, primary response model.	Exponential-regression analysis.
Composite Indices:				
PSI Models	AASHO Model	ESAL, SN, Soil Support, mean rut depth, cracking and patching, slope variance.	Empirical, deterministic, functional performance model.	Exponential-regression analysis.
	HPMS (FHWA Highway Performance Monitoring System)	PSR as a function of the SN and ESAL.	Empirical, deterministic, functional performance model.	Exponential-regression analysis.
	PSI Model of State of Idaho	ESAL.	Empirical, deterministic, functional performance model.	S-shaped curve.
	State of Minnesota	PSR (PSI) predicted as a function of itself, PSR one year previous, pavement type and traffic volume.	Empirical, deterministic functional performance model.	Straight-line.
	Sigmoidal Model (Texas Transportation Institute)	Traffic and location of the site.	Empirical, deterministic, functional performance model.	S-shaped-curve (sigmoidal function).
	PENNDOT Performance Prediction Model Performance Prediction Model	Age of the pavement.	Empirical, deterministic, functional performance model.	Straight-line, regression.
	State of Virginia	Load and design variables; a composite distress index called maintenance raiding (DMR), and age of the pavement.	Empirical, deterministic, functional performance model.	Exponential.
	Iowa DOT For Rigid and Composite Pavements	Base type, aggregate durability, joint or reinforcement type, and ESAL.	Empirical, deterministic, functional performance model.	Straight-line.
	State of Washington	Pavement age, ESAL, thickness of the overlay.	Empirical-mechanistic, deterministic, structural performance model.	Regression analysis.

Table 21. Modeling techniques used for current prediction models (continued).

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
	Mississippi PCR	Pavement age, traffic volume, thickness of surfacing, structural thickness.	Empirical, deterministic, functional performance model.	Regression analysis.
	Alberta's PQI	Pavement age, traffic, soil type, and structural thickness .	Empirical, deterministic, functional performance model.	Equation N.A.
	OPAC and PARS Models (Performance is predicted as a function of pavement age, traffic, and thickness of overlay)	Pavement characteristics, age, traffic, thickness of overlay, period of rehabilitation, PCI.	Empirical, deterministic, functional performance model.	Regression analysis.
Models for Rehabilitated Pavements				
	NCHRP Project 14-6 (AGENCY and IMPACT)	Pavement condition, structural factors and traffic.	Empirical-mechanistic, deterministic, functional and damage models.	Regression analysis.
	1985 ARE Study (Prediction models for alligator and wide cracking, ravelling, potholes, roughness and rutting)	Pavement Characteristics, pavement history, traffic, pavement condition, environment and geometry.	Empirical-mechanistic, deterministic, functional and structural performance models.	Regression analysis.
	EAROMAR-2 System (Predictions of different categories of distress that are translated into PSI)	Structural, materials and drainage properties, construction and loading history, current surface condition, seasonal temperature, rainfall, freezing index, AASHTO regional factor, subgrade soil classification, inflation rates.	Empirical-mechanistic, deterministic, functional performance model.	Regression analysis.
	PAVER Management System (Based on the rate of deterioration of pavement conditions, PCI, over short and long term periods)	Age, pavement type, and surface distress.	Empirical, deterministic, structural and functional performance models.	4th degree polynomial (Constrained Least Squares).

Table 21. Modeling techniques used for current prediction models (continued).

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
	Indiana Study (Based on PSI-ESAL loss focus on pavement roughness)	Modified index of pavement performance, PSI-ESAL loss,Climate and environmental influence on the effectiveness of pavement maintenance work.	Empirical, deterministic, functional performance model.	Equations N.A.
	Arizona Overlay Design Procedure (Based on deterioration models for roughness, fatigue and plastic deformation)	Roughness before overlay and after, limiting criteria for roughness, predicted change in roughness due to overlay, slope of roughness versus time relationship, tensile strain at the bottom of the AC layer due to standard wheel load and economic analysis parameters.	Empirical-mechanistic, deterministic, damage models.	Regression analysis and exponential.
	Life-Cycle Cost Study (Distress modeled for flexible: Alligator crack.,ravelling and rutting; for rigid: pumping, faulting, cracking and deterioration of joint and crack sealants	Increase of the PCI due to any rehab. or reconstruction, PCI_t, PCI_0, PCI_{t-1}, PCI_{loss}, $PCI_{correct.\ by\ maint.}$, ESAL, age of the pavement, Structural capacity of the pavement, for flexibles: SN corrected for subgrade and environmental conditions, for rigids: slab thickness.	Empirical, deterministic, structural performance models.	Regression analysis.
	NAPCOM	18 kip (80 kN) calculated as vehicle miles travelled (VMT) and load equi. factors (LEF), functional class, surface type, structural number, initial serviceability at last construction/rehabilitation, cost, freezing index, temperature, precipitation, Thornwaite index.	Empirical-mechanistic, deterministic, structural performance models.	Regression.

