1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-92/1259-1F		

4. Title and Subtitle	5. Report Date
A Proposed Bridge Management System Implementation Plan for Texas	May 1993
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Ray W. James, George Stukhart, W. Frank McFarland, Alberto Garcia-Diaz, Roger P. Bligh, Satindar Baweja, and John O. Sobanjo	Research Report 1259-1F

9. Performing Organization Name and Address	10. Work Unit No.
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	
	11. Contract or Grant No.
	Study No. 2-5-91/2-1259

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Transportation Planning Division P. O. Box 5051 Austin, Texas 78763	Final-November 1990- December 1991
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration

Research Study Title: Development of Engineering Processes for a Comprehensive Bridge Management System for Texas

16. Abstract

This report describes the engineering processes, information requirements, and recommended framework for a comprehensive bridge management system (BMS) designed to meet the needs and resources of the Texas Department of Transportation. Engineering processes and algorithms were developed for various submodels which will comprise the overall BMS structure. These include level of service goals, unit costs data, deterioration models, a feasible improvements knowledge-based system, life-cycle cost models incorporating agency benefits, a user benefits model, and optimization procedures. The engineering information requirements for each of these submodels were identified, and procedures for articulation of the submodels into an integrated BMS structure were outlined. The BMS was designed for application at both the state and district levels. Future effort required includes computerization and implementation of the processes, algorithms, and procedures contained within this report.

17. Key Words	18. Distribution Statement
BMS, bridge management systems, bridges	No restrictions. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	144	

Form DOT F 1700.7 (8-69)

SUMMARY

This report covers a one-year study of the models and procedures (engineering processes) necessary for programming and implementation of a proposed comprehensive bridge management system (BMS) for the Texas Department of Transportation.

SUMMARY STATEMENT ON RESEARCH IMPLEMENTATION

Immediate, phased implementation is recommended in this report. Specifically, implementation should be accomplished by programming the necessary computer codes with close engineering interaction. Initially, the identified fundamental codes should be programmed for application on central mainframe computers with future portability and PC/mainframe communications in mind. Second, user-friendly, interactive, PC-based codes should be developed for pre- and post-processing tasks. Also, interaction with other proposed or developing systems (including GIS, pavement management systems, safety management systems, congestion management systems, etc.) should be kept in mind.

ACKNOWLEDGEMENTS

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views, opinions, or policies of the Texas Department of Transportation or the Federal Highway Administration (FHWA). Currently, at the submittal of this report, TxDOT is examining whether to continue with programming and implementation efforts for the BMS described herein or to adopt the PONTIS bridge management system which was developed under an FHWA contract since the inception of this project. This report is being published as documentation of work performed and does not necessarily constitute a decision on which BMS TxDOT will officially adopt. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes.

A PROPOSED BRIDGE MANAGEMENT SYSTEM IMPLEMENTATION PLAN FOR TEXAS

by

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George Stukhart
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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in²	square inches	645.2	centimetres squared	cm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	In
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

°F -40   0   32 40   80   98.6 120 160 200 212 °F

°C -40 -20   0   20   37 40   60   80   100 °C
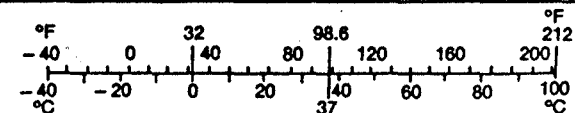
These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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INTRODUCTION

This report identifies engineering aspects of models recommended for a proposed Bridge Management System (BMS) for Texas and defines the data needed to implement the models discussed. Various models of bridge deterioration have been studied, along with other BMS components such as the Feasible Alternatives Synthesizer, the Bridge Maintenance Model, the Bridge Cost Model, the Benefits Model, the Optimization Model, and the Bridge Inspection procedures.

A satisfactory method for quantifying maintenance effectiveness could not be developed because of the scarcity of data. It should be noted that maintenance options are not considered by other proposed or developing bridge management systems. In this approach, it is proposed to consider maintenance activities separately from other bridge management activities such as rehabilitation and replacement. Instead, local (district level) expert judgement should be used to develop recommended maintenance strategies, rather than selection of optimal strategies by economic analysis. If, through eventual implementation and usage of the proposed bridge management system, sufficient data on maintenance effectiveness can be developed to quantify the effectiveness in retarding deterioration of various different maintenance alternatives, the maintenance alternatives may be quantitatively compared by the optimization process proposed in parallel with the other bridge management actions. The only maintenance level considered in the proposed BMS will be "normal" maintenance, defined to be those maintenance practices which have led to the present conditions of the bridge components in Texas.

Report 1212-1F discussed the general situation with regard to bridge maintenance in Texas. Most bridge maintenance in the Department is done on an as-needed basis, and there is actual scheduling of preventive maintenance. This is not uncommon. Most maintenance managers are confronted with severely limited resources and increasing needs for these resources. Nevertheless there is a need for greater maintenance effort to prolong the life of bridges; such expenditures would result in the postponement of capital outlays. It is recognized that maintenance will achieve these benefits through the reduction in the rate of deterioration, but it is difficult to quantify the benefits of maintenance in the same fashion as rehabilitation, improvement, and replacement. As a result, maintenance costs and benefits cannot be optimized as an integral element of the bridge management system.

Several studies have treated maintenance prioritization, and several routines have been developed using expert opinion to decide ideal maintenance levels within budget constraints (Nash and Johnston 1985, Harper 1990). Although these studies optimize maintenance policies within budget constraints, the relationship to reduction in capital costs is not shown. A few papers, such as those by New York State (Thomas and DeFabio 1988) and New York City (Consortium 1990) discuss such a relationship. They indicate that an increased expenditure of a certain amount of maintenance funds will prevent "good" bridges from becoming deficient. For example, New York State

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reports that capital costs of $66 million could be postponed by the expenditure of $15 million in maintenance. This study (Thomas and DeFabio) was based on reports that indicated 215 bridges per year would become deficient at a cost of $100 million. By way of comparison, the Strategic Highway Mobility Plan for Texas indicates that 370 on-system bridges will become deficient during the five-year period starting in the year 2000 at a cost of $67 million. There is no estimate of the corresponding preventive maintenance needed to maintain the state of deterioration on these 370 bridges at the same level as the average of the 1990-1995 period. The cost data necessary to show such savings is not available in Texas. However, using the data from New York would indicate that preventive maintenance should average $4-5 million per year for this group of bridges, reaching the age that rehabilitation or replacement becomes necessary in ten years. If all the other age windows are considered, one could probably show that an annual preventive maintenance budget of $15-20 million would not be unreasonable.

RECOMMENDED ENGINEERING ASPECTS OF PROPOSED BRIDGE MANAGEMENT SYSTEM

The stated objective of Task 1 is to develop and recommend engineering aspects of analytical tools and procedures to accomplish the following tasks:

- Objectively assess needs and set strategies for maintenance, rehabilitation, improvement, and replacement of the state's bridges,
- Select and prioritize projects for the comprising of district and state network level programs of work, and
- Coordinate inspection, maintenance, design, and construction at the district and state level.

The BMS model proposed in Study 1212 is being extended and modified to address these tasks. The model proposed earlier serves as the basic framework for the proposed BMS presented here.

Related to Task 1 is Task 3, which was to develop the engineering processes for the submodels required in the recommended BMS. The findings and recommendations resulting from the study Tasks 1 and 3 are reported in the following sections.

Deterioration Model

As potential components of the framework of a BMS, the following forms of bridge deterioration models have been investigated as to their suitability for use as analytical tools: regression models (simple linear, piecewise-linear, and nonlinear) based on the available bridge condition data (BRINSAP); probabilistic models (including Markov processes); and simple linear models based on the expert opinions of Texas bridge personnel. Because of considerable scatter in the available data, a statistically acceptable fit of any of the models cannot be developed. However, the nonlinear model proposed by West et al. (1989) can be used to describe a reasonable lower bound to the condition-vs-age data, as discussed below, and is proposed as a basic model of condition deterioration.

The benefits of a bridge deterioration model include its possible use by the bridge engineer to predict the future deteriorated condition of the bridge or its structural components. The deterioration model can also be used to compute the expected condition of a bridge after maintenance, rehabilitation, or replacement (MR&R). In other words, the effectiveness of the bridge MR&R activity is reflected on the bridge deterioration process.

Prediction of Bridge Condition

As mentioned in the study conducted using Texas bridges (Study 1212) and also noted by West et al. (1989), the available data on bridge condition at most state transportation agencies are such that the effects of the "hidden" or undocumented maintenance and rehabilitation activities previously done to the bridge cannot be adequately accounted for in modeling the bridge deterioration. Thus, some of the models formulated based on this available data, such as the exponential models, will predict unrealistic estimates of a bridge service life; the exponential curve flattens out as the bridge ages. To resolve this problem, West et al. proposed using a linear

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approximation of the models. West suggested that the exponential curves formulated from the existing bridge data be used to predict bridge condition under normal maintenance and rehabilitation, but that a simple linear model -- a tangent to the curve at the vertical intercept -- will be more realistic in predicting the true bridge condition. This linear model is assumed to represent the "natural" deterioration of the bridge with no maintenance or rehabilitation.

Instead of this tangent as the linear approximation, it may be more realistic to use the simple linear deterioration models derived in Study 1212 based on the expert opinions elicited from the Texas DOT bridge personnel. Examples of three forms of bridge deterioration models include: (1) a two-parameter exponential deterioration models for steel superstructures on interstate highways fit to NBI data; (2) a linear approximation model tangent at age 0 to the exponential curve suggested by West et al. (1989); and (3) a simple linear deterioration model for steel superstructures based on the bridge experts' "most likely" estimates. A comparison of the three models is illustrated in Figure 1.

As an illustration, consider a steel superstructure on an interstate highway. With the aid of these three forms of deterioration models mentioned, the condition rating of the superstructure can be predicted as follows:

(1) Using a two-parameter exponential model:

$$CR(t) = \beta_1 e^{-t/\beta_2}$$

where

$$
\begin{aligned}
CR(t) &= \text{Bridge component condition rating,} \\
t &= \text{Age of the bridge (yr),} \\
e &= 2.7183..., \text{base of natural logarithms,} \\
\beta_1 &= \text{Average estimate of initial bridge CR, and} \\
\beta_2 &= \text{Exponential decay coefficient.}
\end{aligned}
$$

From results of Study 1212, $\beta_1 = 7.938$, $\beta_2 = 184.626$. Therefore, the expected condition rating of the superstructure at an age of 50 years is

$$CR(50 \text{ yr}) = 7.938 \ e^{(-50/184.626)} = 6.055 = 6.$$

(2) Using the tangent linear approximation model:

The slope of the linear model is given by the derivative of the exponential curve at $t = 0$, i.e. the ratio β_1/β_2. The deterioration equation of the simple linear model is:

$$CR(t) = \beta_1 - (\beta_1/\beta_2)t.$$
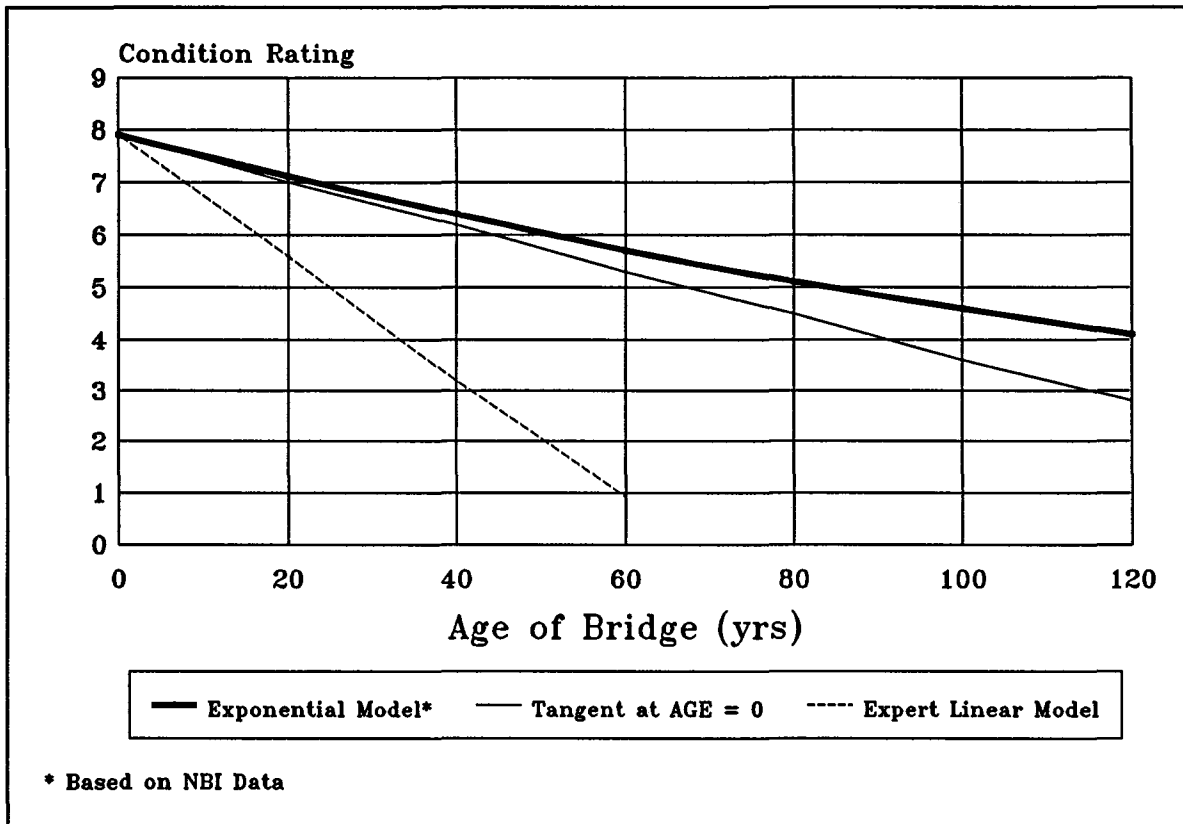
Figure 1. Deterioration Models for Steel Superstructures on Interstate Highway

Again, from Study 1212, β_1 = 7.938, β_2 = 184.626. Therefore, the expected condition rating of the superstructure at an age of 50 years is

$$CR(50 \text{ yr}) = 7.938 - (7.938/184.626)(50) = 5.789 = 6.$$

(3) Using simple linear models based on expert opinions:

The deterioration equation for steel bridge superstructures is

$$CR(t) = 7.864 - 0.117t.$$

Therefore, the expected condition rating of the superstructure at an age of 50 years is

$$CR(50 \text{ yr}) = 7.864 - 0.117(50) = 2.014 = 2.$$

This difference in the expert opinion and in the regression curves for the expected condition at 50 years is significant, and an explanation for the difference is not known. The biasing of the historical data with maintenance and undocumented rehabilitation activities is thought to be the most important factor. As will be discussed later, the proposed models based on lower bounds to the historical data offset this biasing to some extent.

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Fitting the West Model to Historical Data for Texas Bridges

Data for Texas bridges was obtained from TxDOT and FHWA NBI archives for the years 1978, 1983, and 1988. This data was analyzed by geographic region, using the five regions identified in Report 1212-1F, as shown in Figure 2. It should be emphasized that the analysis reported herein is based on the regions identified in 1212-1F (Figure 2) and on the district boundaries. The results are expected to be valid for the new regions, however, or for any other similar district boundary definition which may result. Within each region, the condition ratings for the major components (roadway, superstructure, and substructure) were analyzed with respect to age, material of construction, and class of service to determine by regression the parameter β_2. Other independent variables were

Figure 2. Geographical Regions Proposed for Purposes of Modelling Bridge Component Deterioration

considered, particularly ADT, but the scatter in the data prevents meaningful correlation to other parameters. Bridges with indication of rehabilitation were omitted from the analysis since the rehabilitation destroys the relationship between condition and age. However, some unknown amount of "rehabilitation," that is, actions which have improved the condition ratings of the components, may have been accomplished by state maintenance forces without federal aid and would, therefore, not be indicated in the BRINSAP records. This means that some, perhaps many, of the condition rating data points will be artificially above the desired CR versus age curve. The statistical analysis indicated that scatter in the data was very significant, and there was no statistical correlation of CR to age. Because of this, a different approach has been taken.

Based on the assumption that the lower bound of the data represents the actual deterioration of structures in service without the benefit of significant maintenance or rehabilitation, the West model is fitted to the lower bound of the widely scattered data, as follows. The value of the parameter β_2 which will cause 5 percent of the component condition values to fall below the curve is selected. A representative result of this process is shown in Figure 3. It is noted that this approach will provide values that are sensitive to the scatter in the data. As noted below, several of the calculated entries are judged to be unrealistic by comparison with the remainder of the calculated entries, and values based on expert judgement are suggested instead.

The results of the regression are presented in Table 1 through Table 5 for the 5 regions defined. Because of the small number of bridges sampled in some categories, the reported values of the parameter β_2 are sometimes unrealistic. It is suggested that only those values based on sample sizes of more than ten bridges be used. Where less than ten data points are available or where the calculated entry is judged to be unrealistic, the data in the tables
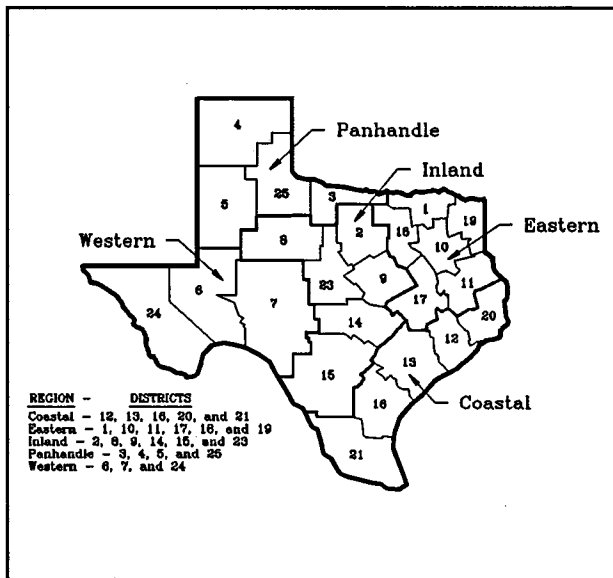
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should be replaced by data based on engineering judgement and other table entries. The table entries shown in italics are so obtained.

A crude measure of the effect of the combination of maintenance and undocumented rehabilitation is seen in the difference between the values of the parameter β_2 reported in Table 1 through Table 5 and the corresponding value reported in Report 1212-1F. (Note that the negative signs associated with β_2 in Report 1212-1F should be disregarded.) For example, the value $\beta_2 = 184$ years in the steel superstructure example discussed earlier is approximately 600 percent of the corresponding value reported in the tables in this section. The combined effects of undocumented rehabilitation activities and of maintenance activities thus significantly reduce the net deterioration rate of steel superstructures.

Effectiveness of Bridge Maintenance and Rehabilitation on Deterioration

In a network level allocation of funds for

Figure 3. Fit of West et al. Model to Texas Data for 1500 Concrete Bridge Decks on State Highways in the Coastal Region

bridge maintenance, rehabilitation, and replacement (MR&R), the multi-period optimization model may be used. At any stage or period of the planning horizon specified in this optimization model, a bridge is selected to be improved with a particular MR&R strategy. Since the MR&R strategy is intended to improve or at least preserve the deteriorated state of the bridge, it will be necessary to compute and update the expected new condition or state of the bridge. The bridge deterioration models formulated in this study may be used to accomplish this. Once a particular MR&R strategy is selected for a bridge, the condition rating is updated, and the deterioration process is assumed to follow the modeled pattern in the remaining time of the specified planning horizon. If within this planning horizon the same bridge deteriorates to a state below the level of service desired, it should considered again by the optimization model. Thus, funds may be allocated for a particular bridge more than once in the planning horizon based on the interaction between the bridge deterioration model and the network optimization model. As demonstrated in the following sections, the various bridge deterioration models can be combined with estimates of expected extension in bridge service lives from Study 1212 to derive updating equations for bridge deterioration.