Table 21. Modeling techniques used for current prediction models (continued).

Group	Prediction Model	Required Input Detailed	Classification / Categorization	Modeling Technique Used
	VESYS (Only for flexible pavements, prediction models for Rutting, Fatigue cracking and Roughness)	•Resilient Moduli, fatigue and permanent deformation characteristics of AC layers. •Stress-Strain and permanent deformation parameters for unstabilized crushed stone subbase layers. •Resilient Moduli and permanent deformation of the subgrade. •Traffic distribution (load distribution amplitude and duration, number of applied load distribution. •Environmental variables (mean temperature of bituminous layers and the subgrade moisture content).	Mechanistic-empirical, probabilistic, primary response.	Regression analysis and mechanistic.
	EXPEAR (For JRCP,JPCP, prediction models for Faulting, Cracking, Pumping, Joint deterioration, and for AC/PCC, Reflective cracking and Rutting)	Structural adequacy, roughness, drainage, joint deterioration, foundation movement, loss transfer, loss of support, shoulder conditions.	Empirical-mechanistic, deterministic, structural performance models.	Regression analysis.

Some examples from table 21 are summarized as follows:

Example No. 1:

Group: Models for Rehabilitated Pavements.
Prediction Model: PAVER Management System.
Required Input: age, pavement type, and surface distresses.
Classification/ Categorization: empirical, deterministic, structural and functional performance models.
Modeling Technique: 4th degree polynomial (Constrained Least Squares).

Example No. 2:

Group: Composite Indices, PSI Models.
Prediction Model: PSI Model of Idaho.
Required Input: ESAL.
Classification/ Categorization: empirical, deterministic, functional performance models.
Modeling Technique: S-shape Curve.

DEVELOP PROCEDURES FOR COMPARING MODELING TECHNIQUES

Prior to a comparison of modeling techniques, it is important to understand the basic requirements of a model. There are four criteria to use in developing reliable pavement models.(72) These criteria include:

- An adequate data base built from inservice pavements (a review of each data base was included in the Interim Report, September 1991).
- The inclusion of all variables that significantly affect pavement performance (the list of data elements required for current prediction models was included in Technical Memorandum - 1).
- An adequate functional form of the model.
- A model that meets the proper statistical criteria for precision and accuracy (error of prediction, coefficient of determination (R^2), etc.).

Each prediction model requires a unique set of inputs. The inputs can be obtained from the design and construction information, distress surveys, physical testing, nondestructive deflection testing, etc. In addition, many of the models require the user to calculate or select inputs based on a set of recommendations that accompanies the model. The models can be compared using a combination of statistical procedures and graphical examination of the results.

It is important to realize that the accuracy of the existing models, when used to predict performance of inservice pavements, cannot be determined conclusively with the available data. Until a more comprehensive data base is developed/completed (when the information from the SHRP-LTPP data base becomes available) that is considered representative of the entire population of pavements in the four environmental regions, it is impossible to determine the overall accuracy of the models, or to develop models that accurately reflect the total population of the pavements, or to improve existing models.

A ***Model Tool Box*** concept is proposed where models are compared and the best model is selected. Statistics can be used to compare the actual, field-measured performance indicators to those predicted by the various models. The basic measures used to examine the validity of any modeling technique are:

- Number of data points. Generally, a large number of data points results in a more valid prediction equation model.
- Coefficient of determination (R^2) which is used to show how much of the variation in the dependent variable is explained by the prediction equation.
- Standard error of the estimate (SEE) which is used to estimate the standard deviation of the dependent variable about the equation line and it is in units of the dependent variable.

CONCEPTS FOR MODELING EFFECTS OF M&R

Maintenance operations and rehabilitation operations are usually managed by different units within a highway agency. Since pavement maintenance can have a major effect on pavement performance and rehabilitation, lack of coordination between units responsible for pavement maintenance and rehabilitation may result in an inefficient utilization of resources. Therefore, a pavement management system should be able to address both maintenance and rehabilitation. Figure 15 shows the relative effect on performance of different rehabilitation types. Each alternative is appropriate for a certain pavement type and condition.

There are two kinds of consequences of major pavement rehabilitation: short term and long term. The immediate or short-term effect is due to the correction of pavement deficiencies, which usually results in an improvement in pavement condition. This is shown as a sudden jump in pavement condition in figure 16. The amount of improvements is based on the type of rehabilitation applied to the pavement, and in some cases the condition of the pavement before rehabilitation.

The long-term effect of the rehabilitation is the effect of the rate of deterioration. Usually, a major rehabilitation increases the structural capacity of a pavement and results in improved performance.

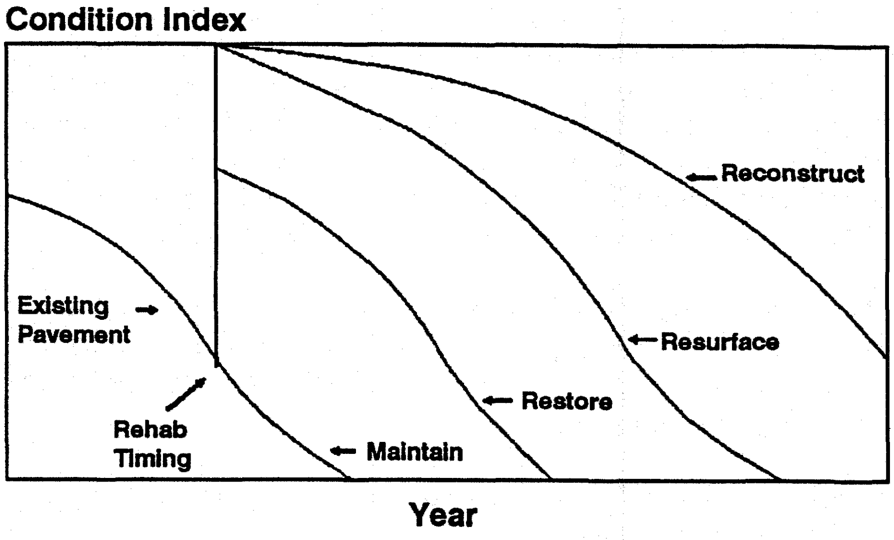


Figure 15. Relative effect on performance of different rehabilitation types.

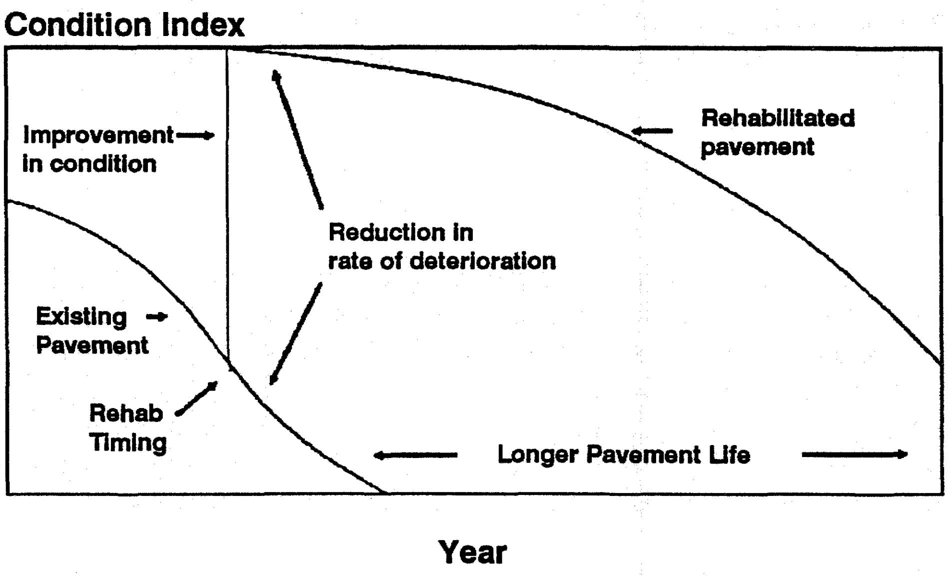


Figure 16. Immediate or short-term Effect due to the correction of pavement deficiencies (sudden jump in pavement condition).