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Table 1. Values of β_2 (yr) for Texas Bridges in Coastal Region (Numbers in italics are based on engineering judgement; total number of bridges used in analysis shown in parentheses)

Class	Component	RC	PS CONC	STEEL	TIMBER	OTHER
FM Hwy	Deck	44.1 (2625)	12.0 *[35]* (12)	32.0 (12)	33.0 (52)	50.8 (1275)
	Super-structure	52.0 (1908)	27.4 *[40]* (171)	48.3 (240)	45.1 (61)	35.0 (15)
	Sub-structure	44.1 (2013)	----	46.2 (252)	34.0 (70)	42.0 (60)
Interstate Hwy	Deck	31.1 (1999)	----	----	----	46.3 (285)
	Super-structure	41.6 (555)	40.7 (966)	31.0 (508)	----	----
	Sub-structure	30.6 (1968)	----	41.5 (40)	----	52.0 (24)
State Hwy	Deck	39.4 (1500)	43.0 *[35]* (6)	44.0 *[35]* (4)	----	41.5 (393)
	Super-structure	43.4 (726)	30.6 (432)	40.7 (258)	162.0 *[40]* (4)	29.0 *[40]* (9)
	Sub-structure	34.0 (1365)	----	27.5 (30)	162.0 *[40]* (4)	46.5 (33)
US Hwy	Deck	34.4 (2110)	26.0 *[35]* (6)	----	----	38.1 (468)
	Super-structure	38.8 (726)	40.3 (822)	40.4 (541)	----	----
	Sub-structure	36.6 (1959)	----	56.0 (72)	3.0 *[40]* (3)	45.6 (51)

Table 2. Values of β_2 (yr) for Texas Bridges in Eastern Region (Numbers in italics are based on engineering judgement; total number of bridges used in analysis shown in parentheses)

Class	Component	RC	PS CONC	STEEL	TIMBER	OTHER
FM Hwy	Deck	53.8 (2598)	----	----	25.0 (25)	67.4 (831)
	Super-structure	52.4 (2385)	28.3 (33)	48.8 (174)	25.5 (22)	----
	Sub-structure	27.1 (1773)	----	39.0 (669)	24.0 (28)	29.0 (144)
Interstate Hwy	Deck	44.5 (802)	----	----	----	68.6 (360)
	Super-structure	46.2 (477)	41.1 (156)	61.9 (178)	----	----
	Sub-structure	46.6 (807)	----	----	----	82.0 *[40]* (4)
State Hwy	Deck	42.3 (861)	3.0 *[35]* (3)	10.0 *[35]* (4)	----	60.0 (414)
	Super-structure	43.3 (564)	21.5 (69)	46.5 (276)	103.3 *[40]* (10)	----
	Sub-structure	42.3 (780)	----	25.9 (93)	42.0 (22)	13.5 *[40]* (27)
US Hwy	Deck	27.0 (793)	----	----	----	88.8 *[40]* (225)
	Super-structure	32.1 (501)	21.6 (150)	32.9 (253)	----	----
	Sub-structure	30.4 (846)	----	30.0 (30)	10.0 *[30]* (10)	18.2 *[30]* (18)

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Table 3. Values of β_2 (yr) for Texas Bridges in Panhandle Region (Numbers in italics are based on engineering judgement; total number of bridges used in analysis shown in parentheses)

Class	Component	RC	PS CONC	STEEL	TIMBER	OTHER
FM Hwy	Deck	42.7 (966)	----	164.0 *[40]* (4)	----	29.2 (237)
	Super-structure	35.4 (813)	63.5 (27)	61.4 (106)	----	86.0 *[65]* (6)
	Sub-structure	55.4 (561)	----	41.8 (334)	----	97.0 (57)
Interstate Hwy	Deck	26.3 (448)	----	----	----	103.0 *[30]* (3)
	Super-structure	26.1 (63)	43.3 (228)	30.8 (151)	----	----
	Sub-structure	40.6 (429)	----	33.0 (13)	----	----
State Hwy	Deck	23.7 (454)	23.0 *[35]* (3)	----	----	58.3 (195)
	Super-structure	33.3 (186)	27.9 (159)	45.9 (139)	----	----
	Sub-structure	32.3 (381)	----	33.7 (82)	----	301.0 *[65]* (21)
US Hwy	Deck	26.4 (688)	----	----	----	40.3 (144)
	Super-structure	36.5 (321)	42.7 (258)	40.2 (184)	----	----
	Sub-structure	35.4 (651)	----	30.0 (100)	----	12.0 *[65]* (12)

Table 4. Values of β_2 (yr) for Texas Bridges in Western Region (Numbers in italics are based on engineering judgement; total number of bridges used in analysis shown in parentheses)

Class	Component	RC	PS CONC	STEEL	TIMBER	OTHER
FM Hwy	Deck	43.5 (715)	----	----	----	65.4 (528)
FM Hwy	Super-structure	51.8 (507)	10.0 *[40]* (30)	42.6 (97)	----	----
FM Hwy	Sub-structure	45.1 (510)	----	45.3 (82)	----	21.0 *[45]* (42)
Interstate Hwy	Deck	35.5 (2077)	----	----	----	51.9 (198)
Interstate Hwy	Super-structure	45.3 (1038)	24.2 (705)	43.3 (238)	----	----
Interstate Hwy	Sub-structure	30.7 (1650)	----	45.5 (33)	43.3 *[40]* (10)	56.9 (288)
State Hwy	Deck	42.9 (370)	----	----	----	67.8 (258)
State Hwy	Super-structure	47.8 (186)	48.5 (51)	50.8 (94)	----	----
State Hwy	Sub-structure	37.3 (297)	----	67.0 *[40]* (7)	----	107.0 *[40]* (27)
US Hwy	Deck	31.0 (661)	----	----	----	68.7 (321)
US Hwy	Super-structure	39.2 (330)	29.1 (111)	36.8 (184)	----	----
US Hwy	Sub-structure	33.6 (561)	----	41.0 (42)	4.0 *[40]* (4)	38.0 (18)

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Table 5. Values of β_2 (yr) for Texas Bridges in Inland Region (Numbers in italics are based on engineering judgement; total number of bridges used in analysis shown in parentheses)

Class	Component	RC	PS CONC	STEEL	TIMBER	OTHER
FM Hwy	Deck	49.2 (4059)	----	----	62.0 *[30]* (4)	50.4 (429)
	Super-structure	62.9 (3393)	26.1 (231)	62.9 (468)	124.0 *[40]* (4)	92.0 (12)
	Sub-structure	5.7 *[45]* (3072)	----	56.9 (810)	96.0 *[65]* (16)	64.5 (207)
Interstate Hwy	Deck	23.4 (5644)	----	----	----	32.8 (150)
	Super-structure	40.3 (1524)	22.2 (2454)	30.6 (1834)	----	----
	Sub-structure	28.8 (5484)	----	28.0 (16)	----	44.8 (318)
State Hwy	Deck	33.6 (2341)	43.0 *[40]* (3)	----	----	58.8 (228)
	Super-structure	54.5 (1137)	28.6 (663)	41.8 (720)	144.0 *[40]* (4)	283.0 *[40]* (3)
	Sub-structure	40.7 (2217)	----	64.5 (183)	44.0 *[40]* (4)	43.4 (141)
US Hwy	Deck	22.5 (2124)	30.8 (21)	----	4.0 *[25]* (4)	54.7 (138)
	Super-structure	41.1 (888)	20.0 (681)	36.5 (666)	4.0 *[40]* (4)	----
	Sub-structure	28.1 (2031)	----	52.3 (123)	10.0 *[30]* (10)	79.2 (117)

As mentioned earlier, some bridge deterioration equations or models were formulated in the form of simple linear models based on the expert opinions of the Texas DOT bridge engineers. For illustration purposes, consider these models for a reinforced concrete bridge, that is, the bridge deck, superstructure, and substructure are all made of reinforced concrete. Using the "most likely" estimates of the experts as reported in Study 1212, the deterioration equations are as follows.

Deck:	$CR(t) = 7.560 - 0.145t$
Superstructure:	$CR(t) = 7.775 - 0.107t$
Substructure:	$CR(t) = 7.740 - 0.107t$

Bridge Condition Updating Equations

A survey of expert opinion on the expected extension in the service lives of bridge components due to limited or major rehabilitation was conducted as part of Study 1212 (see Report 1212-1F, Appendix G). Consider the particular case of a reinforced concrete bridge deck. Assume, for example, that the deck is at a condition rating 4, the superstructure at a condition rating 4, and the substructure at a condition rating 5. If a limited rehabilitation is done to the entire bridge structure, the "most likely" estimates of expected extension in service lives, according to bridge experts, will be 4.2 years, 5.1 years, and 6.9 years for the deck, superstructure, and substructure respectively. Using these estimates, the original deterioration models can be modified into updating equations as follows.

Deck:	$CR(t) = 7.560 - 0.145(t - 4.2)$
Superstructure:	$CR(t) = 7.775 - 0.107(t - 5.1)$
Substructure:	$CR(t) = 7.740 - 0.107(t - 6.9)$

In general, a simple linear deterioration model of the form

$$CR(t) = C - m[t]$$

can be modified to include the effects of rehabilitation as follows.

$$CR(t) = C - m[t - e]$$

where

$CR(t)$ = Expected condition rating of the bridge component at age t,

C = Initial (age 0) condition rating of the bridge component,

m = Estimated deterioration rate, yr^{-1},

t   = Age of the bridge component, yr, and

e   = Estimated extension in service life, yr.

Thus, if the estimate of e is known at any period of the planning horizon, the condition rating of the bridge can be updated using these equations. A similar modification of the nonlinear deterioration models may be developed by extension. As better estimates of the extension in life, e, are developed, the data may be used to improve the condition updating equations. As a default, the estimates reported in Appendix C of Report 1212-1F are suggested.

Feasible Alternatives Synthesizer

The proposed feasible alternatives synthesizer (FAS) is a knowledge-based system (KBS), sometimes referred to as an expert system, which will use existing engineering knowledge about bridge maintenance, rehabilitation, improvement, and replacement to suggest one or more feasible alternatives for each bridge considered. The knowledge employed will be drawn from the technical literature or will be formulated from existing practices. Knowledge which has been identified includes rules by Harper et al. (1990) and Zuk (1987), who present knowledge in the form of expert system rules. Other rules will be formulated from existing FHWA-approved TxDOT policy for present decision making processes. This process is documented and implemented by the TEBS program (Boyce et al. 1987). The level of service (LOS) criteria initially proposed by FHWA for use with BMS is used to develop rules for improvement alternatives. Finally, rules based on accepted bridge engineering practices in other states will be formulated and evaluated.

The FAS uses bridge data acquired from the Bridge Inventory, Inspection, and Appraisal Program (BRINSAP) database (SDHPT 1984). The BRINSAP database contains nearly 100 items of data related to the structural and functional condition of bridges. Only a portion of this data is needed by the feasible alternatives synthesizer to suggest appropriate alternatives for each bridge considered in sequence. The data is downloaded for each bridge from BRINSAP and used in the FAS expert system.

It is noted that most of the expert knowledge discussed above addresses primarily the question of rehabilitation or replacement. Maintenance, especially a determination of an appropriate level of maintenance, is not addressed by the knowledge described above. Additional maintenance rules can be formulated based on information gained from TxDOT and other bridge engineers. It is anticipated that knowledge about preventive maintenance effectiveness within Texas will be insufficient by itself. The problem in Texas, and in most states, is that preventive maintenance has generally not been practiced or evaluated for effectiveness. This problem will be addressed by using expert opinion (rather than expert knowledge) to formulate estimates of maintenance effectiveness, ie. reduced deterioration rates, for one predefined level of maintenance, denoted "ordinary" maintenance. A higher level of maintenance, "extraordinary" maintenance, may be appropriate on certain structures. Effectiveness data for extraordinary maintenance has not been developed. One other level of

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maintenance, "deferred," will represent the base case of no preventive maintenance and will serve as a reference for measurement of effectiveness of ordinary and extraordinary levels of maintenance. To provide a common understanding, the definitions of these maintenance levels as used in this report are presented below, along with several related terms:

Maintenance is any field action taken to reduce or eliminate the rate of deterioration of the bridge or its components. Maintenance can be classified as either scheduled (sometimes called preventative maintenance) or unscheduled (sometimes called corrective), depending on whether the action is accomplished at regular, planned intervals or in response to perceived increased rates of deterioration. Traditionally the term "maintenance" has been used to refer to work accomplished by "maintenance" forces and may include some actions which do not fit the above definition. In this study, attention is limited to scheduled maintenance. Three levels of scheduled maintenance are defined as follows:

Deferred Maintenance is the policy of expending no effort or funds on scheduled maintenance activities for a structure. This policy may be appropriate (cost effective) in cases in which the structure is planned for replacement at a known future date. Unfortunately it is sometimes applied as a result of financial exigency.

Ordinary Maintenance is a predefined level of maintenance which is appropriate for the majority of bridges of each type under ordinary levels of service. The exact actions comprising ordinary maintenance will depend on the type of construction of the bridge.

Extraordinary Maintenance is a predefined premium level of maintenance which may be appropriate for a few structures. While it is not appropriate to state in advance which types of structures may be most appropriately maintained by extraordinary maintenance, it has been estimated that premium maintenance efforts applied to network critical bridges in good condition may be cost effective.

Rehabilitation is any field action which renews or improves the condition of a component or bridge. Rehabilitation, according to this definition, will include several activities which have traditionally been included in the definition of maintenance. Repair of impact damage, for instance, is an action taken to restore (renew or improve) the condition of a component to a higher condition following some deterioration (impact damage). Rehabilitation is then subdivided into the following categories:

Limited Rehabilitation is a rehabilitation action which is limited to a single major component or a significant portion of the structure. This definition is somewhat fuzzy, and sometimes the best determination of whether rehabilitation is "limited" or "major" is the cost of the project.

Major Rehabilitation is a rehabilitation action which restores or improves the condition of a major component (substructure, superstructure, or roadway) or of the entire structure.

Improvement is an action taken to increase the original design capability of the bridge, either through strengthening, widening, or increasing clearances above or beneath the structure. Improvement is most

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commonly undertaken when the original design criteria has been increased since the bridge was constructed, as would be the case of an H15 designed bridge which has become part of a highway network designed for heavier loads. Another example of improvement is by a realignment of the approaches to a bridge to reflect improved safety standards.

Replacement is the replacement of one bridge with another at the same location. Sometimes the new bridge is placed adjacent to the old bridge, which may or may not be left in service.

To construct rules which lead to one or more of the above actions, the exact scope of each of these activities must be defined for the major types of bridges and bridge components in service in Texas. The following tables indicate the breakdown which is proposed for use here.

Roadway

Type of construction	Activity						
	Maintenance		Rehabilitation		Replace	Improve	
	Ordinary	Extraordinary	Limited	Major		Widen	Raise
RC decks (bare)	Clean joints (ft-joint); apply linseed oil treatment (ft^2 deck area)	Clean joints (ft-joint); patch spalls when __ % spalled (ft^2 deck area); install cathodic protection system (ft^2 deck area)	Repair sealed joints (ft-joint); local full-depth deck repair, patch spalls and seal cracks (ft^2 deck area)	Partial depth overlay (ft^2 deck area); Replace sealed joints (ft-joint)	Remove deck, construct new deck (ft^2 deck area)	Add drilled shafts, bents, beams, deck (ft^2 added deck area)	Raise beams (ft-beam), fill approach (yd^3 fill), construct new approach pavement (ft^2 new pavement area)
RC decks, AC overlay	Clean joints (ft-joint width); patch overlay (ft^2 deck area)	Clean joints (ft-joint); patch spalls and seal cracks when __ % spalled (ft^2 deck area); install cathodic protection system (ft^2 deck area)	Repair sealed joints (ft-joint); local full-depth deck repair, patch spalls (ft^2 deck area); apply sealcoat (ft^2 deck area)				
Precast panels or other post-tensioned decks	Clean joints (ft-joint), patch spalls (ft^2 deck area)	Clean joints (ft-joint), patch spalls when __ % spalled (ft^2 deck area); install cathodic protection system (ft^2 deck area)	Repair limited sealed joint distress (ft-joint); patch spalls (ft^2 deck area)	Replace sealed joints (ft-joint); patch spalls (ft^2 deck area); apply AC overlay riding surface (ft^2 deck area)			

Note: Length of joints can be calculated as product of deck width and (1 + no. of spans), when sealed joints are used.

Superstructure

Type of construction	ACTIVITY						
	Maintenance		Rehabilitation		Replace	Improve	
	Ordinary	Extra-ordinary	Limited	Major		Widen	Strengthen
PS concrete girders		Wash girder ends under open joints (ft-width)			Replace deck and girders with least cost structure (ft^2)	Add drilled shafts, bents, beams, deck (ft^2)	(same as replace)
RC beams or pan girders	Clean pan girder joints and drains (ft^2 deck area)	Wash beam ends under open joints (ft-width)	Patch limited spalling over exposed rebars (ft^2 deck area)	Patch extensive spalling over exposed rebars (ft^2 deck area)	Replace deck and beams or slab with least cost structure (ft^2)	Add drilled shafts, bents, beams, deck (ft^2)	(same as replace)
Steel beams or plate girders	Clean debris from flanges and bearings (ft^2-deck area)	Clean debris from flanges and bearings, reset bearings (ft^2-deck area); Spot paint (ft^2-steel)		Replace corroded members (ton steel); clean and paint (ft^2)	Replace deck and girders with least cost structure (ft^2)	Add drilled shafts, bents, beams, deck (ft^2)	Remove deck, add cover plates and shear connectors for composite action (ft^2 deck area)
Steel trusses -- deck	Clean debris from truss members and bearings (ft^2-deck area)	Clean debris from truss members and bearings (ft^2 deck area); spot paint (ft^2-steel)	Replace or repair some corroded members (ton steel)	Replace all corroded members (ton steel); clean and paint (ft^2-steel)	Replace deck and superstructure with least cost structure (ft^2)	Add drilled shafts, bents, superstructure, deck (ft^2)	Strengthen limiting members in floor system (ft^2)
Steel trusses -- through	Clean debris from lower chord and bearings (ft^2-deck area)	Clean debris from lower chord and bearings (ft^2-deck area); spot paint (ft^2)	Replace or repair some corroded members (ton steel)	Replace all corroded members (ton steel); spot paint (ft^2-steel)	Replace bridge with least cost structure (ft^2)	Replace bridge with least cost structure (ft^2)	Strengthen limiting members in floor system (ft^2)
RC Slabs	Sweep debris; wash deck if salt has been applied (ft^2 deck area)		Patch limited spalling over re-bars (ft^2 deck area)		Replace slab with least cost structure (ft^2 deck area)	Add drilled shafts, bents, and slab (ft^2 deck area)	(same as replace)

Note: Algorithms to estimate area and weight of superstructure steel from bridge deck area and span length are needed. Item 75 identifies painted or weathering steel.

Substructure

Type of Construction	ACTIVITY						
	Maintenance		Rehabilitation		Replace	Improve	
	Ordinary	Extra-ordinary	Limited	Major		Strengthen	Add scour protection
Timber bents and piles	Remove debris (ea.)		Replace deteriorated bracing (bd-ft)	Replace deteriorated members (bd- ft)	Replace bents and piles with least cost substructure (ea.)	Replace limiting members or add bracing (bd-ft)	Place rip-rap or gabbions (ton)
RC piers and drilled shafts or PS piles	Remove debris (ea.)	Wash RC caps and piers (ea.)	Patch cover over exposed rebar (ft^2)	Jacket piles, add cathodic protection (ft^2)	(Same as above)		(Same as above)
RC caps and steel piles	Remove debris (ea.)	Wash RC caps and piers (ea.), Spot paint piles (ft^2)	Patch cover over exposed rebar (ft^2)	Patch cover over exposed rebar (ft^2), clean and paint piles (ft^2)	(Same as above)	Add piles and bracing (ton)	(Same as above)

Channel

Channel Classification (during periods of lowest flow)	ACTIVITY			
	Maintain		Improve	
	Ordinary	Extra-ordinary	Straighten	Add erosion protection
Low volume and velocity flow	Remove debris	Remove debris and cut brush	Cut channel with excavator	Add gabbions or riprap
High volume or high velocity flow	Remove debris	Remove debris and cut brush	Cut channel with dragline or dredge	Add gabbions, riprap or jetties

Approach

Type of approach pavement	ACTIVITY					
	Maintain		Rehabilitation		Improve	
	Ordinary	Extra-ordinary	Limited	Major	Widen	Straighten
Bituminous pavement with RC approach slab	Seal cracks (ft^2)	Seal coat	Patch potholes	Bituminous overlay (ft^2)	Widen embankment (yd^3), construct bituminous pavement (ft^2)	Construct embankment (yd^3), pavement (ft^2)
Concrete pavement and RC approach slab	Seal cracks (ft^2)			Bituminous overlay (ft^2)	Widen embankment (yd^3), construct bituminous pavement (ft^2)	(Same as above)

The knowledge implemented in the expert system is primarily in the form of rules and facts. The decisions regarding feasible alternatives are formulated in the form of rules and the bridge data from BRINSAP. The data generated during intermediate decision steps are formulated as facts. The rules are of the IF <conditions> THEN <action1> ELSE <action2> type format where the <conditions> are the facts that describe a bridge and the <actions> are the recommended alternatives under the given conditions. Since the rules are essentially independent pieces of knowledge, additional information can be easily added to the expert system without requiring drastic changes to existing rules.

The rules evaluate the structural and functional conditions of the bridge and recommend one or more of the following alternatives: Maintenance, Replacement, Rehabilitation, Improvement, Abandonment, or Do Nothing. The recommendations can then be combined with the information on the type of construction of the bridge and detailed activities can be generated. After the recommendations have been suggested for one bridge, the bridge data for the next bridge to be considered is downloaded from BRINSAP. and the procedure is repeated. This cycle is continued until the appropriate recommendations have been generated for all the bridges to be considered. The costs and benefits of the recommended activities are then calculated for each bridge to facilitate the selection of optimal activities using the optimization techniques.

A list of rules which were developed for the feasible alternative synthesizer is given below. The rules have been presented here in an English-like format to ensure readability. These rules can be validated only by implementing them in an expert system tool and running a number of test cases. For the purpose of validation, these rules were implemented in the CLIPS (1989) expert system tool and several test cases were generated. This validation process is essential to resolve conflicts and redundancies among rules and contradictory recommendations. Note that the term "routine" is used to denote "ordinary" maintenance activities.

Rule 1: IF Sufficiency Rating > 80 THEN
      (Routine) Maintain Bridge
Rule 2: IF Sufficiency Rating >= 50 to <= 80 THEN
      Rehabilitate Bridge or
      Improve Bridge
Rule 3: IF Sufficiency Rating < 50 THEN
      Replace Bridge or
      Rehabilitate Bridge or
      Improve Bridge or
      Abandon Bridge
Rule 4: IF Roadway Condition >= 6 THEN
      (Routine) Maintain Deck
Rule 5: IF Superstructure Condition >= 6 THEN
      (Routine) Maintain Superstructure
Rule 6: IF Substructure Condition >= 6 THEN
      (Routine) Maintain Substructure
Rule 7: IF Roadway Condition <= 5 THEN
      Rehabilitate Deck
Rule 8: IF Superstructure Condition <= 5 THEN
      Rehabilitate Superstructure

Rule 9: IF Substructure Condition < = 5 THEN
Rehabilitate Substructure

Rule 10: IF Roadway Condition < = 4 and Superstructure Condition < = 4 THEN
Replace Bridge

Rule 11: IF Roadway Condition < = 4 and Substructure Condition < = 4 THEN
Replace Bridge

Rule 12: IF Superstructure Condition < = 4 and Substructure Condition < = 4 THEN
Replace Bridge

Rule 13: IF Roadway Condition > = 7 and Superstructure Condition > = 7 and
Substructure Condition > = 7 THEN
(Routine) Maintain Bridge

Rule 14: IF Roadway Condition > = 5 & < = 6 and Superstructure Condition > = 7 and
Substructure Condition > = 7 THEN
Repair Bridge or
(Routine) Maintain Bridge

Rule 15: IF Roadway Condition > = 3 & < = 4 and Superstructure Condition > = 7 and
Substructure Condition > = 7 THEN
Rehabilitate Deck or
Replace Deck or
Repair Deck or
(Routine) Maintain Bridge

Rule 16: IF Roadway Condition > =0 & < = 2 and Superstructure Condition > = 7 and
Substructure Condition > = 7 THEN
Replace Deck or
Rehabilitate Deck or
(Routine) Maintain Bridge

Rule 17: IF Roadway Condition > = 7 and Superstructure Condition > =5 & < = 6 and
Substructure Condition > = 7 THEN
Repair Superstructure or
(Routine) Maintain Bridge

Rule 18: IF Roadway Condition > = 5 & < = 6 and Superstructure Condition > = 5 & < = 6 and
Substructure Condition > = 7 THEN
Repair Superstructure and Deck or
Repair Deck or
Repair Superstructure or
(Routine) Maintain Bridge

Rule 19: IF Roadway Condition > = 3 & < = 4 and Superstructure Condition > = 5 & < = 6 and
Substructure Condition > = 7 THEN
Repair Superstructure and Rehabilitate Deck or
Repair Superstructure and Replace Deck or
Rehabilitate Deck or
Replace Deck or
Repair Superstructure and Deck or
Repair Deck or
Repair Superstructure or
(Routine) Maintain Bridge

Rule 20: IF Roadway Condition > = 0 & < = 2 and Superstructure Condition > = 5 & < = 6 and
Substructure Condition > = 7 THEN
Repair Superstructure and Replace Deck or
Replace Deck or
Repair Superstructure and Rehabilitate Deck or
Rehabilitate Deck or Maintain (Routine) Bridge

Rule 21: IF Roadway Condition $>= 7$ and Superstructure Condition $>= 3$ & $<= 4$ and
      Substructure Condition $>= 7$ THEN
      Rehabilitate Superstructure or
      Replace Superstructure or
      Repair Superstructure or
      (Routine) Maintain Bridge

Rule 22: IF Roadway Condition $>= 5$ & $<= 6$ and Superstructure Condition $>= 3$ & $<= 4$ and
      Substructure Condition $>= 7$ THEN
      Rehabilitate Superstructure and Repair Deck or
      Replace Superstructure or
      Rehabilitate Superstructure or
      Repair Superstructure and Repair Deck or
      Repair Superstructure or
      Repair Deck or
      (Routine) Maintain Bridge

Rule 23: IF Roadway Condition $>= 3$ & $<= 4$ and Superstructure Condition $>= 3$ & $<= 4$ and
      Substructure Condition $>= 7$ THEN
      Rehabilitate Superstructure and Deck or
      Rehabilitate Superstructure and Replace Deck or
      Replace Superstructure or
      Repair Superstructure and Rehabilitate Deck or
      Repair Superstructure and Replace Deck or
      Rehabilitate Superstructure and Repair Deck or
      Repair Superstructure and Deck or
      Rehabilitate Deck or
      Replace Deck or
      Repair Deck or
      Rehabilitate Deck or
      Rehabilitate Superstructure or
      Repair Superstructure or
      (Routine) Maintain Bridge

Rule 24: IF Roadway Condition $>= 0$ & $<= 2$ and Superstructure Condition $>= 3$ & $<= 4$ and
      substructure Condition $>= 7$ THEN
      Rehabilitate Superstructure and Replace Deck or
      Replace Superstructure or
      Repair Superstructure and Replace Deck or
      Replace Deck or
      Rehabilitate Superstructure and Rehabilitate Deck or
      Repair Superstructure and Rehabilitate Deck or
      Rehabilitate Deck or
      (Routine) Maintain Bridge

Rule 25: IF Roadway Condition $>= 7$ and Superstructure Condition $>= 0$ & $<= 2$ and
      Substructure Condition $>= 7$ THEN
      Replace Superstructure or
      Rehabilitate Superstructure or
      (Routine) Maintain Bridge

Rule 26: IF Roadway Condition $>= 5$ & $<= 6$ and Superstructure Condition $>= 0$ & $<= 2$ and
      Substructure Condition $>= 7$ THEN
      Replace Superstructure or
      Rehabilitate Superstructure and Repair Deck or
      (Routine) Maintain Bridge

Rule 28: IF Roadway Condition $> = 3$ & $< = 4$ and Superstructure Condition $> = 0$ & $< = 2$ and
  Substructure Condition $> = 7$ THEN
  Replace Superstructure or
  Rehabilitate Superstructure and Deck or
  Replace Deck and Rehabilitate Superstructure or
  Rehabilitate Superstructure and Repair Deck or
  Rehabilitate Superstructure or
  (Routine) Maintain Bridge
Rule 29: IF Roadway Condition $> = 0$ & $< = 2$ and Superstructure Condition $> = 0$ & $< = 2$ and
  Substructure Condition $> = 7$ THEN
  Replace Superstructure or
  Rehabilitate Superstructure and Replace Deck or
  Rehabilitate Superstructure and Deck or
  (Routine) Maintain Bridge
Rule 30: IF Roadway Condition $> = 7$ and Superstructure Condition $> = 7$ and
  Substructure Condition $> = 5$ & $< = 6$ THEN
  Repair Substructure or
  (Routine) Maintain Bridge
Rule 31: IF Roadway Condition $> = 5$ & $< = 6$ and Superstructure Condition $> = 7$ and
  Substructure Condition $> = 5$ & $< = 6$
  THEN Repair Substructure and Deck or
  Repair Deck or
  Repair Substructure or
  (Routine) Maintain Bridge
Rule 32: IF Functional Classification is one of (01,11,12,21,22,41,42) and
  is One-Way and Roadway Width $<$ (11*No. of Lanes + 6) THEN
  Widen Bridge
Rule 33: IF Functional Classification is one of (01,11,12,21,22,41,42) and
  is Two-Way and Roadway Width $<$ (11*No. of Lanes + 8) THEN
  Widen Bridge
Rule 34: IF Functional Classification is one of (02,03,13,14,23,24,43) and
  Roadway Width $<$ (No. of Lanes*Lane Width) + (2* Shoulder Width) for
  the given Average Daily Traffic THEN
  Widen Bridge
Rule 35: IF Functional Classification is one of (04,05,15,25,45) and
  Roadway Width $<$ (No. of Lanes*Lane Width) + (2* Shoulder Width) for
  the given Average Daily Traffic THEN
  Widen Bridge
Rule 36: IF Functional Classification is one of (06,16,26,46) and
  Roadway Width $<$ (No. of Lanes*Lane Width) + (2* Shoulder Width) for
  the given Average Daily Traffic THEN
  Widen Bridge

Incorporation of Bridge Maintenance Activities into a BMS

Report 1212-1F discussed the general situation with regard to bridge maintenance practices in Texas. Most bridge maintenance in the Department is done on an as-needed basis and there is little, if any, program for scheduled or preventive maintenance. This is apparently not uncommon. Most maintenance managers are confronted with severely limited resources and increasing needs for these resources. Nevertheless, there is a need

for greater maintenance effort to prolong the life of bridges. Such expenditures would result in the postponement of capital outlays. It is recognized that maintenance will achieve these benefits through the reduction in the rate of deterioration, but it is difficult to quantify the benefits of maintenance in the same fashion as rehabilitation, improvement, and replacement. As a result, maintenance costs and benefits cannot be optimized as an integral element of the bridge management system. Other proposed bridge management systems (notably the PONTIS system being implemented in California) employ a potentially useful technique which can be used for maintenance activities. In the PONTIS system, the activities (both maintenance and rehabilitation) are essentially "pre-optimized" by analysis of certain deterioration mechanisms and deterioration states.

Several studies have treated maintenance prioritization, and several routines have been developed using expert opinion to determine ideal maintenance levels within budget constraints (Nash and Johnston 1985, Harper 1990). Although these studies optimize maintenance policies within budget constraints, the relationship to reduction in capital costs is not shown. A few papers, such as those by New York State (Thomas and DeFabio 1988) and New York City (Consortium 1990), discuss such a relationship. They indicate that an increased expenditure of a certain amount of maintenance funds will prevent "good" bridges from becoming deficient. For example, in New York State capital costs of $66 million could be postponed by the expenditure of $15 million in maintenance. This study (Thomas and DeFabio) was based on reports that indicated 215 bridges per year would become deficient at a cost of $100 million. By way of comparison, the Strategic Highway Mobility Plan for Texas indicates that 370 on-system bridges will become deficient during the five year period starting at the year 2000 at a cost of $67 million. There is no estimate of the corresponding preventive maintenance needed to maintain the state of deterioration on these 370 bridges at the same level as the average of the 1990-1995 period. The cost data necessary to show such savings is not available in Texas. However, the data from New York would indicate that preventive maintenance should average $4-5 million per year for this group of bridges, reaching the age when rehabilitation or replacement becomes necessary in ten years. If all the other age windows are considered, one could probably show that an annual preventive maintenance budget of $15-20 million would not be unreasonable.

Alternatively, bridge maintenance needs can be determined subjectively by field inspection and an inventory base. These needs are translated into strategies which reflect varying levels of service. Specific strategies consider various methods of doing the work, a variety of materials, and proven practices (Kruegler et al 1986). Various combinations will result in different effectiveness and periods of extended life. Typical maintenance actions have been identified using the survey of districts in the Texas DOT developed in connection with Study 1212. These combinations are included in the discussion below. Using these actions, which may account for 60 percent or more of the total maintenance activity, specific strategies are developed. The user may decide to use either the minimum level of effort or some more extensive work. This decision depends on budget policies, future work that may be done on the particular bridge or network, current condition of the bridge, functional requirements, safety, and economy of use of resources. The effectiveness of these various levels of effort will depend on the judgement of the users.

Ideally, a decision as to the level of effort could be made for each bridge and a maintenance life-cycle cost analysis for every bridge. This does not appear to be feasible because of the detailed cost and deterioration data needed. However, one can establish average life-cycle costs for typical maintenance activities and apply a maintenance model for use on all bridges. This requires capturing much more data than is currently available in the TxDOT maintenance databases or using data from other regions which are adjusted using Texas labor and material indices. The procedure to be adopted in this study is to collect and process maintenance data based on the strategy above using the most significant work items. It is intended that a group of experts will study these work items and select the most likely strategies. A similar procedure has been done in North Carolina (Nash and Johnston 1985). These levels of work will then be assigned costs to use in developing a maintenance model. In lieu of establishing a model for every bridge, it may be feasible to select a deterioration model for each major bridge component and for types of construction.

Levels of Bridge Maintenance Needs

In order to define levels of maintenance needs that may occur during the service life of a bridge, the following specific tasks were carried out:

1. Identification of important bridge maintenance activities based on their frequency of annual application and their effectiveness in retarding bridge deterioration (results of the expert opinion survey executed in connection with Study 1212);

2. Definition of the scope of each bridge maintenance activity; and

3. Establishment of maintenance conditions - levels of distress or deterioration.

Identification of Important Bridge Maintenance Activities

Through a devised package of questionnaires, the expert opinions of Texas bridge engineers were elicited in the evaluation of a set of bridge maintenance activities. These activities were rated by their frequency of annual application and their effectiveness in retarding bridge deterioration. Based on indices computed for these two criteria, the following eleven top-rated activities were identified as the most important bridge maintenance activities: bituminous surface overlay, clean joint, seal or waterproof joint, clean drainage opening, clean or paint structural steel, repair collision damage (steel), repair collision damage (concrete), clean concrete pile cap, clean and paint steel piling, and remove debris from channel. The identification procedure is illustrated in the following sections. Higher values of the indices reported below for "Application Rating" and "Effectiveness Rating" mean that an activity is relatively more commonly applied or is thought to be relatively more effective, respectively. "Select" means that the activity's effectiveness rating was acceptably high.

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Roadway/Deck

	Activity	Application Rating	Effectiveness Rating	Comments
1.	Linseed oil treatment	2.08	--	
2.	Bituminous surface overlay	1.91	3.82	Select
3.	Clean joint	1.82	3.82	Select
4.	Seal or waterproof joint	1.79	3.78	Select
6.	Clean drainage opening	1.99	3.87	Select
7.	Full depth patching	--	3.58	
8.	Replace joint	--	3.65	
9.	Reset steel joint	--	3.58	

Superstructure

	Activity	Application Rating	Effectiveness Rating	Comments
1.	Clean or paint struct steel	1.48	4.22	Select
2.	Repair collision damage (steel)	1.54	4.08	Select
3.	Repair connection damage (steel)	1.44	3.92	Select
4.	Repair collision damage (concrete)	1.47	3.80	Select

Substructure

	Activity	Application Rating	Effectiveness Rating	Comments
1.	Clean concrete pile cap	1.34	--	
2.	Clean/paint steel piling	1.33	3.42	Select
3.	Repair retaining wall	1.30	--	
4.	Repair collision protection	1.43	--	
5.	Repair foundation problems	1.30	--	
6.	General maintenance	1.34	--	
7.	Clean and paint steel pile cap	--	3.33	

Other (Approaches, Culverts, Channels, etc.)

	Activity	Application Rating	Effectiveness Rating	Comments
1.	Erosion control	1.82	--	
2.	Remove debris from channel	1.97	3.40	Select
3.	Repair guard fence	2.27	3.42	Select
4.	Repair traffic signs	2.40	--	
5.	Repair warning devices	1.85	--	

Scope of Bridge Maintenance Activities

Bituminous Surface Overlay

A bituminous surface overlay involves the placing of a new surface over the bridge structural deck to provide a smooth riding surface and to protect the deck from effects of traffic, weathering, and chemical action. This activity is carried out if cracks and distortion are detected and is used to restore pavement quality (i.e. drainage, geometry, skid resistance, and riding quality). This activity also helps prevent excessive bridge deck deterioration in the form of spalls or potholes due to the presence of deicing chemicals. An overlay requires the

removal of the old wearing surface and preparation of the exposed concrete slab or steel plate. The new surface is installed according to specifications and recommendations for new bridges.

If the presence of cracks and distortion is localized, maintenance is carried out by removing the surface course down to the deck by making square or rectangular cuts, placing the mix, and compacting as per specifications. Serious failures should be patched immediately upon discovery. Timely sealing will inhibit the penetration of chloride compounds into the deck and thus effectively prevent corrosion of reinforcing steel and spalling of deck.

The work should be scheduled throughout the year in coordination with the statewide bridge inspection program. Patching may be carried out once every two years or if the total area affected is between 10 percent to 20 percent. The bridge would require a complete overlay once every five to twelve years. There should not be a reduction in the maintenance level unless the bridge has been scheduled for capital rehabilitation within the next three to four years.

Other types of surface overlays are discussed in the New York City study (Consortium 1990). These include polymer impregnation of bridge decks and concrete overlays. The Amarillo district reports that they are currently using a 2 in. dense concrete overlay.

Clean Joint

Cleaning a joint involves manual removal of debris in the joint opening and flushing of all exposed surfaces beneath the joint opening to remove accumulated debris. The activity is carried out when the presence of foreign material is detected. This activity prevents excessive rusting of steel, deterioration of concrete, and damage to the joint seal. A joint becomes ineffective when the trough becomes filled with sand, gravel, and debris. Periodic cleaning allows the joint to function as designed, providing allowances for translational, transverse, and rotational movements of the superstructure. The cleaning aspect of a maintenance program is one of the single most effective methods of preventing premature deterioration of bridge structures. This work should be scheduled at least once a year in the spring following snow and rain periods and in conjunction with other cleaning activities. This activity is aimed primarily at bridges in good condition as a preventive maintenance measure but should also be performed on structures in fair or poor condition to prevent hazardous conditions from arising.

Seal or Waterproof Joint

This is the process of replacing or repairing the material (e.g., elastomer strip, neoprene, epoxy resins) used for waterproofing the joint. The purpose of the flexible material in the joint is to prohibit passage of moisture and debris. The activity is carried out when the joint seal is damaged, thus affecting water tightness. Sealing and waterproofing the joint protects underlying structural parts from aggressive materials and dirt which may infiltrate these break and restores a smooth riding surface. When making the repairs, the bonding surface should be free of concrete, paint, corrosion, oil, and grease. The surface should be cleaned by sandblasting prior to primer

application. After sandblasting, the joint is blown to remove loose dust and the primer is applied. In open joints, backing should be provided to hold the fluid sealant.

This activity should be scheduled during winter or late fall since the joints are wider and easier to clean and fill during this period. The joint should be resealed when 50 percent of the joint leaks or when it is 2 in. wide.

Clean Drainage Opening

Cleaning of a drainage opening typically involves manual cleaning or flushing to remove debris, dirt, vegetation, and aggressive materials and thus permit adequate drainage for the road or deck. The cleaning is carried out when the presence of foreign material is detected. The debris and dirt is removed from the opening and it is washed with high pressure jets. The frequency of the maintenance activity should be often enough to allow adequate drainage of the bridge surface.

The activity should be scheduled in the spring following snow and rain periods and in conjunction with other cleaning activities. It should be performed at least once a year.

Clean or Paint Structural Steel

This activity begins with preparation of the existing surface by washing, sanding, or burning, followed by mechanical or manual brushing of the steel surface in the affected areas. Application of a base coat of paint is then followed by one or more undercoats and a finishing coat. The cleaning and painting of the structural steel is done to retard the deterioration process of the steel due to rust and corrosion caused by atmospheric conditions and/or chemicals.

The painting operation should be carried out on all areas where old paint has been removed or damaged (after repairs or impact damage) or where the presence of rust or flaking of existing paint is detected by visual means. The frequency of this activity depends on the surface area affected. There are three levels of maintenance established when considering the painting activity:

1. Spot painting of coating that is basically sound but needs local touch up and repairs.

2. Complete repainting of a surface which requires refinishing but does not require extensive surface preparation.

3. Repainting surfaces which require both extensive surface preparation and refinishing.

When less than 35 percent of the area is affected, spot painting is recommended. Spot painting consists of application of a prime coat on all areas where old paint has been removed or damaged either prior to or during surface preparation. This activity prevents excessive rusting and deterioration of steel due to exposure to the atmosphere.

The painting activity may be scheduled every eight years with painting of the splash zone every eight years midway between scheduled superstructure painting. Spot painting may be carried out once every four years halfway between the other scheduled painting activities.

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Repair Collision Damage (Steel)

This constitutes the activities necessary to repair damage at different points on the structure which may have been damaged due to collision. This maintenance activity would be carried out in the event of damage to the bridge structure due to a traffic accident or any other type of collision. The member/members deformed by colliding vehicles or excessive loads may be straightened by heat if no sharp kinks or tears are present. Cracks and tears may be repaired by welding with proper joint preparation and welding procedures provided parts can be returned to original alignment. This activity may include one or more of the other maintenance activities.

The work should be carried out as often as is deemed necessary based on the degree of damage. The repair may have to be carried out on an emergency basis if the extent of damage is such that user safety or comfort is affected.

Repair Connection Damage

Repairing connection damage constitutes repairing or removing and replacing connection units on a bridge structure which are damaged or deteriorated due to age. This activity may require engineering analysis when vital connections are damaged.

Repairing of damage will prevent stress concentrations or redistribution of stress, thereby preventing fatigue failure and/or distortion. This activity needs to be carried out when corrosion, missing or loose bolts, cracked welds, etc. are detected or when there is failure of a connection due to general yielding, localized gross yielding, corrosion, or cracking due to fatigue or stress corrosion. The repair would consist of the removal and replacement of the connection, bolt, rivet, or weld.

The frequency of repair depends on the degree of damage to the connection. Repairs may be scheduled once every two years to coincide with the painting activities. It may be required more often when routine inspection detects damage to critical connection units.

Repair Collision Damage (Concrete)

This constitutes the activities necessary to repair damage at different points on the structure which may have been damaged due to collision, and restoration of structural integrity, soundness, durability and smoothness. Repairs would be carried out in the event of damage to the bridge structure due to a traffic accident or any other collision. It may consist of preparation of the surface (removal of defective concrete, removal of oil and grease, and/or removal of surface mortar) and subsequent repair using primers and cement mortars. The damaged concrete needs to be removed to whatever depth it has been damaged and replaced. Unsound concrete should be located by visual inspection or tapping. Spot patching may be carried out in areas of minor damage.

The activity should be carried out as often as necessary based on the degree of damage. The repair may have to be carried out on emergency basis if the extent of damage is such that user safety or comfort are affected.

Clean Concrete Pile cap

Cleaning a concrete pile cap consists of washing and removing any foreign material from the pile cap. This helps prevent any general deterioration of the concrete due to deicing chemicals or chemicals in water which might otherwise lead to differential settlement of superstructure and unplanned stresses. The cleaning would consist of flushing the pile cap with a compressed water/air jet followed by removal of any foreign material and debris by hand.

This activity should be scheduled at least once a year, preferably in the spring following snow and rain periods and in conjunction with other cleaning activities.

Clean and Paint Steel Piling

This activity involves preparation of the existing surface by washing, sanding, or burning, followed by mechanical or manual brushing of the steel surface in the affected areas. The surface preparation is followed by application of a base coat, which in turn is followed by one or more undercoats and a finishing coat. The purpose of this activity is to prevent excessive rusting and deterioration of the steel piles due to exposure to atmosphere or other corrosive agents.

The painting operation should be carried out on all areas where old paint has been removed or damaged (after repairs or impact damage) or where the presence of rust or flaking of existing paint is detected by visual means. The frequency of this activity depends on the surface area affected. There are three levels of maintenance established:

1. Spot painting of existing coating that is basically sound but needs local touch up and repairs.
2. Complete repainting of a surface which requires refinishing but does not require extensive surface preparation.
3. Repainting the surfaces which require both extensive surface preparation and refinishing.