When applying a surface treatment (flexible pavement), or performing localized repairs such as crack and joint sealing, the immediate increase in pavement condition is not representative of the expected increase in life. Therefore, this immediate condition increase is termed "Apparent Condition Improvement." As figure 17 illustrates, the effective increase in condition (ΔC) can only be determined several months or a few years after application of the surface treatment or localized repair. The ΔC is normally related to the increase in pavement life Δt. It may be more realistic to calculate ΔC based on an estimated Δt.(70) The Δt can be estimated from field experience. Also, research results from SHRP H-101 will most likely produce guidelines toward estimating Δt for various rehabilitation alternatives.

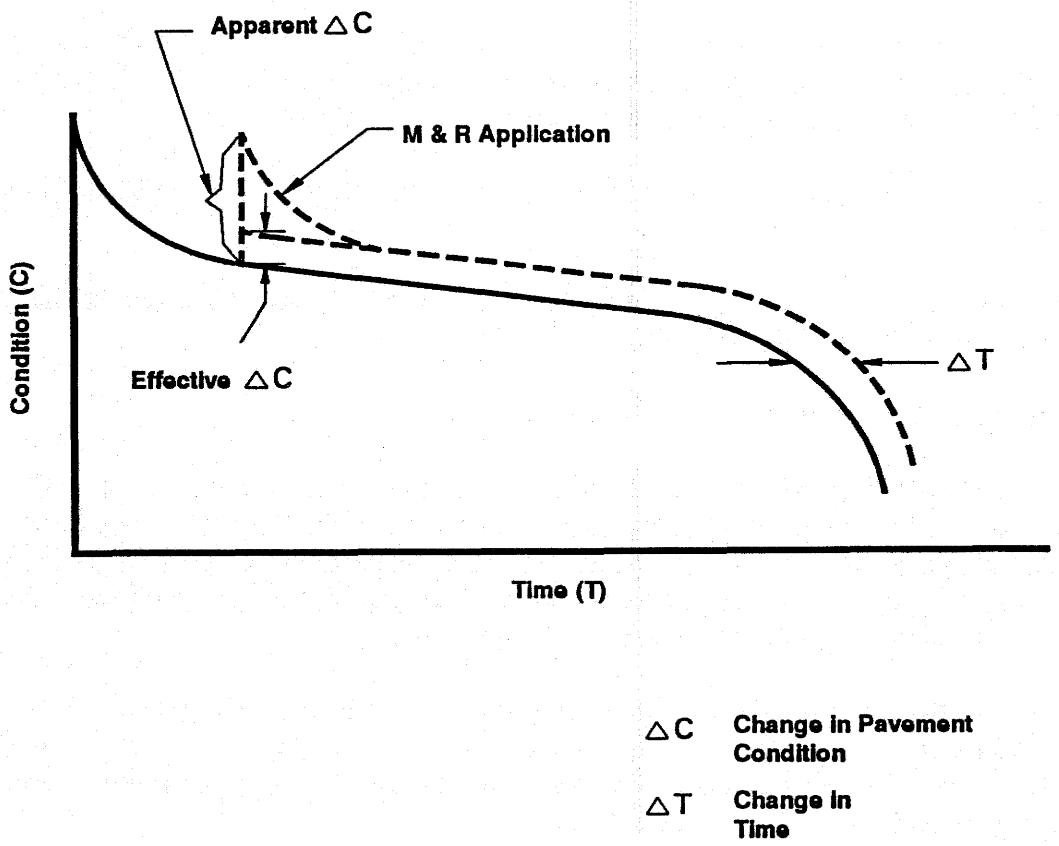


Figure 17. Apparent condition improvement and effective increase in condition.(70)

DEVELOP COMPUTER FLOWCHART OF LIFE COST ON CONCEPTUAL OPERATION OF A MODEL

A Pavement Management System is a "set of tools or methods that assist{s} decision makers in funding cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition."(73) The key elements of a PMS are: pavement inventory, a data base system, and data analysis and reporting capabilities.