When less than 35 percent of the area is affected, spot painting is recommended. Spot painting shall consist of application of a prime coat on all areas where old paint has been removed or damaged either prior to or during surface preparation. On surfaces where small areas of bare metal are closely spaced, spot painting will involve a prime coat over the entire surface to facilitate application of the finishing coat. The painting of steel piling may be scheduled every eight years midway between the superstructure painting activity.

Maintain Channel

This is the process of application of grouted riprap in the form of bank protection and the removal of any debris (which might damage the bridge structure) from the channel. This prevents damage to the structure and serious erosion of banks, and it saves having to make expensive repairs at a later date.

Levels of Distress/Deterioration for Various Bridge Maintenance Conditions

Bituminous Surface Overlay:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Cracks, Spalls (Delamination)	Percent of Surface Area Affected	1. 10 % of Bridge Deck (Low) 2. 20 % of Bridge Deck (Med) 3. 30 % of Bridge Deck (High) 4. 40 % (Limited Rehabilitation)

Clean Joint:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Presence of Foreign Material	Percent of Length Affected	1. 10 % of Joint 2. 50 % of Joint 3. 100 % of Joint

Seal/Waterproof Joint:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Water Tightness	Percent of Length Affected	1. 25 % of Length 2. 50 % of Length 3. 100 % of Length
Excessive Opening	Width of Opening	1. 1" Wide 2. 2" Wide

Clean Drain Opening:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Presence of Foreign Material	Percent of Area Affected	1. 25 % of Drain Opening 2. 50 % of Drain Opening 3. 100 % of Drain Opening

Clean or Paint Structural Steel(Superstructure):

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Corrosion	Percent of Surface Area	1. 5 % of Area 2. 10 % of Area 3. 20 % of Area 4. 20 % of Area
Section Loss	Degree of Section Loss	1. Limited 2. Moderate 3. Extreme

Repair Collision Damage (Steel):

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Rupture from Collision	Degree of Damage	1. Limited Damage 2. Moderate Damage 3. Severe/Extensive

Repair Connection Damage (Steel):

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Corrosion Missing bolts or rivets Cracked welds Plastic deformation	Degree of Damage	1. Limited Damage 2. Moderate Damage 3. Extensive/Severe

Repair Collision Damage (Concrete):

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Rupture from Collision	Degree of Damage	1. Limited Damage 2. Moderate Damage 3. Severe/Extensive

Clean Concrete Pile Cap:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Silt Accumulation	Percent of Surface Area	1. 5 % of Area 2. 30 % of Area 3. 100 % of Area

Clean or Paint Steel Piling:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Corrosion	Percent of Surface Area	1. 5 % of Area 2. 10 % of Area 3. 20 % of Area 4. 20 % of Area
Section Loss	Degree of Section Loss	1. Limited 2. Moderate 3. Extreme

Remove Debris from Channel:

Maintenance Condition	Parameter	Suggested levels of Maintenance Needs
Presence of Debris	Percent of Area Affected	1. 25 % of Channel 2. 50 % of Channel 3. 100 % of Channel

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Summary of Identified Bridge Maintenance Needs

1. Bridge maintenance needs should be defined by levels of service using the results of the survey of expert opinion in Report 1212-1F.

2. The maintenance tasks defined above can be used to set strategies reflecting varying levels of service.

3. Inspection and reporting of preventive maintenance should identify current bridge conditions for each of these levels of deterioration.

4. Relationships between added service life and maintenance cannot be demonstrated, but it is apparent that the current level of maintenance activity is not adequate to prevent future deterioration.

FHWA Recommendations on Bridge Maintenance:

Based on interviews, a literature search, and an assessment of the state of the practice, a nation-wide bridge maintenance study funded by the Federal Highways Administration (FHWA) suggested a list of information requirements (Kruegler et al. 1986). These guidelines can form the basis for justifying and developing an effective long-term bridge maintenance program. A summary of these requirements and their applicability to this study is listed below. The information required for expert opinion judgements and value assessments of the levels of distress/deterioration are listed first. Comments pertaining to the results of this study are included after each recommendation:

1. A bridge inventory database which identifies each bridge on the system and the major elements of each bridge. *BRINSAP basically performs this role.*

2. A comprehensive bridge maintenance inspection program which will identify the condition of each bridge and the condition of major elements of each bridge. *BRINSAP includes condition ratings for substructure, superstructure, and roadway. The Pontis BMS requires the use of more detailed data which is not presently collected. Consistent with the wishes of TxDOT at the time of this study, the BMS outlined herein is based primarily on the use of existing data.*

3. Achievable and measurable bridge maintenance program objectives which are consistent with the agency goals. *There is a need for a set of program objectives on bridge maintenance.*

4. A policy decision on the percentage of the annual budget to be targeted for each general maintenance strategy to ensure a reasonable and fair distribution of maintenance funds. *These budget levels vary from one district to another. It is not possible to recapture the detailed data needed for bridge maintenance costs, nor is it possible to set a comprehensive policy on the level of maintenance without more detail.*

5. General bridge maintenance strategies which reflect the varying degrees of level-of-service. *These are discussed under Tasks 1 and 2.*

6. Specific maintenance activities categorized under each of the maintenance strategies. *Specific strategies are illustrated in the discussions under Tasks 1 and 2 and the recommended inspection frequencies.*

7. Maintenance activities that are being performed or that should be performed. Determine relative cost-effectiveness. *This task has actually been accomplished on a limited basis. Study 1212 used expert judgement to determine which strategies were more important than others. A comparison of life-cycle costs with and without maintenance is the only effective method of determining which of the various strategies are most cost effective. The computerized procedure recommended in this report can provide a tool to make such studies.*

8. Unit costs for each of the maintenance activities based on historical data, if available; otherwise, estimate unit costs. Establish a procedure to capture appropriate cost data. *Such a procedure is in the cost section of this report.*

9. Actual bridge maintenance requirements for each bridge, identified by the results of inspections. *See the recommendations for inspection included in this report.*

10. Maintenance requirements matched to the maintenance activities. *This has been done under Tasks 1 and 2.*

11. Prioritized maintenance requirements/activities on each bridge based on the physical needs of each bridge and priorities for all the bridges on the system, one against another. *This can be achieved with a comprehensive computerized system as is proposed in this report.*

12. A beginning bridge maintenance program using the funding allocated for each strategy, cost estimates for each maintenance activity and the priority list developed. This is sometimes called "pre-legislative budgeting."

13. Relationships between added service-life data and specific maintenance activities. *A sample calculation illustrating one set of maintenance and limited rehabilitation has been included in this report.*

14. A procedure to capture future service-life data. *This study relied on subjective estimates because actual data is not available. Capturing this data requires a more detailed cost reporting and increased inspection effort extending over 20 or 30 years.*

15. An annual program refined by checking work schedules and defining costs in more detail, sometimes called "post-legislative budgeting."

16. An implemented work program. Perform quality assurance inspections and provide feedback on the results.

The term "strategies" as used in these recommendations means a set of specific maintenance activities assigned to each bridge according to an established bridge maintenance program.

Initial Costs Model

This section of the report deals with the structure of the agency cost model database. An initial cost database is needed to develop cost-effective decision models for maintenance, rehabilitation, and replacement of a bridge or bridge component. The life-cycle models developed in Study 1212 require the initial maintenance, rehabilitation and replacement costs, and service life of all bridge activities over the life of a structure. To select alternatives the user of the BMS must have access to one source. This cost model is intended to combine all necessary costs into one database to evaluate tradeoffs between any of the alternatives. The cost model can be used by the Texas Department of Transportation as part of the overall BMS. It is realized that there are other databases in existence, however, a single comprehensive BMS must be able to combine all essential agency cost data if it is to function effectively.

The total cost of a bridge to the society includes both long-term agency expenditures and user costs. User costs are realized in higher vehicle operating costs due to detours, lost travel time, and higher accident rates. These are not directly paid or assumed by the government. However, user costs should be considered in the decision-making procedures. If needed expenditures are deferred by the highway agency, the total cost is merely shifted and will appear as increased user cost, a later but higher agency cost or both. The cost structure proposed in this section of the report includes only agency costs. User costs are addressed as benefits.

A system which provides the means for classifying and storing cost data must provide for ease of data collection, storage, and retrieval. The cost system has three subobjectives:

1. To define the bridge components and activities for which costs are needed.
2. To define the means for collecting and storing cost data.
3. To develop the costs for the bridge components and activities.

The framework for the proposed agency cost database is a work package breakdown structure. The structure defines activities, type of structure, component, and unit of measure.

The first two subobjectives are achievable through a work breakdown structure developed for a single bridge which will be called the Bridge Breakdown Structure or BBS. Subobjective 3 above, the actual cost data to be used in this structure, cannot be fully achieved by the researchers for reasons discussed below. However, users of the BMS will certainly develop their own cost data. If they do so in the form recommended in this section, they will be able to use a systematic bridge analysis. The default costs developed in this study can be used for implementation and evaluation of the engineering processes of the BMS. For this purpose actual 1991 costs have been included for most activities.

Cost Needs by the Bridge Management System (BMS)

It is worthwhile to review the objectives of the BMS so that the cost model can conform to these objectives. For this discussion, the BMS may be defined as any system or series of engineering and management functions which, when taken together, result in the actions necessary to manage a bridge program (FHWA 1987).

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These necessary actions could be the following.

- Evaluating bridge problems
- Selecting bridge improvement projects
- Programming and initiating projects
- Inventorying and inspecting bridges
- Evaluating priorities
- Selecting and programming projects

A comprehensive BMS should satisfy the following criteria.

- Have a suitable database
- Incorporate analytical tools for objectively assessing bridge needs
- Integrate all decisions and activities relating to the bridge including design, programming, maintenance, rehabilitation, and replacement
- Provide a systemwide perspective to complement the project perspective

A comprehensive BMS will rely on automated data processing. However, it is not intended to be a wholly automated series of computerized procedures which eliminates the need for judgement. It is not intended to make all decisions on bridge improvement activities. Rather, it will include automated procedures to provide analysis and necessary information for program managers to make more cost-effective decisions.

The Role of the Cost Database in Selecting Feasible Alternatives

The feasible alternatives synthesizer (FAS) in the bridge management system (BMS) generates a list of feasible alternative tasks that may be carried out on a bridge. To successfully compare, analyze, and evaluate these alternatives, a life-cycle cost analysis is carried out. This analysis requires initial cost information. Figure 4 shows how a cost database will be located within the BMS. Most of the expert knowledge discussed above addresses primarily the question of rehabilitation or replacement. Maintenance, especially a determination of the appropriate level of maintenance, is not addressed by the knowledge described above.

There are two levels of cost detail that need to be available for the cost model of the BMS. The first level is the broad cost data which is available from the historic costs available in the various state highway department databases. This historic cost data can be used to develop cost estimates for the statewide bridge need studies, replacement and rehabilitate programs, and a database to justify future funding requirements. The second level is the more detailed unit cost data which can be used by the bridge managers for developing annual work programs, annual budget requirements, and cost effectiveness studies, and for prioritizing work activities.

Knowledge of the costs of bridge work activities will provide an excellent base for predicting costs of future work activities. A credible and usable cost database will serve the following purposes.

- Determining the benefit/cost of current and future work
- Estimating current and future budgets
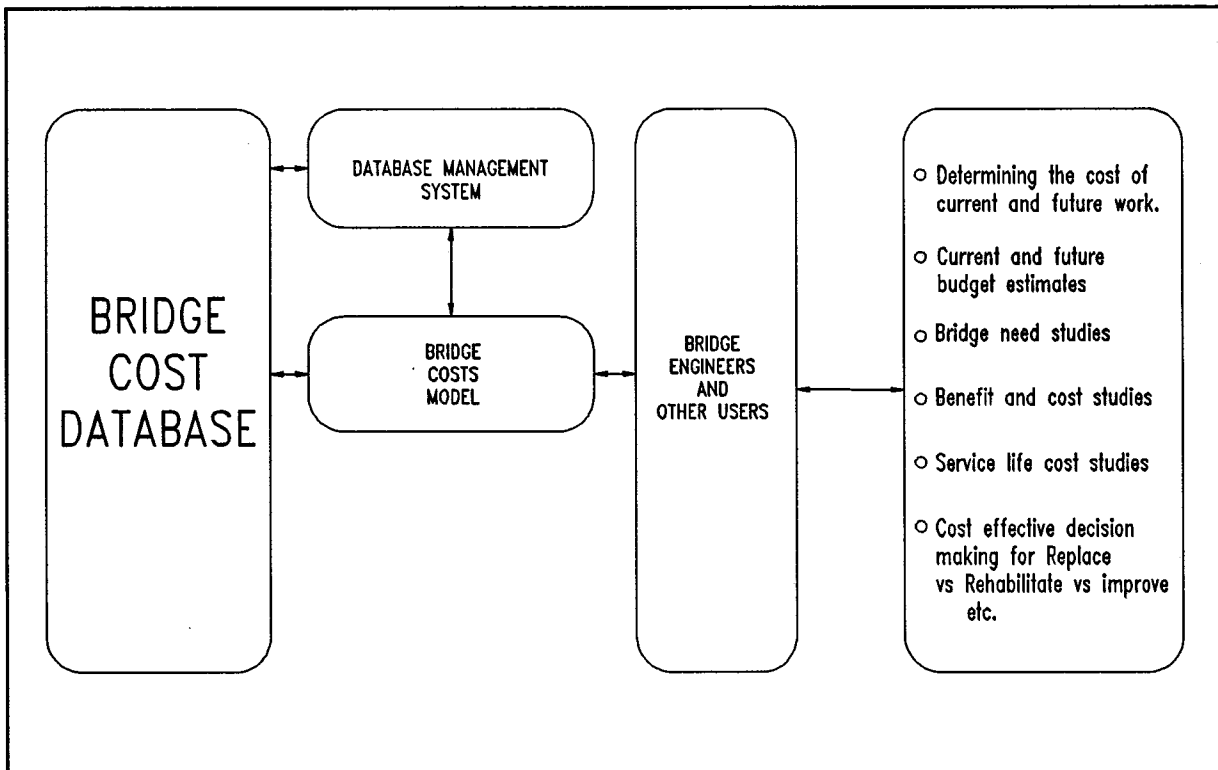
Figure 4. Bridge Costs Database

- Studying bridge needs and service lives

- Decisionmaking for alternatives such as replace-vs-rehabilitate

- Analyzing performance and cost trends

- Maintaining individual bridge expenditure and work histories

Tracking of costs on a systematic basis will make them available for the uses mentioned above. As more use is made of these costs and more bridge project costs are tracked, a feedback loop is formed. This helps to continuously upgrade the data in the cost database, thus improving its use.

Non-Bridge Costs

The cost database will provide the cost to the agency of work on an existing bridge. Other costs that make up the complete bridge project comprise a large and sometimes major portion of the project's total cost (Bridge Management Work Group 1987). These non-bridge costs are the following.

1. Approach roadway
2. Right-of-way acquisition
3. Utility relocation
4. Engineering
5. Traffic management

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The BMS must compute and allocate these costs based on general cost experience because the system has limited data to define any of these items. If specific information is available for a bridge, any of the items can be manually computed and the results entered into the system. Costs for all the above items are defined as a percentage of the project maintenance, rehabilitation, or construction cost, as appropriate. These percentages can be defined by the user based on engineering judgement.

Cost Classifications

Certain cost classifications are important for understanding the BMS cost database. These include the concepts of direct and indirect costs defined in several references. They also include the classifications below which help understand the complexities of specific cost figures.

- Differential Cost: The difference in total cost at one volume and total cost at another volume is the differential cost of these two volumes. Differential cost is sometimes used to embrace those changes in cost occurring from one point in time to another. Another use of the term is to refer to the differences in the cost of utilizing one particular method for accomplishing a task compared with another (Terril et al. 1964). For example, the unit cost for a partial overlay of a bridge deck might differ from the unit cost for a complete overlay, although both constitute the same activity.

- Replacement Cost: The cost of replacing a unit or a whole structure is its replacement cost. The cost of replacement may be less than or greater than that of new construction. There may be several of the non-bridge costs included. Also productivity may be considerably reduced if work must be scheduled during traffic.

- Standard Cost: These are predeterminations of certain elements of cost under specific work conditions. Standard costs are usually set for the basic elements of cost -- material, labor, and overhead. They represent the cost per unit of product or per unit of activity in an operation (Terril et al. 1964). For example, a unit cost may be set for excavation for certain soil conditions. For major variations in soil conditions, this cost would have to be modified.

Factors Affecting Unit Costs

Cost data collected from different sources vary due to a wide variety of factors. Some of these are listed below.

- Time
- Location
- The type and size of structure
- The scope and quantity of work
- Similarity of projects (learning curve effect)
- The specifications for materials and workmanship

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- Quality variations
- The environment, difficulty of working conditions and other factors affecting productivity
- Overhead, profit and competition
- The economy and financial situation of contractors
- Local regulations
- Site conditions

Of these, time is probably the most important. Escalation (or deescalation) will affect prices; the time to complete the project will affect the productivity, cash flow, and ability to plan work.

Cost Escalation and Indices

The change in the value of the currency is called inflation or deflation, depending on whether the value declines or increases. The increase in the price of commodities over time is called escalation. These commodities may be materials, labor, equipment or other classes of items. The measurement of the change in a particular "basket" of commodities is an index or, more precisely, a cost index. A cost index is the price level at a given time and place divided by the price level for the same item at a base or standard time and place. Indices are published by various organizations and magazines. Published indices are compiled in various ways. One of the most common is the Engineering News-Record (ENR) construction index of certain fixed quantities of cement, lumber, structural steel, and common labor. There are limitations on using any index. One of the most serious is that the composition of the commodities changes over time.

In the life-cycle cost comparison or other analyses that use the time value of money, there is no effect on the outcomes if:

1. Constant dollars are used so that all costs are based on the same base period or
2. Inflation affects prices and the discount rate equally so that these two factors offset each other, leaving the same result as in constant dollar evaluations.

If there is differential escalation, the problem is more complex because each unit cost must be escalated according to the indices of the prices that make up the unit cost. Further, the discount rate must be increased by an amount that takes into account the anticipated inflation in interest rates.

Bridge Work Breakdown Structure

There is a limit to the amount of information that can be successfully managed, comprehended, and used at any one organizational level. A management system must be broken down into well-defined hierarchal components at successive levels of detail. This must be done so that the detailed data can be identified with manageable work packages and can be summarized into successively larger packages without redundant effort. The goal of this approach is to structure a cost control system that is compatible with the BMS:

- It identifies the various bridge components and tasks for which cost data is required and relates these to work tasks.
- It permits the collection and storage of data at various levels of detail.
- It catalogs the total effort at various levels of detail and is hierarchical in format to enable a summary of data at any level.

The bridge breakdown structure (BBS) model is similar to that used in the cost control systems of the government and the engineering construction industry.

Definitions

The terms used in this section are defined as follows: A work breakdown structure (WBS) is the hierarchical representation of a complete project or program, its components being arrayed in ever increasing detail. A WBS element is a component at any level of a WBS. A cost breakdown structure (CBS) is the hierarchical representation of all cost accounts in a project to include indirect and overhead. The WBS is included within the CBS. A task is an operation performed by an individual, crew(s), and/or equipment, such operation being directly or indirectly required for completion of the work package.

Developing the BBS

To create any work breakdown structure, start with the total scope of work in the project and break it into its major system subdivisions (engineering, construction, procurement, etc.) and their subdivisions, with each component at each level being distinguishable from others. Each succeeding level of a WBS will reflect the way work is traditionally managed.

In the BBS, the bridge is treated as the total scope of work (level 0). One way of organizing the work is to divide the bridge into major tasks, ie., engineering, construction, and maintenance (level 1). Another is to treat the bridge components and subcomponents as level 1. Since the focus of this study is on the maintenance, repair, and replacement of bridge components, we will use the latter. At the Department of Transportation other cost control systems using other levels could be possible. Figure 5 shows the representation of the different levels of the BBS adopted for this study.