The main component of any PMS is its pavement inventory, since all pavement evaluations and recommendation for rehabilitation and other pavement analysis are made based on various data collected for pavement sections in the network. These data consist of design, condition, traffic, climate, and many other type of information. The PMS component that makes it useful is data analysis and reporting. The data analysis and reporting capabilities of a PMS are its ability to utilize the collected data and other available knowledge to provide answers to a variety of questions. The main areas of data analysis are:

- Future condition prediction models.
- Project level rehabilitation needs analysis.
- Network level optimization analysis.
- Other special analysis.

In order to combine these main areas, a flow chart was developed.(74) The flowchart shown in figure 18 illustrates data requirements and conceptual operation of a microcomputer-based model to select and design maintenance and rehabilitation activities.

The flow chart is very much self explanatory, and the main steps can be summarized as follows:

- Identify Pavement Performance Indicators. The user will select the type of indicator such as roughness, PSR, PCI etc.

- Identify Data Elements involved in the analysis.

- Select the M&R activities. For all deficient pavement sections, one or several alternatives may be selected as candidate rehabilitation for the network analysis. Engineering judgement can also be the basis for the selection of rehabilitation type most appropriate for the pavement sections. This can also be accomplished in two ways: subjectively, and by the use of decision trees.

- Select performance prediction model from the ***Model Tool Box*** to predict the life of the M&R activity. In the ***Model Tool Box***, the user will find several prediction models that have been developed by different agencies to predict pavement serviceability, overall condition, distresses, etc.

- Evaluation and selection of the model. Statistics can be used to compare the actual, field-measured performance indicators to the performance indicators predicted by the various models. The basic measures used were described in an earlier section on modeling techniques.

- Calculation of Present Worth and Future Costs. Cost Data required for an economic analysis was discussed in chapter 5.

- Perform LCC. The LCC evaluates the economic consequence of different strategies and alternatives in terms of long-term costs. An economic analysis procedure is described in the next section.

- Optimize Network Budget including prioritization. The general formulation of optimization is to maximize (or minimize) the objective function in the presence of several constraints. In network level pavement management analysis, this formulation translates into either maximization of pavement investments (benefits) considering budget limitations, or minimization of network rehabilitation costs considering network performance standards. Optimization can consider several alternative strategies for every section in the network; thus trade-offs among projects are considered. Currently, the general trend is toward a network level management system that uses engineering judgement and deterministic knowledge (prediction and condition models), together with the optimization methods, in solving the network level problems.