In this scheme, level 1 would be the various bridge components listed below.
- Roadway
- Superstructure
- Substructure
- Channel
- Retaining Wall
- Approach

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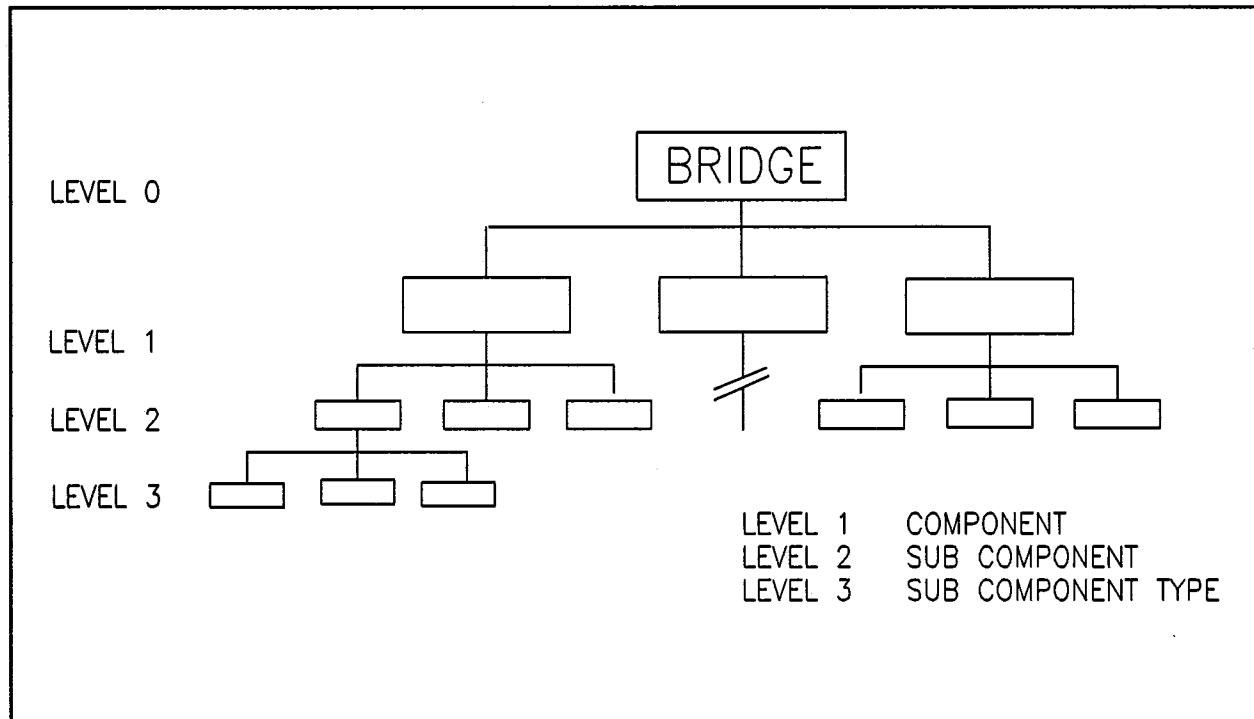
Figure 5. Bridge Breakdown Structure
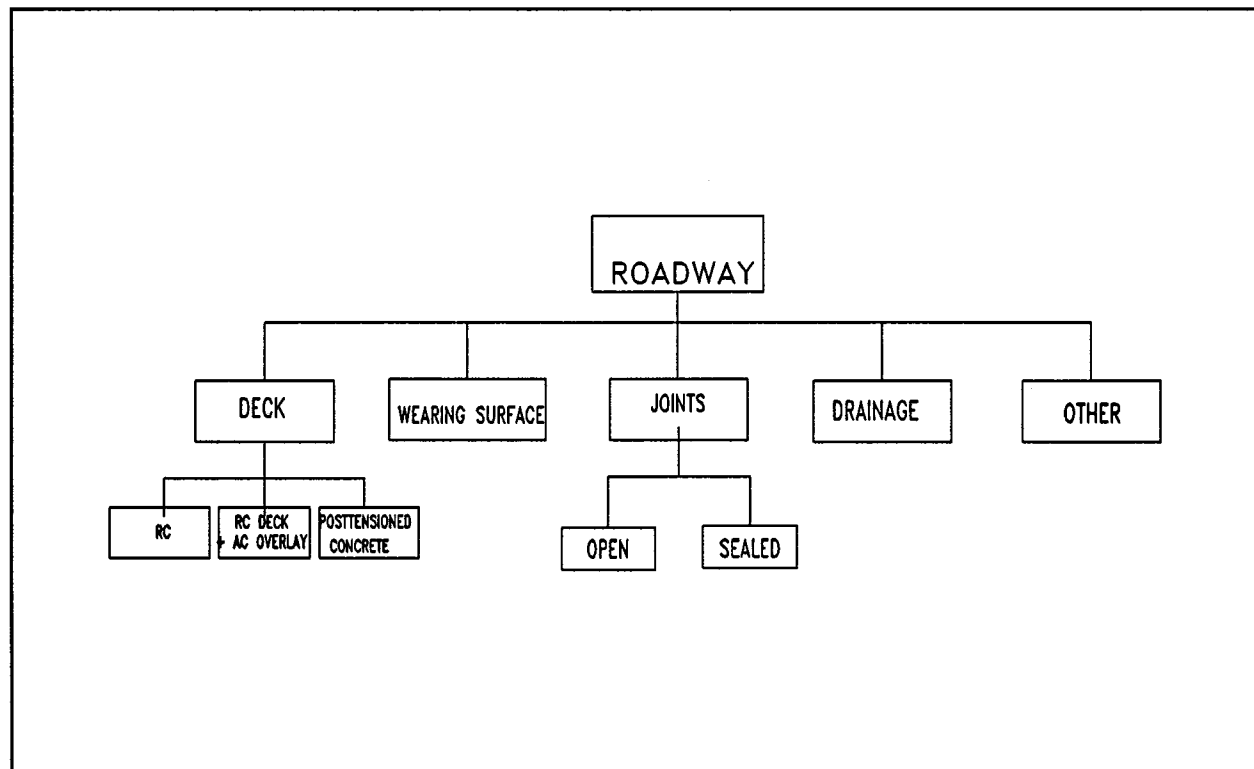
Figure 6. BBS -- Roadway; Levels 1,2,3

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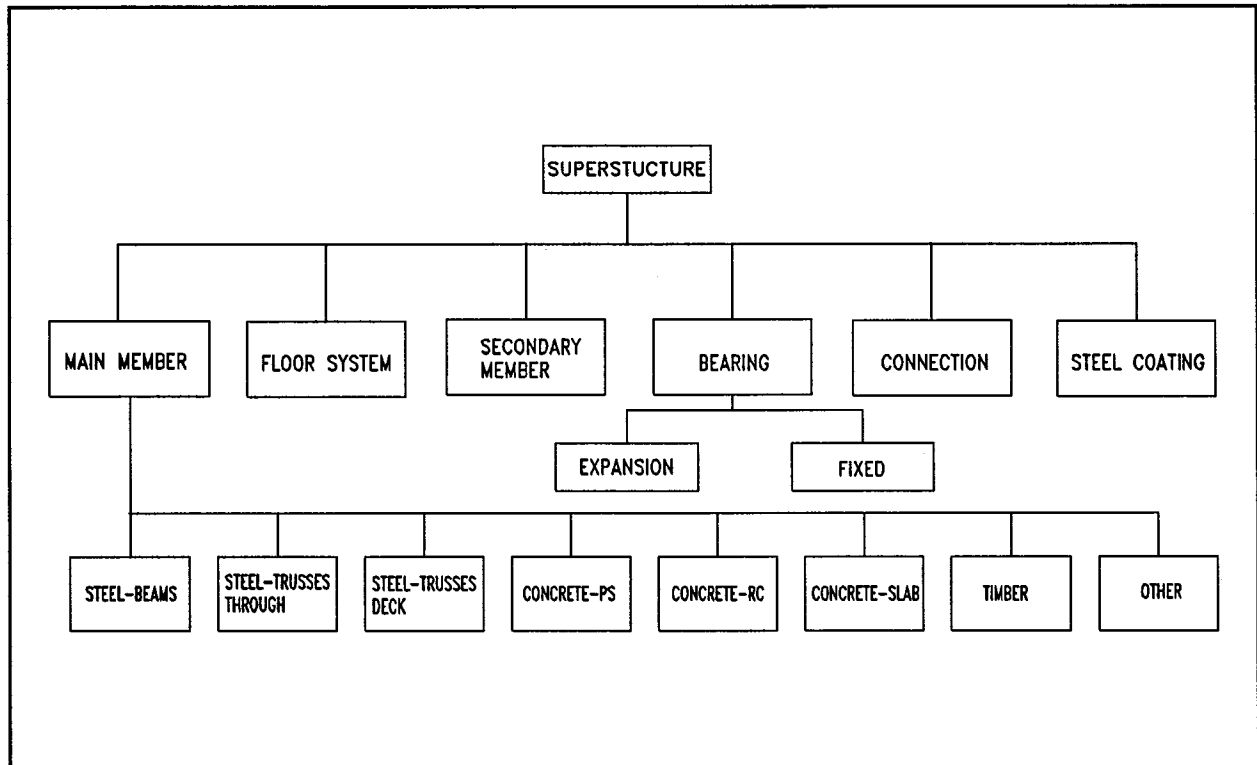
Figure 7. BBS -- Superstructure; Levels 1,2,3
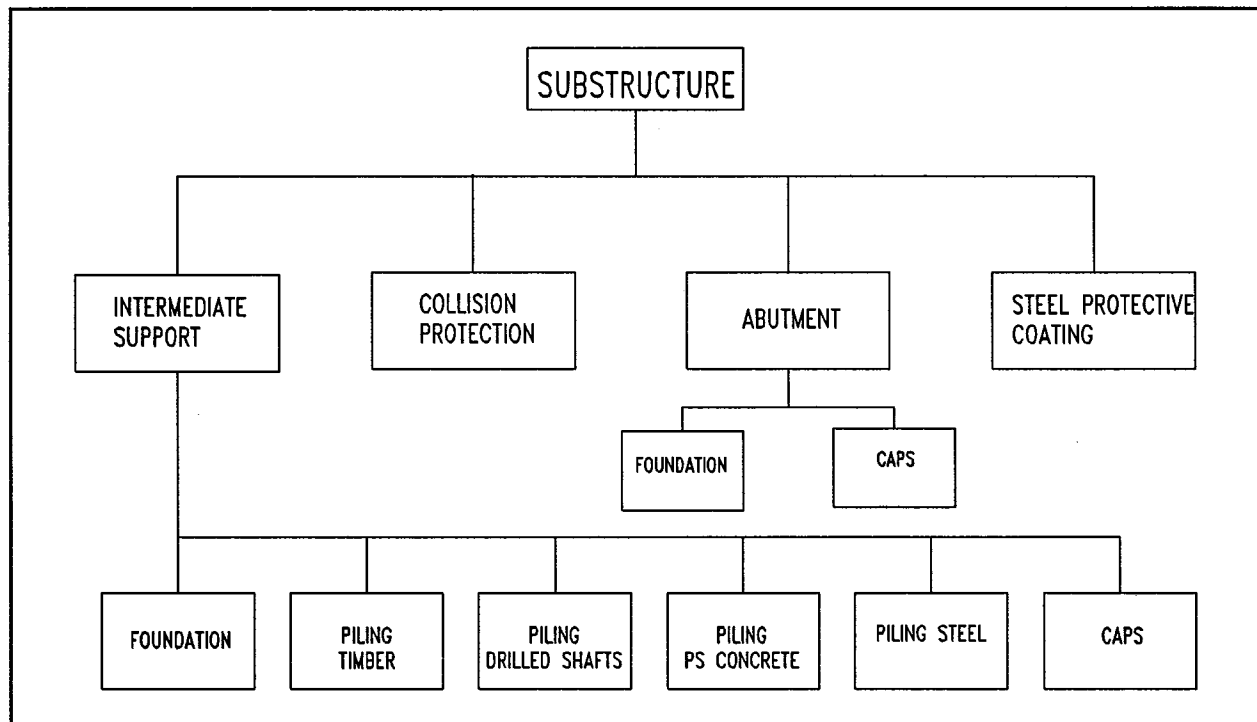
Figure 8. BBS -- Substructure; Levels 1,2,3

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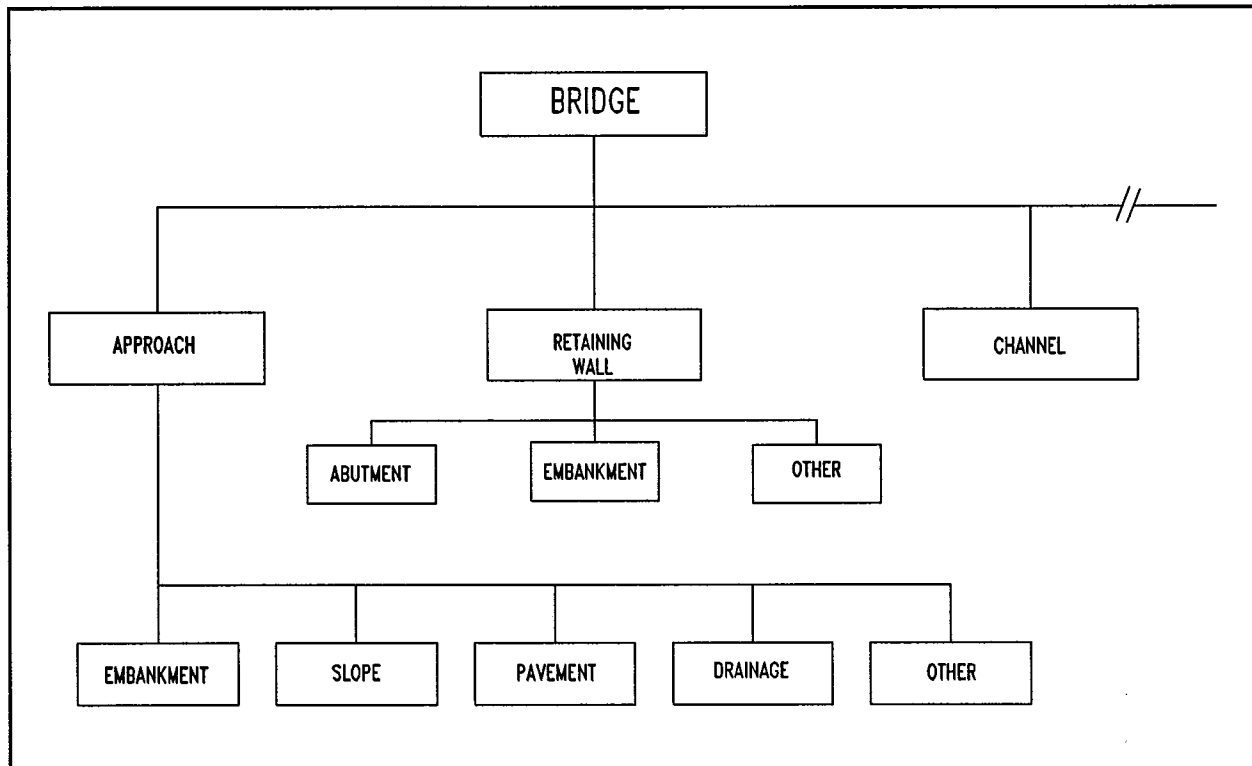
Figure 9. BBS -- Approach, Retaining Wall and Channel; Levels 1,2,3

Figure 6 through Figure 9 show how the bridge is divided into component and subcomponent levels. This approach establishes the components for which cost data was needed. The next stage is to determine what category of work is to be done on these components. These are defined for an existing bridge as *replacement, improvement, rehabilitation (limited and major), and maintenance.* Having established the various work activities and the bridge components on which these activities are to be carried out, tables were developed for the various costs that need to be tracked (see Appendix A). This is done by relating each of the above mentioned work activities to the bridge components. Figure 10 shows this relationship for the roadway.

Coding System

A coding system provides a sure way of identification of each work activity, simplifies data handling, and provides economy of computer storage. A good system of coding is one which simplifies the task of referring to the items in the database. For example, a four-digit code name enables four levels of the characteristic definition of the subject to be represented. The coding process consists of assigning a symbol or a group of symbols to each item in a list of items so that any item can be identified conclusively from all the other items that appear in the list. The generally accepted coding system uses either alphabetical or numerical symbols or a combination of both. Of these alternatives, there is a preference for purely numerical systems. The code used in this study is a five-digit

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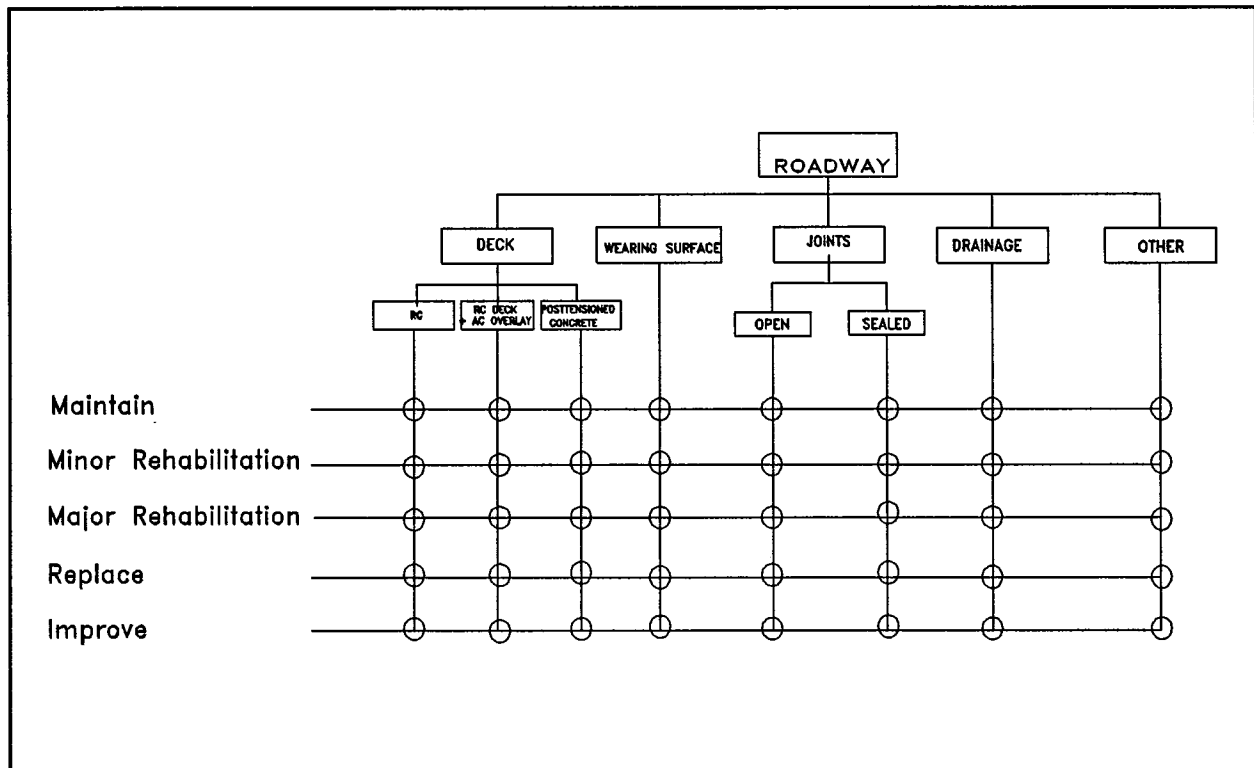
Figure 10. Relating Work Activity to Bridge Component

numerical identifier. Figure 11 shows its structure. Values for the first digit, the primary component identifier, and the last digit, the activity identifier, are listed below with their appropriate descriptors.

Main Component	Numerical Code
Roadway	1
Superstructure	2
Substructure	3
Channel	4
Retaining Wall	5
Approach	6

Activity	Numerical Code
Maintain	1
Minor Rehabilitation	2
Major Rehabilitation	3
Replace	4
Improve	5

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```
3        3        00        2

X        X        XX        X
│        │        │         │
│        │        │         └──Activity
│        │        │        2=  Repair
│        │        └──────────Type (of element)
│        │
│        └──────────────────Element (of main component)
│                          3=  Collision Protection
│
└──────────────────────────Main Component (of bridge)
                           3=  Substructure
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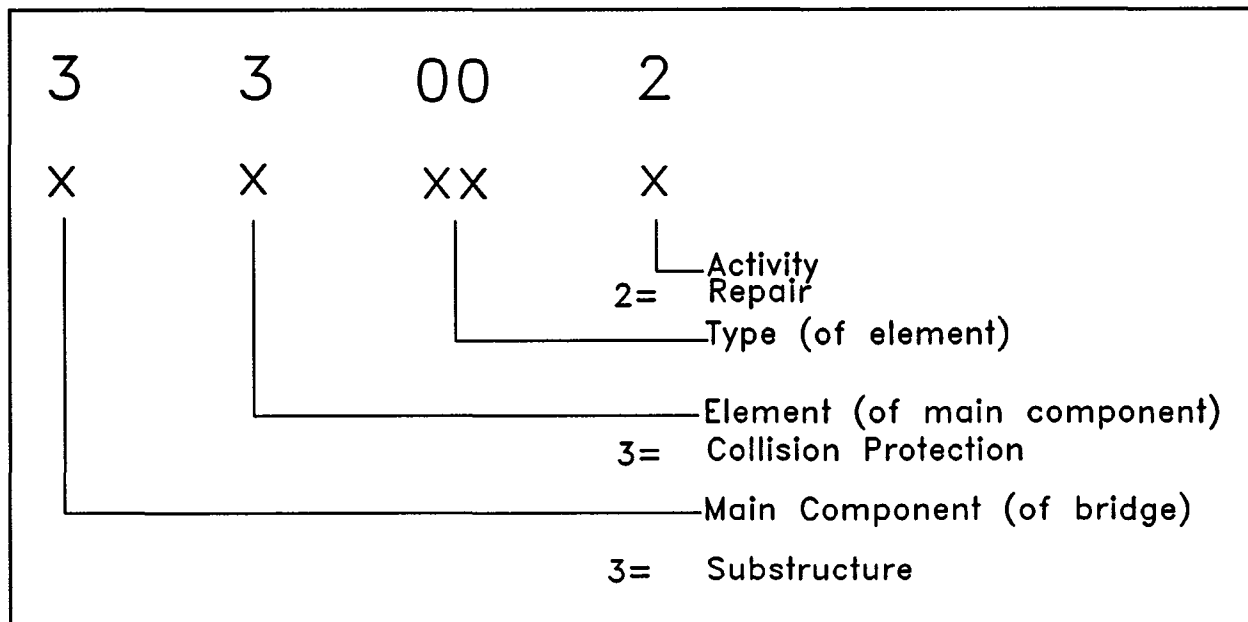
Figure 11. Interpreting the Coding Structure

The element and type identifiers are related to the main component identifier. When the five digits are put together, the result uniquely identifies a work activity for a particular component of a bridge. The code number 33002 is illustrated in Figure 11. In this example, the "type" of substructure is unique (00). To identify another subcomponent such as intermediate supports, several types are possible. For example, steel piling, spread footing, or drilled shafts could be specified. See the section entitled "Required Initial Cost Data" for the complete structure of the proposed database.

This database structure only permits identification of the structure components and associated BMS activities possible on a completed bridge. It is intended to supplement inventory, inspection, or appraisal information already contained in BRINSAP. The cost code can and should be expanded to incorporate other cost information such as engineering activity.

Data Requirements

Cost information is available in many locations in TxDOT. For example, actual records of past projects are in the Design and Construction Information System (DCIS) and in the bridge costs file maintained by the Division of Bridges and Structures (D-5). Information is also available from many commercial sources and from experts in the field.

Formulation of credible and usable cost figures involves selection of available information which can be difficult to obtain. Under such circumstances the data collected and selected should conform to certain criteria. Data must be valid, accurate, and consistent. A single database with readily available cost data on various bridge activities is presently not available for the state of Texas. One reason is that bridge cost work is frequently

incorporated into highway work. For example, patching of spalls for a bridge may be one work item in the bid for work on the highway section on which this bridge is located. Another reason is that contracts for bridge maintenance may include several bridges or work other than maintenance in the same bid item. Also, maintenance work items in the Maintenance Management Information System (MMIS) have a different cost structure (see p. 23, Report 1212-1F).

TxDOT Cost Databases

The databases presently being maintained by the highway department which contain bridge cost information are:

Design and Construction Information System (DCIS) DCIS is a database system that is supported by a distributed network of users. The Department of Transportation is responsible for the update. The DCIS database is a central storage place that is organized to make it easy to input and retrieve project-related information. Currently there are 13,000 projects in DCIS. It includes four sections: the DCIS project information, DCIS work program, DCIS project estimate -- this section has the engineers' estimates and cost breakdowns of each work activity, and the DCIS contract letting containing information regarding bidding and letting of the project. This last section contains the low bids of the selected contractor.

Bridge Costs File The bridge costs file is a database maintained by the Division of Bridges and Structures. It contains cost information for bridge projects that have been let to outside contractors beginning in the year 1980. The cost information is obtained from low bid summaries and is updated by D-5 on a regular basis. Most of the information contained in the bridge cost file is available in DCIS. However, in the bridge costs file the information is consolidated. The database contains approximately 6000 records. Each record contains information on the work done on a particular bridge, the bridge location and identification, the various costs associated, and other information relevant to the bridge. Furthermore, it contains only bridge information, whereas the DCIS file contains all highway-related work. It is therefore easier to extract relevant information from the Bridge Costs File.

Quality of Cost Data

In developing costs for the database there is a need to maintain a continuity of cost data. That is, the type of cost data generated can be reconciled with what costs are needed. Unit cost data was derived by analyzing historical data of total project costs, project description, and work involved. This data was modified using judgement, statistical validation, and expert opinion.

The quality of data is influenced by its accessibility, relevance, applicability and validity. Data derived from specific projects may be less than ideal when applied to other projects, which may be similar but not identical in nature. While it is not possible to identify all the circumstances and factors that make one project identical to another, an average unit cost may be obtained by combining available data to achieve some degree of statistical validity.

In summary, quality data should be readily accessible, it should be relevant to and reconciled with the intended project, and it should be valid for the given time and location. Furthermore, the data should be statistically valid. That is, the user should have a high degree of confidence that the true value will be in the range of the samples selected.

Default Initial Cost Values

For BMS analyses it is necessary to develop some default values of costs for the alternatives suggested by the feasible alternatives synthesizer (FAS) even though it is realized that actual costs may vary from these standard default costs. Some of these variations can be predicted, but most cannot. However, since it is likely that the user will have his own cost data to supplement the default data presented herein, these variations are not material. Nevertheless, to use standard costs in the BMS, their reliability, as measured by their variance, needs to be established.

The two components of any standard cost are unit and value. In developing the standard costs for the feasible alternatives that will be considered by the BMS, $/SF of deck area was adopted as the unit where appropriate. This was to allow easy and extensive use of the developed data.

Procedure

The bridge costs file was used as the basis for developing the standard costs. Relevant fields were extracted from the database using a SAS program. The data fields extracted were the following.

- Bridge width
- Bridge length
- Deck area in square feet
- Cost per linear foot
- Superstructure cost per square foot
- Substructure cost per square foot
- Miscellaneous cost per square foot
- Description fields
- Coded descriptions

Using the description fields the data was sorted into the following categories.

- Widen
- Replace
- Rehabilitate
- Improve

This data was further classified according to bridge type. Since the bridge costs file contained data from 1980 onwards, all cost data values had to be brought up to 1990. This was done using standard cost indices.

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Suggested Default Initial Costs Data

The minimum required cost data that must be incorporated into the proposed BMS is listed in the following tables. Using existing data, costs were developed for as many of the bridge alternatives possible. These alternatives, which include various improvement, rehabilitation, and replacement strategies for different types of bridges and their components, are consistent with the level of detail provided by the feasible alternatives synthesizer (FAS). The costs tabulated below are given in 1990 dollars. Due to a lack of extensive cost data, some of the cost items could not be readily obtained. However, an initial estimate of these values can be approximated from the costs of similar work items on other types of bridges or from expert judgement until better costs are obtained. As future cost information becomes available, these tables can be readily updated.

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Steel I-Beam	Improve	Widen	58.74	44.76	23
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck		30.83	11.73	21
	Replace Deck and Superstructure				
	Replace Bridge		40.62	21.55	16

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Plate Girder	Improve	Widen	44.15	10.60	6
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck		41.01	18.00	5
	Replace Deck and Superstructure				
	Replace Bridge		49.95	18.98	32

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample size
PS I-Beam (PC)	Improve	Widen	54.45	25.53	124
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck		30.76	13.61	23
	Replace Deck and Superstructure				
	Replace Bridge		35.18	25.26	1,049

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
PS Slab (PC)	Improve	Widen	53.87	17.2	8
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Slab			
		Substructure			
	Replace Slab				
	Replace Bridge		53.22	44.34	32

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	No. of uses
Reinforced Slab (CIP)	Improve	Widen	50.89	30.70	52
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Slab			
		Substructure			
	Replace Slab				
	Replace Bridge		38.16	19.25	117

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Voided Slab (CIP)	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Slab			
		Substructure			
	Replace Slab				
	Replace Bridge		53.50	0	1

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
CGC Pan Girder	Improve	Widen	53.63	20.97	81
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Pan Girder			
		Substructure			
	Replace Pan Girder		44.36	36.85	10
	Replace Bridge		36.25	13.40	409

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Reinforced Tee Beam (CIP)	Improve	Widen	39.03	4.18	4
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck				
	Replace Deck and Superstructure				
	Replace Bridge		38.40	10.10	3

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
PS Single Tee (PC)	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck				
	Replace Deck and Superstructure				
	Replace Bridge		22.18	2.85	3

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Concrete Box Girder (CIP)	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Superstructure			
		Substructure			
	Replace Superstructure				
	Replace Bridge		36.34	8.50	4

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
PS Box Beam (PC)	Improve	Widen	54.91	17.49	18
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck		45.54	12.55	20
	Replace Deck and Superstructure				
	Replace Bridge		46.52	21.54	185

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Reinforced Slab (PC)	Improve	Widen	56.24	0	1
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Slab			
		Substructure			
	Replace Slab				
	Replace Bridge		47.6	5.1	3

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Reinforced Girder with CIP Slab	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Deck			
		Superstructure			
		Substructure			
	Replace Deck				
	Replace Deck and Girders				
	Replace Bridge				

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Segmental Concrete Box	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Superstructure			
		Substructure			
	Replace Superstructure				
	Replace Bridge				

Main Span Type	Feasible Alternative		Unit Cost ($/SF of deck area)	SD of Data	Sample Size
Postensioned Rib Slab	Improve	Widen			
		Raise			
		Strengthen			
		Align Approach			
	Rehabilitate	Slab			
		Substructure			
	Replace Slab				
	Replace Bridge		57.3	41.67	3

Recommendations for Collection of Future Costs Data

The bridge breakdown structure described above is recommended for use as the agency cost model within the overall bridge management system (BMS). The BBS will provide a basis for collecting and storing bridge costs for the various alternatives suggested by the feasible alternatives synthesizer (FAS). In so doing, it will enhance the system's ability to estimate future funding needs for maintenance, rehabilitation and replacement. The systematic storage of cost data will supplement BRINSAP by providing cost histories for different types of bridges. This data will therefore not only be useful within the framework of the BMS, but will also allow bridge engineers and managers to more accurately estimate costs and project funding needs. However, the limitations of the data, some of which were mentioned above, must be kept in mind to ensure that results are not misinterpreted.

In order to implement and use the proposed BBS, the Department will have to refine and/or expand its existing databases. The standard cost value table illustrates that many fields are not available at an aggregated level, and an attempt to fill in all fields within the BBS structure was not entirely successful. Much of this additional data, along with overall improvements to the databases, will have to be incorporated over time as the BMS is implemented and used.

It should be noted that, if desired, the proposed bridge breakdown structure (BBS) could be used to support a more detailed cost structure on an element by element basis. The database system could then be used to combine costs at several independent levels of the overall work package to arrive at a unit aggregate costs for the FAS alternatives. This approach would also be useful if, in the future, the Department expands its inventory and appraisal data to allow the BMS to perform a more detailed analysis.

Agency and User Benefits

The use of life-cycle cost analysis and benefit-cost analysis for evaluating transportation projects has been increasing in recent years, but it has not yet received universal acceptance and has not evolved to the stage that a standardized procedure and assumed parameters are accepted by all professionals in the field. There are, however, certain basic accepted concepts which are in widespread use even if some of the details and assumptions may vary. NCHRP Report 133, Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects (Curry and Anderson 1972), and the 1977 AASHTO Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (AASHTO 1977) have been widely used as reference guides and will be useful as general background references.

In the last several years, major advancements have been made in life-cycle cost analysis procedures and methods of calculating user costs for bridge alternatives. Two references present the state of the art in this analysis very well. The first of these is the Federal Highway Administration's procedure for analyzing bridge alternatives (FHWA 1987). The second is research in North Carolina, especially the report by Farid, Johnston, and others (1988). These life-cycle cost procedures represent a major advancement in the state of the art for bridge analysis and will provide the basic framework for this study.

In order to evaluate the alternative improvement strategies for every bridge on a network system, it is necessary to consider the life-cycle costs associated with each alternative. Life-cycle cost analysis is particularly suitable for evaluating multiple alternatives which have unequal life expectancy, level of service, and/or maintenance costs. Based on the expected deterioration rate, costs required to bring a bridge back to a desired level of service will be utilized to generate a life-cycle profile. Since the deterioration rate, hence the service life, for a particular bridge may be affected by a number of factors, life-cycle cost profiles must be established for various bridge types, service conditions, levels of maintenance, etc. A discount rate must also be selected in order to combine future and present costs and compare various alternatives against a baseline scenario.

Agency Benefits

Agency benefits are categorized as reductions in life-cycle cost resulting from actions of the agency, such as maintenance, certain types of rehabilitation, and any other actions that effectively extend the service life of the bridge. More specifically, agency benefits are defined as the present worth of future cost savings to the department due to a bridge expenditure (FHWA 1987).

To determine agency benefits, the present worth of all future costs to the agency over the life of the bridge, such as maintenance, rehabilitation, and replacement expenditures, are calculated for two different life-cycle cost scenarios. The first assumes no improvement is made to the bridge, thus the service life is not extended and replacement takes place at the end of the bridge's remaining life. This scenario constitutes the baseline or reference life-cycle cost which typically has the highest future cost, including future agency and user costs. For reasons discussed later, the base alternative is considered to be the general do-nothing alternative (with no major capital expenditure in any period).

The second case assumes that an expenditure is made to extend the life of the bridge for a specified number of years. This scenario determines the life-cycle cost for the improvement activity. Thus, future agency benefits for an improvement alternative are assumed to equal the reduction in future agency costs relative to the base alternative plus any increase in salvage value relative to the base alternative. Future agency costs are assumed to include all agency costs associated with an alternative except the capital cost for the improvement being considered. The initial capital cost is used as the cost of the alternative in the optimization analysis which is discussed later. The equations required to perform the economic analysis, as well as an illustrative example, can be found in Report 1212-1F.

Investment Analysis

The investment analysis is a short-term analysis, usually one to five years in length, which determines the optimal means of allocating funds among a selected network of bridges under a fixed budgetary constraint. In order to achieve this goal and evaluate the alternative activities for every bridge on the network system, it is necessary to examine the costs incurred by both the highway agency and the users. These costs include the first or initial one-

time cost associated with the capital expenditure being evaluated, maintenance costs, and user costs such as accident costs and vehicle operating costs.

As discussed in the section entitled **Optimization Procedures**, the investment analysis requires a single cost and benefit associated with each alternative being considered for a particular bridge. The cost used in the optimization scheme is taken to be the initial cost of the alternative to the agency as described above. Default values of initial costs for various improvement strategies can be found in the section entitled *Default Initial Cost Values*. The net benefit for an alternative is taken to be the summation of savings or reductions in user costs and future agency costs.

Life-cycle-cost analysis is particularly suited for the determination of future agency costs, since it allows direct comparison of multiple alternatives which have unequal life expectancy. As alluded to above, the agency benefits for a given alternative are calculated as the difference between two life-cycle costs -- the cost stream associated with the improvement activity subtracted from the cost stream for a selected baseline scenario. In the investment analysis, this base alternative is taken to be the do-nothing alternative which, by definition, has the highest future agency costs. The do-nothing alternative assumes that a bridge replacement will occur immediately following the analysis period. Other characteristics of the do-nothing alternative are described in detail in the sections below.

Each improvement alternative, if performed, will extend the life of the bridge and postpone the need for replacement. Based on this life extension and the appropriate deterioration rates for the structure, a life-cycle profile for the alternative can be generated. As mentioned above, the actual initial cost of the alternative to the agency is not included in the life-cycle profile but, rather, is used as the initial cost in the optimization scheme. However, there will be maintenance costs after the improvement, as well as future bridge replacement cycles which must be taken into consideration.

As implied above, the selected alternative will raise the existing condition of a component to some level above its present value, that is, it will provide an extension in service life. Using the new condition rating for the component, deterioration formulas may be used to find the remaining life of the structure. At this future time on the life-cycle profile, a bridge replacement is assumed. Furthermore, a replacement cycle with an appropriate maintenance gradient is assumed to occur every LOB (life of bridge) years thereafter, where LOB is taken to be the life expectancy of a new bridge. The value for LOB is taken from the appropriate deterioration curves, that is, the curves associated with a particular type of bridge, on a certain functional class of roadway, in a certain geographic location, etc. (see **Deterioration Model**). Using the fundamental equations of economic analysis presented in Report 1212-1F, the present worth of the life-cycle-cost stream, assuming perpetual service, can be found. The present worth value of the improvement case is subtracted from the present worth value for the do-nothing case to determine future agency costs.

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In a manner similar to that used to determine future agency costs, benefits due to reductions in user costs are calculated by subtracting the present value of user costs after the improvement from the present value of user costs before the improvement. These user costs are typically calculated as uniform gradients that increase with time dependent factors such as ADT, deck condition, load-capacity deterioration, etc., and are subsequently brought back to present worth. Details of user benefits and how they are calculated are described in the sections which follow.

Needs Analysis

A bridge needs analysis usually will be made to cover a period of about twenty years. The needs analysis is a procedure for developing an estimate of the funds that will be needed over this period of time to maintain Texas bridges at a given level of service. In this analysis there is no budget constraint so each bridge can be analyzed separately. Only activities which provide a selected minimum level of service are considered as alternatives. A life-cycle-cost analysis is then performed to determine which of these alternatives is least costly, that is, which has the least total agency and user costs in present worth terms. The life-cycle costs are calculated in a manner similar to that described for the investment analysis with one minor exception. In the needs analysis the initial cost of an alternative is added into the life-cycle-cost stream. In this way all costs associated with the bridge are considered at the same time and a direct comparison of life-cycle costs can be made among the various alternatives for each bridge in order to select the activity that will minimize costs while providing the desired level of service. This procedure is outlined in more detail in Optimization Procedures.

For some bridges that are relatively new, the minimum level of service can be met with only routine maintenance expenditures. For other bridges, the level of service will decline below the minimum tolerable level and the bridge must be rehabilitated or rebuilt in order to bring it back to acceptable level of service. An analysis similar to the one outlined here can be found in the Bridge Needs and Investment Program (BNIP). In the BNIP analysis a well-structured set of rules has been established to outline the set of investment decisions that will maintain the level of service above the minimum acceptable level. These rules lead to a set of investment decisions for each bridge in the analysis. It is recommended that procedures for coordinating the highway needs analysis developed using HPMS be integrated and coordinated with the bridge needs analysis. (A research study is being funded in FY93 to develop ways of accomplishing this integration and coordination.)

Average Daily Traffic

User cost estimates typically are calculated on an annual basis by multiplying the estimate of daily user cost by 365 days per year (or, sometimes, 365 1/4 days per year is used). In the BMS it is necessary to estimate user costs not only for the current year but also for future years. Therefore, estimates are needed not only for current ADT but also for ADT in future years. For consistency with other analyses, it is recommended that estimates for future ADT for use in the BMS be derived by using the forecasts of future ADT developed for the Highway Performance Monitoring System. These twenty-year ADT estimates are developed in Texas each year for each

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roadway section. These estimates are developed for use with the HPMS needs analysis and are available from Division D-10.

Discount Rate

As mentioned previously, benefits and costs occurring over time must be discounted to present value since benefits and costs occurring in the future are not as valuable as those in the present. The choice of an appropriate rate to discount future benefits and costs is important for several reasons. A rate that is too high will tend to favor projects which have a shorter payback period, projects with the flow of benefits occurring closer to the present, as opposed to projects with benefit flows over a longer period of time. An incorrect discount rate will affect the total amount of resources going to public investment projects and will, therefore, result in a misallocation of resources.

For private investment decisions the discount rate should be the marginal cost of capital, but for publicly funded projects, both the marginal productivity of capital and rate of time preference between current and future consumption must be considered. Depending on what assumptions are made about what the discount rate represents, different rates are estimated. The actual number used typically ends up being a value judgement by the analyst or acceptance of some number used in another application.

For transportation projects, the 1977 AASHTO Manual (AASHTO 1977), for example, recommends using the real cost of capital, which Hirshleifer and Shapiro (1969) estimate at about 4 percent for low-risk investments. NCHRP Report 133 (Curry and Anderson 1972) recommends a discount rate of between 6 and 10 percent, based upon taxpayers' opportunity cost of capital for transportation projects of average risk. The actual discount rate used by different highway agencies and at different times varies widely, although most seem to be in the 5 to 7 percent range according to a Texas Transportation Institute survey (Buffington et al. 1979). Florida, for example, uses 7 percent (McLeod and Adair 1980); and the default discount rate in the HEEM-II computer program used in Texas is 8 percent (Memmott and Buffington 1983).

The AASHTO manual on benefit-cost analysis discusses how the discount rate normally should not include inflation, and analyses that use constant dollars should use a discount rate that excludes inflation -- the "real" discount rate. "Constant dollars refers to an expression of costs stated at price levels prevailing at a particular (constant) date in time, whereas current dollars is an expression of costs stated at price levels prevailing at the time the costs are incurred." The AASHTO manual further notes that:

"...the common practice of calculating benefits in constant dollars (usually at prices prevailing when the economy study is made) and discounting benefits at market rates of interest is in error, because the market or nominal rate of return includes (1) an allowance for expected inflation as well as (2) a return that represents the real cost of capital...

...if future benefits and costs are calculated in constant dollars, only the real cost of capital should be represented in the discount rate used. The real cost of capital has been estimated at about 4 percent in recent years for low-risk investments.

If benefits and costs are projected in inflated or "current" dollars, then the full current market rate of interest should be used. A range of 8 percent to 12 percent is common to represent the average long-term market interest rate in recent economy studies of public projects..."(AASHTO 1977, pp. 14-15).

The AASHTO Manual notes that "... a rate of about 4 to 5 percent seems appropriate for projects of average risk evaluated in constant dollars." Since the precise rate to be used is not fully resolved, the proposed analysis will allow the user to input the discount rate but probably will assume that costs are in constant terms and a default rate of 5 percent is recommended.

Single Period Formulation

In the single-period life-cycle-cost model developed by the Federal Highway Administration, the base alternative is the most expensive alternative, bridge replacement. Other alternatives are compared to this alternative, and reductions in cost are considered as benefits in the single-period optimization problem. The method proposed for the BMS for Texas is similar to the FHWA method, except that it is proposed that the alternative with the largest future costs be used as the base alternative rather than the bridge replacement alternative. Agency benefits for an alternative are defined as the decrease in future agency costs (all agency costs except the initial cost of the alternative being considered) relative to the base alternative plus the increase in salvage value for the alternative.

In the single-period formulation it will be assumed, for purposes of calculating future agency costs, that the base alternative is the do-nothing alternative where it is understood that do-nothing means no major capital expenditure is made during the first period. However, it is further assumed that doing nothing in the first period simply postpones replacement, or possibly major rehabilitation, to the next period. Therefore, the do-nothing alternative will have very high future costs, represented by the future replacement in the next period. If the do-nothing alternative is chosen in the first period, then the bridge deteriorates for a year and the do-nothing alternative becomes the base in the next period.

In the single-period optimization case, alternative investments are considered one period at a time, which probably will be one or two years in length. Use of successive single periods are considered as discussed below and in the section entitled **Optimization Procedures**.

Multiple Period Formulation

In the multi-period optimization situation, budgets typically are assumed to be fixed for each sub-period of the analysis horizon. Because the budget for each period is fixed at the time of the sub-period, there is no discounting of costs to time zero. Costs that occur in a particular period simply are subtracted from the budget for that period when an alternative is chosen. That is, since the sub-period budgets are fixed, the optimization problem can be stated as having the objective of choosing the set of projects (with total cost for alternatives chosen for improvement in each sub-period not exceeding each sub-period's budget, not discounted) over time that will

maximize the present value of future benefits or reductions in user and possibly agency costs other than capital costs. It typically is assumed that all funds must be spent as they become available and that they cannot be invested and carried over to future years as a strategy, with the intent to investment in future periods when needs are predicted to be greater (although this assumption can be changed if desired). Therefore, in the multi-period optimization problem, it is reasonable to not discount future agency costs, at least not the costs that are being budgeted, during the analysis period. In fact, such discounting is not compatible with the assumption of absolutely fixed budgets in the multi-period optimization problem.