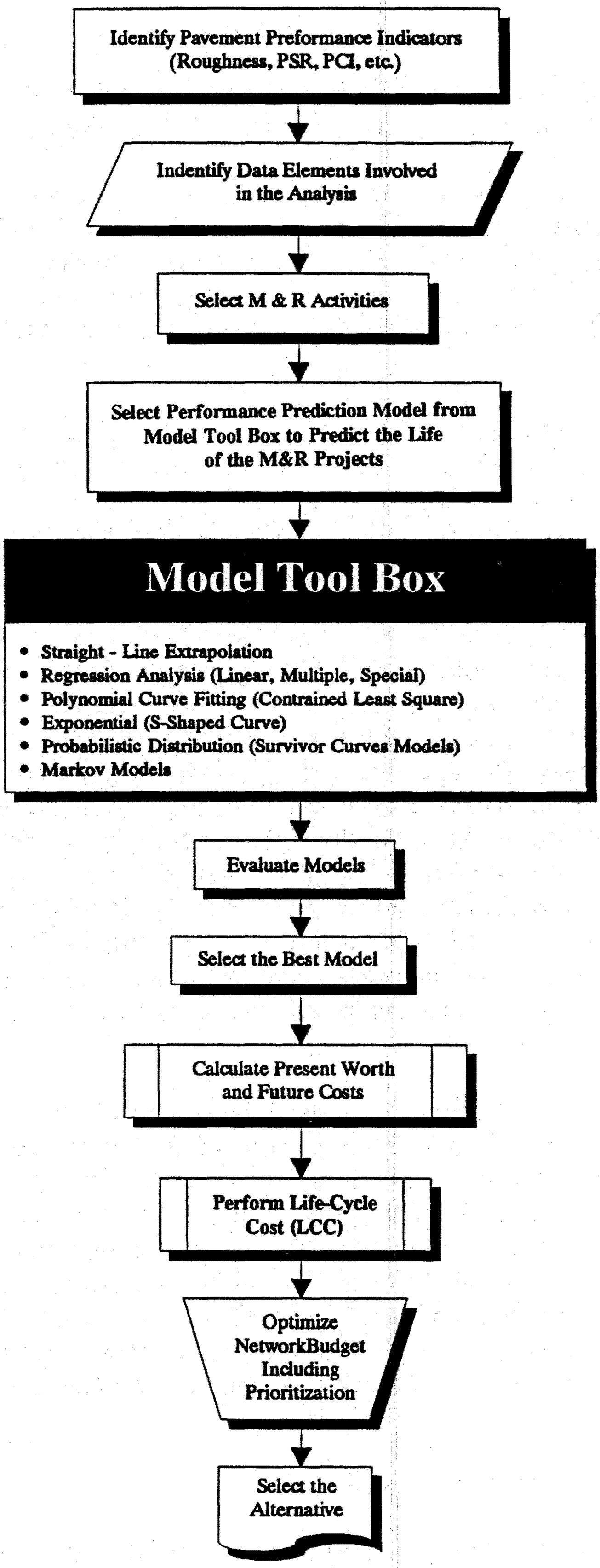


Figure 18. Flowchart for data requirements and conceptual operation of a microcomputer-based model to select and design M&R activities.(74)

- Selection of the alternative. The most important output from this process is to obtain the most economic M&R alternatives, and their timings, for each pavement section.

Several different algorithms exist for allocating pavement rehabilitation funds to different pavement sections an a network. These algorithms range from fairly uncomplicated (such as needs study and different ranking methods), to more complicated (such as long-range optimization). These algorithms are used for a variety of purposes, including network budget planning and performance analysis, allocation of funds to projects, and estimation of future budget needs.

In addition, the cost of rehabilitation for each section, the total rehabilitation cost for the network, and the measurable impact of the M&R program on network performance or benefit should be determined in a network analysis.

RECOMMENDED ECONOMIC ANALYSIS PROCEDURE

Economic decision analysis provides a decision support tool to evaluate the time value costs and benefits associated with systems analysis of the pavement network. Once the different maintenance strategies have been developed, the economic analysis is conducted. LCC analysis evaluates the economic consequence of different strategies and alternatives in terms of long-term costs. ***LCC requires a data base of performance and cost information, along with prediction models to estimate the initial effect and the life of various alternatives.*** LCC can be expressed in terms of their "present worth" (PW) or "equivalent uniform annual cost" (EUAC). The present worth method converts all future costs to their equivalent present costs, using a selected discount rate. The converted future costs can be combined with the initial construction cost to give the present worth cost over the analysis period. The EUAC method converts this present worth to an equivalent annual cost over the analysis period.

The analysis period refers to the time over which the economic analysis is to be conducted. In order to use the PW method, the analysis periods of all alternatives being considered must be equal. New construction design alternatives which have equal design lives (i.e., are designed for the same traffic over the same number of years) can easily be evaluated over the same analysis period.(75) However, life-cycle cost comparisons must at times be made among alternatives with unequal lives. A considerable amount of engineering judgement is required to adapt maintenance strategies or pavement alternatives, so that they may be compared over equal analysis periods using the present worth method. The best solution is to compare equivalent uniform annual costs, which does not require equal analysis periods.

The following general procedure can be used:

- Develop different maintenance strategies over a selected analysis period.

- Decision factors considered important in selecting the preferred alternatives are chosen. These are: initial cost, pavement extension life, repairability and maintenance effort, rideability, etc.

- The decision factors must be weighted. Some decision factors are typically more influential on the final decision than others. This weighing must be done by a group representative of the agency that is involved in decision making.

- Any needed analyses are performed to supply information about each of the alternatives (e.g., construction cost, future maintenance and rehabilitation costs, etc.).

- Calculate the initial cost in present-day dollars for each alternative, as well as future maintenance and rehabilitation costs in present-day dollars.

- Perform the economic analysis using EUAC method for each of the alternatives.

- Compare the EUAC among the alternatives. This value is particularly important since it represents the "average" annual cost per yd^2 of pavement surface that the agency will be paying over the analysis period.

There is no universally accepted method for performing an economic analysis, or for developing feasible design alternatives for a highway improvement. A considerable amount of professional engineering judgement must be applied to each project. Also, design alternatives must be selected within the framework of the overall management of the pavement network.