If the fixed budget for each sub-period is assumed to cover all types of agency costs, including maintenance costs, then these costs should be considered without discounting since they subtract fully from future money available for rehabilitation or rebuild alternatives. This point is critical to recognize in going from a standard life-cycle cost analysis to a true fixed-budget, multi-period optimization problem. A way of simplifying the problem, however, is to assume that the budget being considered is for major capital costs only and to include reductions in maintenance costs as benefits. This possibility is considered in more detail later in this discussion.

As in the single-period formulation, the base alternative for each period in the multi-period scenario will be defined as the do-nothing alternative. As discussed previously, it is assumed that the bridge is replaced as soon as it does not meet minimum tolerable conditions. If it deteriorates to a point where it should be replaced during the analysis period, it is assumed that it will be rebuilt in the year immediately following the analysis period. Because of this assumption, this base alternative will have the following characteristics:

1. It has zero capital costs during the analysis period.
2. It will have relatively high maintenance costs during the analysis period, if these are made a function of the level of deterioration, since the bridge may be in need of a major capital expenditure but none are made during the analysis period.
3. It will have the highest user costs of all alternatives, since no major capital expenditures are made with this alternative. If the bridge is in very good condition, user costs may be low for all alternatives. At a minimum, the overall do-nothing alternative should have user costs that are at least as great as any other alternative.
4. It has high future capital costs for the time period beyond the analysis period, since it is assumed that the needed capital expenditure is made immediately after the optimization period if minimum tolerable conditions justify such expenditure.

Thus, future agency costs and user costs will probably be the highest for this alternative, which is the reason it is chosen as the base alternative. This is similar to the concept used in the FHWA approach with the exception that it is used with future costs instead of all costs.

For purposes of the life-cycle-cost analysis, it is necessary to establish at what time during the sub-period a rehabilitation or rebuild will take place. This timing can be estimated using the appropriate deterioration model for the bridge under investigation, taking into account bridge type, location, functional classification, etc. That is,

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the rehabilitation or improvement activity takes place in the year the condition of a bridge component drops below a specified minimum level. For simplicity, since bridge related activities may take several years to program and complete, it may be assumed that a rehabilitation or rebuild will be accomplished in the middle of the sub-period. After such time that the life extension provided by the alternative has passed, the life-cycle-cost stream assumes a series of bridge replacements at intervals corresponding to the life of a new bridge. These costs, including an appropriate maintenance gradient, are calculated to perpetuity and then discounted to present worth dollars.

Two types of costs are calculated: (1) capital costs during the analysis period and (2) other costs. Other costs include maintenance costs and capital costs beyond the end of the analysis period (future costs) and are calculated for each set or alternative. From these costs, agency benefits are calculated for each alternative. These benefits are defined as reductions in other costs relative to the other costs for the overall do-nothing alternative. The agency benefits are added to the user benefits to get total benefits for a particular alternative for a particular bridge. The calculation of user benefits is described in detail below. After capital costs (initial costs) and total benefits are calculated for each alternative for all bridges, an optimization procedure can then be used to determine the best choice of alternatives for the bridge network being considered. Details of the various optimization schemes are discussed in the section entitled **Optimization Procedures.**

User Benefits

User benefits are benefits to the public resulting from actions that reduce user costs. User costs can be generated due to reduced load capacity, narrow width, poor alignment, and low clearance. For example, bridges with narrow width, low clearance, or bad alignment have a higher accident probability. Bridges with low clearance or low load capacity necessitate that some trucks be detoured, thus generating user costs in the form of increased vehicle operating cost and travel time. On the other hand, improvements that functionally upgrade a bridge, such as straightening the approach alignment, removing a load posting restriction, or increasing horizontal and/or vertical clearances all serve to reduce user costs. In general, any improvement that alleviates user costs prior to the end of a bridge's economic life is taken as a user benefit (FHWA 1987). These benefits are calculated by subtracting the user costs after an improvement from the user costs before the improvement. Thus, reductions in user costs are considered user benefits. Three types of user costs are generally considered in a life-cycle cost analysis (FHWA 1987, p.VI-24):

1. Accident costs;
2. Vehicle operating costs; and
3. Travel time costs.

These user costs are generally computed annually over the life-cycle of a bridge for the various deficiencies described above, and then discounted to a present worth in the same manner as agency costs. They are assumed to be proportional to traffic volume and the level of service deficiencies of a bridge. Thus, the user costs in any

given year, generated from the level of service deficiencies of an existing bridge, can be generally expressed as follows (Chen and Johnston 1987).

$$AURC(t) = [(C_{WDA}*U_{AC}) + (C_{ALA}*U_{AC}) + (C_{CLA}*U_{AC}) + (C_{CLD}*U_{DL}*DL) + (C_{LCD}(t)*U_{DL}*DL)] * ADT(t) * 365$$

where:

$AURC(t)$ = annual user cost of the existing bridge at the year t,

C_{WDA} = coefficient for proportion of vehicles incurring accidents due to deck width deficiency,

C_{ALA} = coefficient for proportion of vehicles incurring accidents due to a bad bridge alignment,

C_{CLA} = coefficient for proportion of vehicles incurring accidents due to a vertical clearance deficiency,

C_{CLD} = coefficient for proportion of vehicles detoured due to a vertical clearance deficiency,

C_{LCD} = coefficient for proportion of vehicles detoured due to a load capacity deficiency,

U_{AC} = unit cost of vehicle accidents on bridges ($/accident),

U_{DL} = unit cost for truck detours ($/mile),

DL = detour length (miles), and

$ADT(t)$ = average daily traffic using the bridge at the year t.

The basic framework for the determination of these coefficients was developed by Chen and Johnston (1987). This work is being expanded and updated for use in the BMS for Texas. Details of the development are discussed below.

Load Capacity Deficiencies

Bridge load capacity deficiencies can be due to low original design loads and/or bridge deterioration. When a bridge is posted for load capacity, vehicles weighing more than the posted capacity must be detoured. Thus, factors which affect the user costs generated due to bridge load capacity include the magnitude of the posted deficiency, the deterioration rate, the weight distribution of vehicles on the route, detour length, and vehicle operating costs.

Load capacity deficiency due to deterioration is influenced by various environmental factors and service conditions. For instance, bridges in marine environments or subject to frequent applications of deicing chemicals may have higher deterioration rates due to corrosion, etc., than would similar bridges in other regions. Similarly, high volumes of traffic may promote fatigue and/or overloads may cause structural damage to the bridge components (Chen and Johnston 1987).

Under federal inspection requirements, the structural members are assessed during each inspection cycle. Based on this inspection data, operating and inventory ratings are calculated for each bridge for various types of loadings. The operating rating is defined as "the maximum permissible load level to which the structure might be

subjected for the vehicle type used in the rating." The inventory rating is defined as "the load level which could safely utilize an existing structure for an indefinite period of time for the same vehicle type used for the operating rating" (FHWA 1979). The computed operating ratings are then compared with legal loads to determine the load restrictions for a particular bridge.

Bridge Load Capacity Deterioration Note that the operating rating recorded in the BRINSAP file is based upon the existing conditions of the bridge. If a bridge is properly maintained, there should be no significant loss in load capacity with increasing age. However, if a bridge is not maintained at a sufficient level and deterioration of the structure is permitted to occur, then a loss in load capacity can occur and increase with time. Therefore, in order to permit computation of future user costs due to load capacity deficiencies, a deterioration rate is required to predict the load capacity throughout the analysis period. The load capacity loss can then be subtracted from the operating rating for use in the user cost analysis.

Table 6. Load Capacity Deterioration Rates (Chen and Johnston 1987)

Condition Rating	Deterioration Rate (tons/year)		
	Timber	Concrete	Steel
6-9	0.00	0.00	0.00
5	0.30	0.20	0.20
4	0.60	0.30	0.30
< = 3	1.00	0.50	0.50

The deterioration rates used by Chen and Johnston (1987) are listed in Table 6. This data is largely a result of expert judgement and experience. Since deck condition almost never controls the rated load capacity, it is assumed that the lower of the substructure and superstructure condition ratings controlled the deterioration rate. Thus, if the rates of condition deterioration are known (see section entitled **Deterioration Model**), the capacity loss in tons/year can be calculated. A more analytical approach using regression analysis of bridge operating rating versus age was conducted using bridge inspection data. However, the correlation coefficients indicated a lack of fit due to a large degree of scatter in the data. It is therefore recommended that this data be used as a default for the Texas BMS until other data becomes available.

Vehicles Detoured Due to Load Capacity Deficiencies When a bridge is posted due to a load capacity deficiency, some fraction of the vehicles desiring to use the bridge must detour. The number of vehicles detoured depends on the magnitude of the load deficiency and the total number and weight distribution of the vehicle population using the bridge. Because of differences in average daily truck traffic (ADTT) and patterns of vehicle weight distribution, the load capacity deficiency will be different for bridges on highways having different functional

classifications. In general, the number of vehicles detoured in a given year for a load-posted bridge can be calculated as follows (Chen and Johnston 1987):

$$N_{DET}(t) = C_{LCD}(t) * ADT(t) * 365$$

where:

$C_{LCD}(t)$ = coefficient for the proportion of vehicles detoured due to load capacity deficiency in year t. The total number of trucks detoured will include single-unit trucks and truck tractor semi-trailers (TTST). Thus, C_{LCD} is simply defined as

$$C_{LCD}(t) = R_{SV}(t) + R_{TT}(t)$$

where:

$R_{SV}(t)$ = ratio of single unit trucks heavier than the bridge's single vehicle posting, SV, to the total vehicles using the bridge, and

$R_{TT}(t)$ = ratio of trailer combinations heavier than the TTST posting to total vehicles using the bridge.

Table 7. Vehicle Percentages for Various Functional Classifications (Chen and Johnston 1987)

Functional Classification	Proportion of Total Vehicles (%)		
	Cars	Single Units	Trailer Combin.
Interstate	83.1	4.41	12.50
Principal Arterial	87.3	6.03	6.63
Minor Arterial	92.1	4.62	3.33
Major Collector	96.3	2.63	1.15
Minor Collector	96.5	2.65	0.81

As mentioned above, vehicle distribution varies with route functional classification. In the study by Chen and Johnston (1987), a comparison of the average vehicle classification distributions from various sources was made. From this information certain trends of dominating truck types on various roadway classifications become obvious. On the interstate system a greater proportion of trucks were trailer combinations, whereas on the primary system, the percentages of single unit trucks and trailer combinations were almost equal. On secondary systems, single unit trucks were present in a higher percentage than were trailer combinations. Table 7 shows classification information

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for passenger cars, single unit trucks, and trailer combinations, for various roadway functional classifications. This data may be periodically updated for use within the BMS using the results of future studies, traffic maps, and data collected from various counting stations throughout the state.

Table 8. Truck Weight Distributions on Bridges by Functional Classification -- Single Units
(FHWA 1985, Chen and Johnston 1987)

Weight (tons)		Interstate			U.S. Routes			State Routes		
From	To	No. of Vehicles	%	Cumm. %	No. of Vehicles	%	Cumm. %	No. of Vehicles	%	Cumm. %
0.0	7.5	1500	56.90	56.90	350	58.92	58.92	761	41.70	41.70
7.5	10.0	384	14.57	71.47	92	15.49	74.14	421	22.72	63.79
10.0	12.5	231	8.76	80.24	46	7.74	82.15	147	7.93	71.72
12.5	15.0	159	6.03	86.27	27	4.55	86.70	76	4.10	75.82
15.0	17.5	132	5.01	91.27	25	4.21	90.91	63	3.40	79.22
17.5	20.0	86	3.26	94.54	15	2.53	93.43	65	3.51	82.73
20.0	22.5	42	1.59	96.13	23	3.87	97.31	96	5.18	87.91
22.5	25.0	23	0.87	97.00	5	0.84	98.15	80	4.32	92.23
25.0	27.5	29	1.10	98.10	9	1.52	99.66	56	3.02	95.25
27.5	30.0	16	0.61	98.71	1	0.17	99.83	51	2.75	98.00
30.0	32.5	8	0.30	99.01	1	0.17	100.00	31	1.67	99.68
32.5	35.0	14	0.53	99.54				5	0.27	99.95
35.0	37.5	2	0.08	99.62				0	0.00	99.95
37.5	40.0	3	0.11	99.73				0	0.00	99.95
>	40.0	7	0.28	100.00				1	0.05	100.00
		2636	100.00		594	100.00		1853	100.00	

Another item required for determining the number of vehicles detoured for a load-posted bridge is the truck weight distribution for each vehicle classification. In 1985, a study of bridge structure loading spectrum was conducted by the FHWA (1985). Using the weigh-in-motion system, weights and numbers of trucks passing over selected bridges on interstates, U.S. highways, and state routes were collected. The results of this study are shown in Table 8 and Table 9.

By multiplying the appropriate weight distribution from Table 8 and Table 9 with its corresponding vehicle classification distribution from Table 7, the percentage of trucks out of the total ADT which are at or below a specified weight range can be determined. It is then a simple matter of interpolation between weight ranges to determine the percentage of trucks which are heavier than a specific load posting. Once the number and types of

Table 9. Truck Weight Distributions on Bridges by Functional Classification -- Trailer Combinations
(FHWA 1985, Chen and Johnston 1987)

Weight (tons)		Interstate			U.S. Routes			State Routes		
From	To	No. of Vehicles	%	Cumm. %	No. of Vehicles	%	Cumm. %	No. of Vehicles	%	Cumm. %
0.0	7.5	222	1.48	1.48	41	2.01	2.01	67	1.34	1.34
7.5	10.0	355	2.37	3.86	56	2.74	4.75	261	5.22	6.55
10.0	12.5	1114	7.45	11.31	129	6.32	11.07	678	13.55	20.10
12.5	15.0	2094	14.00	25.31	231	11.32	22.39	821	16.41	36.51
15.0	17.5	1353	9.05	34.35	222	10.88	33.27	409	8.17	44.68
17.5	20.0	1004	6.71	41.06	155	7.59	40.86	246	4.92	49.60
20.0	22.5	921	6.16	47.22	100	4.90	45.76	188	3.76	53.36
22.5	25.0	844	5.64	52.86	97	4.75	50.51	166	3.32	56.67
25.0	27.5	847	5.66	58.53	87	4.26	54.78	174	3.48	60.15
27.5	30.0	996	6.66	65.19	93	4.56	59.33	207	4.14	64.29
30.0	32.5	1188	7.94	73.13	119	5.83	65.16	218	4.36	68.65
32.5	35.0	1507	10.08	83.21	161	7.89	73.05	287	5.74	74.38
35.0	37.5	1080	7.22	90.43	130	6.37	79.42	335	6.69	81.08
37.5	40.0	723	4.83	95.26	137	6.71	86.13	393	7.85	88.93
>	40.0	709	4.74	100.00	283	13.86	100.00	554	11.07	100.00
		14957	100.00		2041	100.00		5004	100.00	

vehicles detoured are determined, the detour length, time costs, and vehicle operating costs can be used to determine the user costs generated due to a load capacity deficiency. The detour length used in this analysis can be taken directly from the BRINSAP file, although this data item should be reviewed by the districts. Time and vehicle operating costs are discussed in detail in the following sections.

Vertical Clearance Deficiency

As with load capacity deficiencies, bridges with low vertical clearance may generate user costs in the form of increased time and vehicle operating costs for vehicles required to detour due to the deficiency. Therefore, the proportions of vehicles detoured due to vertical clearance deficiencies must be determined in order to calculate the associated user costs.

The percentage of vehicles detoured depends on the truck height distribution of vehicles desiring to use the bridge. As with truck weight distribution, the truck height distribution may vary with roadway functional classification. However, the available data is very limited and may preclude such a detailed analysis. Data from

Table 10. Distribution of Trucks with Heights Greater than 13.5 feet
(Kent and Stevens 1963, Chen and Johnston 1987)

Truck Height (ft)		Single Units		Trailer Combinations	
From	To	No. of Trucks	Percent	No. of Trucks	Percent
13.6	14.0	27	0.043	298	0.330
14.1	14.5	8	0.013	44	0.049
14.6	over	7	0.011	59	0.065

Table 11. Assumed Truck Height Distributions -- All Classifications (Chen and Johnston 1987)

Truck Height (ft)		Single Units		Trailer Combinations	
From	To	% Trucks	Cumm. %	% Trucks	Cumm. %
8.0	8.5	9.085	9.08		
8.6	9.0	9.085	18.17		
9.1	9.5	9.085	27.25		
9.6	10.0	9.085	36.34		
10.1	10.5	9.085	45.42	14.222	14.22
10.6	11.0	9.085	54.51	14.222	28.44
11.1	11.5	9.085	63.59	14.222	42.66
11.6	12.0	9.085	72.68	14.222	56.88
12.1	12.5	9.085	81.76	14.222	71.11
12.6	13.0	9.085	90.85	14.222	85.33
13.1	13.5	9.085	99.93	14.222	99.55
13.6	14.0	0.043	99.97	0.331	99.88
14.1	14.5	0.013	99.99	0.049	99.93
14.6	over	0.011	100.00	0.065	100.00

a study by Kent and Stevens (1963) is shown in Table 10. This data shows that approximately 0.067 percent of single unit trucks and 0.444 percent of trailer combinations exceeded a height of 13.6 feet. The default data for truck height distributions presented in Table 11, which originated from the study by Chen and Johnston (1987), assumes that the height distribution for single units is well distributed between heights of 8 and 13.5 feet. Similarly,

as shown in Table 11, the height of trailer combinations is distributed between 10 and 13.5 feet. Due to lack of sufficient data, it was further assumed in this study that trucks have the same height distribution pattern on all functional classifications. Using the vehicle classification distribution defined previously in Table 7, the percentage of vehicles with a particular height, out of the total number of vehicles using the bridge, can be calculated.

In Texas the legal height for trucks was recently increased from 13.5 feet to 14.0 feet. In some instances, there exist bridges with clearance restrictions, either underclearance or overclearance, less than this value. Underclearance and overclearance values for a given bridge are contained in the BRINSAP file and can be directly compared with the cumulative vehicle height distributions to determine the total number of vehicles detoured. Following the same approach used for the load capacity deficiencies, the BRINSAP file can be used to determine detour length for vertical clearance deficiencies. With the detour length and number of vehicles detoured, truck operating costs can be calculated as described in the sections below.

As mentioned above, data on truck height distributions is very limited. The information presented in Table 11 is representative of a truck fleet with an imposed legal height limit of 13.5 feet. Since the legal height for trucks in Texas has recently been increased to 14.0 feet, it is reasonable to expect gradual changes in these distributions over a period of several years. As future data pertaining to height distribution of vehicles on Texas roadways becomes available, the tables presented here can be readily updated for use within the BMS following the procedures outlined above.

Accidents Related to Deck Width and Alignment Deficiencies

Several studies have shown that bridge width, roadway width, bridge rail design, roadway marking and signing, and roadway geometry are important in determining accident rates and severity. The annual savings in accident costs resulting from bridge improvements that eliminate width restrictions and poor approach geometry are calculated with the following formula (FHWA 1987):

Annual Accident Benefits = (Change in Accident Rate) (ADT) (365) (Cost/Accident).

The "Change in Accident Rate" can be from any of three types of bridge improvements: (1) bridge widening, (2) improving bridge alignment at bridge approaches, and (3) removing bridge clearance deficiency.

Accident Rates Related to Bridges One of the first reviews of bridge studies showed how several studies had emphasized the importance of bridge and roadway width in determining the accident rate (Jorgenson and Westat 1966). Vehicles tend to strike the bridge rail more frequently when the bridge is narrow, either absolutely or relative to the roadway width.

A more recent review of the literature (McFarland et al. 1979) and another recent study of a large number of bridge accidents (Mak and Calcote 1983; Brinkman and Mak 1986) confirm this relationship and develop better

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Table 12. Bridge Accident Rates by Bridge Width
(Based on Mak and Calcote 1983, Tables 15 and 17)

Bridge Category	No. Lanes	Bridge Width (ft)	Shoulder Reduction (%)	Fatal Acc. per 10^8 Veh. Miles	Injury Acc. per 10^8 Veh. Miles	PDO Accident per 10^8 Veh. Miles
Single Structure Undivided	1	<= 18	-	0	185.97	371.93
	1	> 18	-	0	938.60	0
	2	<= 18, < Appr	-	27.733	268.09	517.68
	2	<= 18, >= Appr	-	0	205.50	137.00
	2	18-20, < Appr	-	12.568	164.28	297.15
	2	18-20, >= Appr	-	3.902	78.04	284.86
	2	20-22, < Appr	-	10.538	183.94	343.92
	2	20-22, >= Appr	-	14.491	236.68	309.13
	2	22-24, < Appr	-	10.799	130.20	228.00
	2	22-24, >= Appr	-	12.938	130.03	254.00
	2	> 24	> 50	6.804	106.75	202.35
	2	> 24	1-50	7.628	99.00	198.17
	2	> 24	None	5.916	92.22	170.17
	4	N/A	> 50	6.719	103.31	281.37
	4	N/A	1-50	2.317	83.40	178.38
	4	N/A	None	4.996	87.73	270.07
Single Structure Divided	4	N/A	> 50	2.929	62.98	194.79
	4	N/A	1-50	4.498	65.78	163.62
	4	N/A	None	3.652	54.78	137.87
	Other	N/A	> 50	0.764	69.24	219.69
	Other	N/A	1-50	1.814	45.35	134.24
	Other	N/A	None	0.873	48.89	124.54
Twin Structure Divided	2	<= 24	-	5.459	58.68	159.66
	2	> 24	> 50	4.398	77.22	143.08
	2	> 24	1-50	3.205	62.41	129.91
	2	> 24	None	3.232	57.86	136.91
	Other	N/A	> 50	1.138	128.64	184.42
	Other	N/A	1-50	0.846	102.32	235.93
	Other	N/A	None	1.471	88.73	159.80

estimates for accidents rates at bridges. The latter study is cited in the FHWA manual and used accident data from "...the states of Arizona, Michigan, Montana, and Texas for all reported accidents over a 3-year period occurring on or within 500 feet of bridges [and]...covers 11,880 bridges and 24,809 accidents" (FHWA 1987).