SUMMARY

The prediction models categorization and modeling techniques currently used were described in this chapter. A Model Tool Box concept was proposed where models are compared and the best model is selected. A flowchart was prepared to illustrate data requirements and conceptual operation of a microcomputer-based model to select and design maintenance and rehabilitation alternatives.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this report was to summarize existing pavement condition indices, report available prediction models for each of the condition indices, and identify existing data bases where required variables for the prediction models are collected. The condition indices and their prediction models are presented in chapter 2. A description of selected data base is presented in chapter 3. The presented data bases are: HPMS, SHRP LTPP, COPES, FHWA Design, FHWA Rehabilitation, Texas CRCP, and FMIS. A brief analysis and evaluation of each of the data bases is presented in chapter 4. Chapter 5 presents the detailed data elements that are significant in the SHRP-LTPP data base, as well as data elements for future development models and data elements unavailable in the data base. Chapter 6 describes types of prediction models and modeling techniques currently used. The prediction models are classified and categorized according to modeling techniques. A computer flow chart is developed to illustrate data requirements and conceptual operation models to select and design maintenance and rehabilitation alternatives.

CONCLUSIONS

Regardless of how models are developed, or what types of variables enter into the models or their formulation, the key element in developing or reviewing prediction models is the pavement inventory. Without well defined and well prepared data and an efficient data base system, developing reliable prediction models may not be possible.

The data elements in the SHRP data base are sufficiently detailed to provide a base for further analysis of the models, to validate their applicability under many different conditions, and to propose modifications to the existing models which could extend their usefulness.

Prediction models were discussed and categorized highlighting the measures employed for evaluating the road condition. Judging from this, models for flexible pavements are more plentiful than for rigid pavements.

For the most part, the present deterioration prediction models have been statistically estimated from field data and structures on mechanistic principles of pavement behavior. The methodologies used are empirical, developing parametric models by statistical regression of time-series data which had been collected in studies of inservice pavements. The majority of the models predicted the absolute value of pavement measure, employing the explanatory variables of structural, traffic, and environmental factors.

The emphasis in this study was on the development of modeling tools rather than the development of specific models. The ***Model Tool Box*** will allow each user to be able to develop models that are unique to their environment, soil type, and types of M&R most frequently used.

RECOMMENDATIONS

Many enhancements can be done to improve this study. These range from enhancements to data elements and prediction models, to improvements to benefit functions and network level analysis. The following are recommendations for work in this area:

- It is recommended to implement the results of this study. It is anticipated that the Model Tool Box cannot be developed initially to cover every possible M&R alternative, nor can it cover every pavement type and condition indicator. The Model Tool Box will consist of modeling techniques and default models. The default models will be used directly or calibrated by users who have sufficient data.

- Prediction models must be field verified.

- The use of a more objective condition measure (for example the international roughness index) should be encouraged.

- Improved prediction models are necessary for AC overlaid pavements. Models for rutting of the AC layer and reflective cracking for overlays of JRCP and CRCP are needed. Separate models for pavements with more than one overlay may also be necessary, if they exhibit different performance.

- Assess the effectiveness of other maintenance treatments. Predicting the effectiveness of different maintenance treatments is far more difficult than predicting pavement condition.

- Continue to gather better and more extensive input data. Many reasonably good models are available, but in many cases, there is a severe lack of good input data for the models.

- Develop a model tool box approach that will allow local engineers to work with National level models and refine them using local data, while maintaining the appropriate level of statistical corrections and accuracy.

- Better models are needed for optimizing pavement expenditures, to ensure that the agency receives the greatest benefit from available funds.

- Improved prediction models are needed for both project and network levels, for predicting future condition or performance of pavements if nothing is done, or if different strategies or treatments are used.

- There is a need for more and better cost data, particularly in maintenance.

- There is a need for uniform and accurate measures of maintenance over time. This condition data, together with corresponding information that characterizes the maintenance, quantifies its exposure to climatic and traffic influences, and documents all maintenance or rehabilitation treatments with respect to type, extent and timing, will provide the data that can be analyzed to create better prediction models.

- There is a need for developing new models to consider the "D" cracking in concrete pavements, and prediction models for new types of rehabilitation such as crack and seat, and full-depth asphalts.(52)
- There is a need for developing new models to consider the effects of M&R on future pavement performance.

In this chapter, several potential enhancements and improvements have been identified. The enhancements and improvements proposed here would only serve to build the strong foundation that has already been put in place.

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