It is recommended that the rates shown in Table 12 from the Mak and Calcote study (1983) be used to estimate accidents in the Texas Bridge Management System. These accident rates include all accidents not only on the bridge but also on the roadway for 500 feet in each direction from the bridge. These accidents within 500 feet of the bridge are included so that the influence of the bridge and related roadway geometrics can be included. Since roadway geometrics often are improved when a bridge is widened or when a divided facility is provided, the rates in Table 12 probably reflect improved geometrics with higher-type facilities. Therefore, no separate adjustment is used for roadway alignment. It was concluded that additional study of accident rates near bridges is needed before a more precise adjustment can be made with confidence.

Costs of Accidents Involving Bridges Accident costs for use with the accident rates given above have been selected to represent all types of accidents that occur within 500 feet of bridges (McFarland and Rollins, 1983). These costs, updated to 1990, are listed below in Table 13.

Table 13. Bridge Accident Costs in Texas, Updated to 1990

Accident Severity	Cost per Accident	
	Rural	Urban
Fatal	$1,111,000	$978,000
Injury	24,900	14,300
Property Damage Only	2,100	1,300

Time and Vehicle Operating Costs Associated with Detours

Detailed procedures for estimating the number of trucks that will be detoured for load limits and size restrictions have been developed in research in North Carolina (Farid et al. 1988), and these estimation procedures are recommended for initial use in the BMS. These procedures for calculating the vehicle operating and time costs associated with detours use average values and are very rough approximations of the expected cost of detours. If the available data warrants an increased level of sophistication, it may be possible to incorporate a more accurate analysis using benefit-cost models for bypass projects which has been developed at TTI.

This improved procedure might use traffic relationships in the new highway capacity manual for rural and urban areas to estimate costs for both the principle route, and the detour route, and could allow inclusion of

intersections, assuming optimized signal settings. This procedure could also be used to model the effects of closing one or more lanes during major rehabilitation, including complete shutdown of the bridge. Adding this option to the procedure would allow the estimation of user cost savings from building a new bridge on a different location while keeping the old bridge open to traffic during construction. This alternative may be important if a critical bridge with high traffic must be closed during rehabilitation.

The cost of detouring vehicles when the load capacity or clearance restrictions necessitates such action includes the extra time and vehicle operating cost required when traveling an alternate route instead of the preferred route. The benefit of not having to detour is equal to reductions in this cost and is calculated with the following two formulas (FHWA 1987):

Annual Vehicle Operating Cost Savings From Not Detouring = (ADT) (365) (Change in Fraction of Trucks Detoured) (Change in Distance Traveled by Trucks Detoured in Miles) (Operating Cost/Mile),

Annual Value of Time Savings = (ADT) (365) (Change in Fraction of Trucks Detoured) (Change in Distance Traveled by Trucks Detoured in Miles) (Value of Time Per Hour) / (Speed in Miles Per Hour).

Time Costs for Detours   The FHWA manual uses vehicle operating costs developed in a New York study (FHWA 1977, p.VI-26) and a value of time for trucks of \$14.02 per hour also developed in the same study. For Texas, the truck and passenger values of time recently developed specifically for Texas by McFarland and Chui (1987) will be updated and used in this study. Based on updating these values to 1990, the recommended value of time per vehicle hour in 1990 dollars is \$12.69 for passenger cars, using \$9.76 per person per hour and an assumed occupancy rate of 1.3 persons per vehicle, and is \$23.02 for trucks.

Vehicle Operating Costs for Detours   The operating cost equations used for the segment and intersection calculations were estimated from Zaniewski (1982), updated to the year 1990, and are given below.

Vehicle Operating Costs at Uniform Speeds:
$$\log(PVOC) = 5.6370 - 0.02750 * S + 0.00033 * S^2$$
where

$PVOC$ = passenger car running costs per 1000 vehicle miles, and

S = the uniform speed in miles per hour and is usually assumed to be the approach or mid-block speed.

$$\log(TVOC) = 6.7904 - 0.03464 * S + 0.00041 * S^2$$

where

TVOC = truck running costs per 1000 vehicle miles, and

S = the uniform speed in miles per hour and is usually assumed to be the approach or mid-block speed.

Vehicle Operating Costs for Idling:

Idling Costs, Passenger Car = $0.94/vehicle-hour, and

Idling Costs, Truck = $0.97/vehicle-hour.

Vehicle Operating Costs for Stops:

$$PCYC = 1.2206 + 0.14948 * S + 0.01028 * S^2$$

where

PCYC = passenger car cycling cost from speed S to speed zero in dollars per 1,000 stops ($/1000 cycles), and

S = the vehicle speed in miles per hour and is the approach or mid-block speed.

$$TCYC = -9.8845 + 3.3657 * S + 0.09396 * S^2$$

where

TCYC = truck cycling cost from speed S to zero in dollars per 1,000 stops ($/1000 cycles), and

S = the vehicle speed in miles per hour and is the approach or mid-block speed.

Vehicle Operating Costs for Speed Changes Other Than Stops:

$$\log(PCYC1) = 0.9869 + 0.0324 * S - 0.0001 * S^2$$

where

PCYC1 = passenger car cycling cost for a 10-mph speed change ($/1000 cycles), and

S = the uniform speed prior to making the speed change in miles per hour and is usually assumed to be the approach or mid-block speed.

$$\log(TCYC1) = 3.0784 + 0.0562 * S - 0.0004 * S^2$$

where

TCYC1 = truck cycling cost for a 10-mph speed change ($/1000 cycles), and

S = the uniform speed prior to making the speed change in miles per hour and is usually assumed to be the approach or mid-block speed.

<u>Accident Costs for Detours</u> Although it is not anticipated that accident costs will be included in the initial Texas BMS because this would necessitate collection of additional information on detour routes, the way that these costs can be calculated is given here for possible future use. These costs would be calculated in terms of an increase in accident costs for the detour route over the original route. These accident costs can be calculated separately for intersections/interchanges and for highway segments.

Table 14. Accident Rates and Costs for Highway Sections (Memmott et al. 1986)

	Freeway	Divided	Undivided
Accident Rates per 1000 Million Veh. Miles:			
Urban Highway	244	565	616
Rural Highway	93	261	248
Cost per Accident (updated to 1990):			
Urban Highway	$13,384	$12,597	$ 9,185
Rural Highway	29,688	37,134	36,740

Accident costs are calculated by multiplying the accident rate times the cost per accident. Accident rates for highway segments are taken from the Highway Performance Monitoring System Analytical Package (FHWA 1986). Accident rates for intersections and interchanges are based on a study of accidents in Texas from 1981 to 1986 (Memmott et al. 1986). Costs per accident were taken from a Texas study on accident costs by Rollins and McFarland (1985). Examples of the accident rates and costs for various types of roadways are shown in Table 14 and Table 15. More detailed information is available for specific situations from these references and will be considered when appropriate.

The formula for using the rates for intersections and interchanges is given below. Note that even though the traffic is stated in daily terms, the equation predicts the number of accidents per year.

$$\text{Yearly \# accidents} = \text{ACRF} * (\text{ADT}/1,000)/\text{LN}$$

where:

ACRF = accident rate from the table,

VEH = total daily traffic for all directions of travel, including turning traffic, and

LN = number of main lanes from all directions for the intersection or interchange.

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Table 15. Accident Rates and Costs for Intersections and Interchanges
(Memmott et al. 1986)

	PDO Accidents	Injury Accidents	Fatal Accidents
Accident Rates per Intersection/ Interchange per (ADT/1,000)/#lanes:			
Urban			
At Grade Stop	0.9393	0.5165	.0102303
At Grade Signal	0.4648	0.2145	.0020001
Interchange	0.0879	0.0518	.0014806
Rural			
At Grade Stop	0.8374	0.5484	.0306748
At Grade Signal	0.8655	0.3598	.0075463
Interchange	0.0694	0.0406	.0046282
Cost per Accident (updated to 1990):			
Urban			
At Grade Stop	$1,378	$14,434	$986,088
At Grade Signal	1,378	14,434	986,088
Interchange	1,312	13,646	952,235
Rural			
At Grade Stop	1,903	24,537	1,101,427
At Grade Signal	1,903	24,537	1,101,427
Interchange	2,034	22,832	1,187,136

Time and Vehicle Operating Costs Related to Bridge Deck and Pavement Roughness

Time and vehicle operating costs are higher on rougher bridge decks and pavements because drivers slow down on rough surfaces and also because vehicle operating costs are higher on rough surfaces. Although these effects have not previously been used with bridge decks, it is proposed that, using the relationships discussed below, the same procedures be used with bridge decks as are currently used with pavements.

Effect of Bridge Deck and Pavement Roughness on Vehicle Speeds   One of the factors affecting average travel speed that can be considered in the BMS is the roughness of the bridge deck and the pavement near the bridge. Vehicles tend to slow down on rougher bridge decks and pavements. The Highway Performance Monitoring System (HPMS), developed by the Federal Highway Administration (1986), gives an equation relating

average travel speed to pavement condition. A simplified version of that equation is proposed for use in the Texas bridge management system and is shown below.

$$ASPD = SPD * \left(0.8613 * YPSI^{.0928}\right)$$

where:

ASPD = average travel speed (mph) adjusted for pavement condition,

SPD = average travel speed (mph) with very good pavement condition (PSI=5.0), and

YPSI = yearly present serviceability index.

The average travel speed (SPD) is an input item by vehicle type. It should be noted that the speed refers to ideal pavement conditions. When the average travel speed is not known, either the program default of 60 mph or values from Table 16 can be used.

Table 16. Default Speeds by Rural Functional Class of Highway

Rural Functional Classes	Average Travel Speed, Ideal Pavement Conditions
Interstate	61.8
Principal and Minor Arterial	59.3
Collectors	57.1

When the average travel speed is known for less than ideal conditions, the speed should be adjusted before it is used as input in a computer program. In such cases the average travel speed should be multiplied by the appropriate adjustment factor from Table 17.

This average speed is used in two ways. First, extra time costs of driving at a lower speed on inferior pavements are calculated and used directly in benefit estimates. Time costs are calculated using the values of time presented previously. The second way in which the average speed is used is in calculating vehicle operating costs, as described previously in the discussion of calculation of vehicle operating costs at a constant speed.

Roughness Adjustment Factors for Vehicle Operating Costs   As discussed earlier, the vehicle operating component costs are sensitive to bridge deck and pavement roughness which is measured by the pavement service index (PSI). Based on Zaniewski's data, shown in Table 18 through Table 21, adjustment factors for the effect of PSI on costs of depreciation, of oil consumption, of tire wear, and of maintenance and repair are developed for

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passenger vehicles and for trucks. It appears that truck weights have little effect on pavement adjustments for depreciation, oil, and tire wear but have some influence on maintenance and repair.

Table 17. Adjustment Factor for Effect of Bridge Deck or Pavement
Roughness on Average Travel Speed.

Pavement Serviceability Index	Adjustment Factor for Average Travel Speed
1.0	1.1610
1.5	1.1182
2.0	1.0887
2.5	1.0664
3.0	1.0485
3.5	1.0336
4.0	1.0209
4.5	1.0098
5.0	1.0000

The estimated equations for pavement adjustment to the components for both vehicle types are expressed as functions of PSI only, with the exception of the equation for maintenance and repair, in which truck weight (GVW) is also included as an independent variable in addition to PSI. The estimated equations are listed below. It will be necessary to derive weighted averages of these adjustment factors for adjusting vehicle operating costs for bridge deck and pavement roughness. These adjustment factors represent (roughly) the cost at a given PSI relative to a PSI of 3.5, the value that is assumed in developing the basic operating cost equations.

Passenger Vehicles:

$$AFOIL_{PS} = 2.64952 - .45619 \ PSI$$
$$AFTIR_{PS} = 2.64952 - .45619 \ PSI$$
$$AFMRP_{PS} = 2.58619 - .42952 \ PSI$$
$$AFDEP_{PS} = 1.15917 - .04333 \ PSI$$

Trucks:

$$AFOIL_{TR} = 1.22000 - .06000 \ PSI$$
$$AFTIR_{TR} = 1.74810 - .20476 \ PSI$$

Table 18. Oil Expense Adjustment Factors for Roadway Surface
Condition (Zaniewski 1982, p.38)

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks 2-S2 & 3-S2 Semi's
1.0	1.86	1.16
1.5	1.70	1.13
2.0	1.54	1.10
2.5	1.38	1.07
3.0	1.22	1.04
3.5	1.00	1.00
4.0	0.90	0.98
4.5	0.74	0.95

Table 19. Tire Expense Adjustment Factors for Roadway Surface
Condition (Zaniewski 1982, p.55)

. Tire Expense Adjustment Factors for Roadway Surface
Condition (Zaniewski 1982, p.55)

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks 2-S2 & 3-S2 Semi's
1.0	2.40	1.67
1.5	1.97	1.44
2.0	1.64	1.27
2.5	1.37	1.16
3.0	1.16	1.07
3.5	1.00	1.00
4.0	0.86	0.95
4.5	0.76	0.92

Table 20. Maintenance and Repair Expense Adjustment Factors for
Roadway Surface Conditions (Zaniewski 1982, p.61)

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks	2-S2 & 3-S2 Semi Trucks
1.0	2.30	1.73	2.35
1.5	1.98	1.48	1.82
2.0	1.71	1.30	1.50
2.5	1.37	1.17	1.27
3.0	1.15	1.07	1.11
3.5	1.00	1.00	1.00
4.0	0.90	0.94	0.92
4.5	0.83	0.90	0.86

Table 21. Use-Related Depreciation Adjustment Factors for
Roadway Surface Condition (Zaniewski 1982, p.68)

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks	2-S2 & 3-S2 Semi Trucks
1.0	1.14	1.33	1.32
1.5	1.09	1.23	1.22
2.0	1.06	1.15	1.14
2.5	1.04	1.09	1.09
3.0	1.02	1.04	1.04
3.5	1.00	1.00	1.00
4.0	0.99	0.97	0.97
4.5	0.98	0.94	0.94

$$\log(\text{AFMRP}_{TR}) = .60633 - .57018 \log(\text{PSI}) + .00306 \text{ GVW}$$

$$\text{AFDEP}_{TR} = 1.39036 - .10786 \text{ PSI}$$

where:

AFDEP = adjustment factor for depreciation,

AFOIL = adjustment factor for oil consumption,

AFTIR = adjustment factor for tire wear,

AFMRP = adjustment factor for maintenance and repair,

AFFUL = adjustment factor for fuel consumption,

PSI = pavement's present serviceability index, and

GVW = gross vehicle weight, in kips,

and where subscript PS = passenger car, weighted average of large, medium, small, and pickup, and subscript TR = truck.

Optimization Procedures

The recommended bridge management system performs two types of analyses, here referred to as the investment analysis and the needs analysis. The investment analysis can be conducted in order to determine those strategies resulting in maximal benefits which will be allowed by a specified budget. The needs analysis allows the consideration of a specified level of service goal and will identify the most cost-effective strategy to achieve it. Alternative methodologies for performing these analyses, as well as their advantages and disadvantages, are discussed below.

Investment Analysis

The investment analysis problem can be described as the identification of the most attractive bridge projects for a given set of bridges and a specified level of funding. The measure of effectiveness used in this optimization problem is defined as the dollar value of the benefits associated with the selected projects. A relatively short planning horizon, i.e., two to ten years is envisioned for this analysis, since this is the time frame during which estimates of funding levels can be assumed to be known. There are two general options available for solving the investment optimization problem: single-period optimization and multi-period optimization. Each option is described below.

Single-Period Optimization

The purpose of the single-period optimization routine is to select one rehabilitation or replacement alternative for each bridge of a given system such as a state, district, or part of a district. This is done in such a way that the total benefit derived from the implementation of the selected projects is maximized without exceeding a known budget. It is assumed that the following information is available:

(a) Group of bridges to be considered,

(b) Set of feasible alternatives for each bridge, and

(c) Cost and benefit associated with each alternative.

The basic bridge alternative selection model can be mathematically formulated as follows:

Maximize

$$Z = \sum_{i=1}^{n} \sum_{j \in s_i} b_{ij} \, X_{ij}$$

subject to

$$\sum_{j \in s_i} X_{ij} = 1 \quad \textit{for each bridge i}$$

$$\sum_{i=1}^{n} \sum_{j \in s_i} c_{ij} \, X_{ij} \leq B$$

$$X_{ij} = 0, 1 \quad \textit{for all i and j}$$

where the following notation is used:

n   =   Number of bridges,

S_i =   Set of alternatives (including the do-nothing alternative) for bridge i,

b_{ij} =   Amount of benefits associated with the selection of alternative j for bridge i,

c_{ij} =   Cost of choosing alternative j for bridge i,

B   =   Specified budget for a given planning horizon, and

X_{ij} =   1 if alternative j is chosen for bridge i; and equal to 0, otherwise.

The objective function of the above model maximizes the benefits resulting from a set of budget-feasible bridge alternatives. The first set of constraints allows only one alternative to be selected for each bridge. The last constraint ensures that the total budget available is not exceeded.

An efficient solution procedure for this model is provided by a special-purpose methodology based on a systematic analysis of incremental costs and benefits due to McFarland et al. (1983). This procedure has been computerized in FORTRAN and named INCBEN. When the planning period is relatively short, it is possible to assume that changes in bridge condition during the analysis period are not significant and, therefore, all alternatives selected for a given bridge can be based upon its present condition. If this is the case, a single-period optimization scheme is appropriate.

Description of INCBEN Procedure

This algorithm ensures that the optimal set of bridge alternatives will be chosen for any cumulative cost. The complete development of the algorithm and the associated computer program are described by McFarland et al. (1983). The basic procedure of the INCBEN algorithm is summarized below:

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Step 1: For each bridge arrange all alternatives in increasing order of cost.

Step 2: If there are several alternatives having the same cost for the same bridge, delete all alternatives except the one resulting in the largest benefit.

Step 3: Calculate the ratio of incremental benefit to incremental cost for each nondeleted alternative for each bridge.

Step 4: Delete any alternative for which the incremental benefit-cost ratio is less than one. If desired, this step could be omitted.

Step 5: For each bridge, compare the incremental benefit-cost ratio of the first alternative to that of the second one. If the second ratio is larger than the first ratio, combine the two increments to form a marginal benefit-cost ratio. Leave the first alternative in the array in case budget limitations exclude the second alternative but allow the first one. Then compare the marginal benefit-cost ratio of the first and second alternatives against the benefit-cost ratio of the third alternative and repeat this basic procedure. This will yield an average benefit-cost ratio.

Step 6: Arrange all alternatives, along with their relevant corresponding marginal costs, in decreasing order of their relevant incremental benefit-cost ratios.

Step 7: Initially choose alternatives in order from highest to lowest incremental benefit-cost ratios, accumulating the corresponding marginal costs to determine which alternatives can be included in a budget. Only the most attractive alternative is chosen for each bridge. Once an alternative for a particular bridge is selected, all less cost-beneficial alternatives for the same bridge are excluded. If some alternative (going down the list) cannot be accepted without exceeding the budget limit, then exclude that alternative from consideration and proceed until another alternative or alternatives can be accepted. The initial project selection ends when no more alternatives can be added.

Step 8: A "switching rule" is applied after the initial selection process ends. The last bridge alternative selected in Step 7 is dropped from the list of chosen projects, and the selection process continues adding as many projects as the remaining budget will allow. After this process is completed, the total net benefit of the initial set of bridge alternatives is compared to the total net benefit of the second set. The set having the larger total benefit is selected as the optimal solution.

Multi-Period Optimization

When longer planning horizons (for instance, six to ten years) for the investment analysis problem are desirable, an appropriate decision-making methodology must consider the deterioration process of bridge conditions. There are two basic scenarios for the investment analysis model in this case: sequential single-period optimization, and dynamic programming. Both of these concepts are described below.

Sequential Single-Period Optimization One method of solving this problem is by performing a sequence of successive single-period optimization problems considering periods of one to three years in length. All the periods of the planning horizon are sequentially and independently considered in their chronological order. For each of these individual single-period optimizations, the project selection is performed by the INCBEN algorithm in the manner described above. The benefits in each period are maximized subject to a specified budget.

After each period, the bridges are deteriorated or upgraded as appropriate. If no capital expenditure was selected for a particular bridge in the first period, the condition of the bridge would deteriorate the appropriate number of years for reconsideration in the subsequent period. If a capital expenditure were chosen, then the condition of the bridge would be upgraded based on the type of work performed. A new list of alternatives, reflecting the updated conditions of the bridges and the corresponding benefits and costs, is then generated and the optimization program (INCBEN algorithm) is repeated.

In this manner, bridges that were not originally selected for consideration by the feasible alternatives synthesizer (FAS) could be considered in later periods after more deterioration of the structure has occurred. This strategy also gives an indication of the appropriate timing of activities based on the periods in which they were selected. Another advantage of this methodology is that more than one alternative can be selected per bridge during the planning horizon. Perhaps the most important shortcoming of this approach is its inability to consider the interrelation that exists between periods from the point of view of the timing of each project. Figure 12 shows the overall conceptual approach to be used for this scenario.

Dynamic Programming Optimization An alternative methodology for solving the multi-period optimization problem is to combine the INCBEN algorithm with a dynamic programming approach. The INCBEN algorithm can be run for each period in much the same manner as described above. However, the addition of dynamic programming allows interaction between periods. In this formulation, all periods of the planning horizon are sequentially, but not independently, considered in chronological order. This allows the consideration of the economic impact associated with the timing of the selected projects. Additionally, this option allows an analysis of different funding levels for each period in the planning horizon. However, this approach does have some important restrictions which will be discussed later.

The overall analysis is conducted through a dynamic programming decomposition of the planning horizon using a recursive relationship that will allow the maximization of benefits for the entire planning horizon. The

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OPTIMIZATION APPROACH
MULTI-PERIOD PLANNING HORIZON
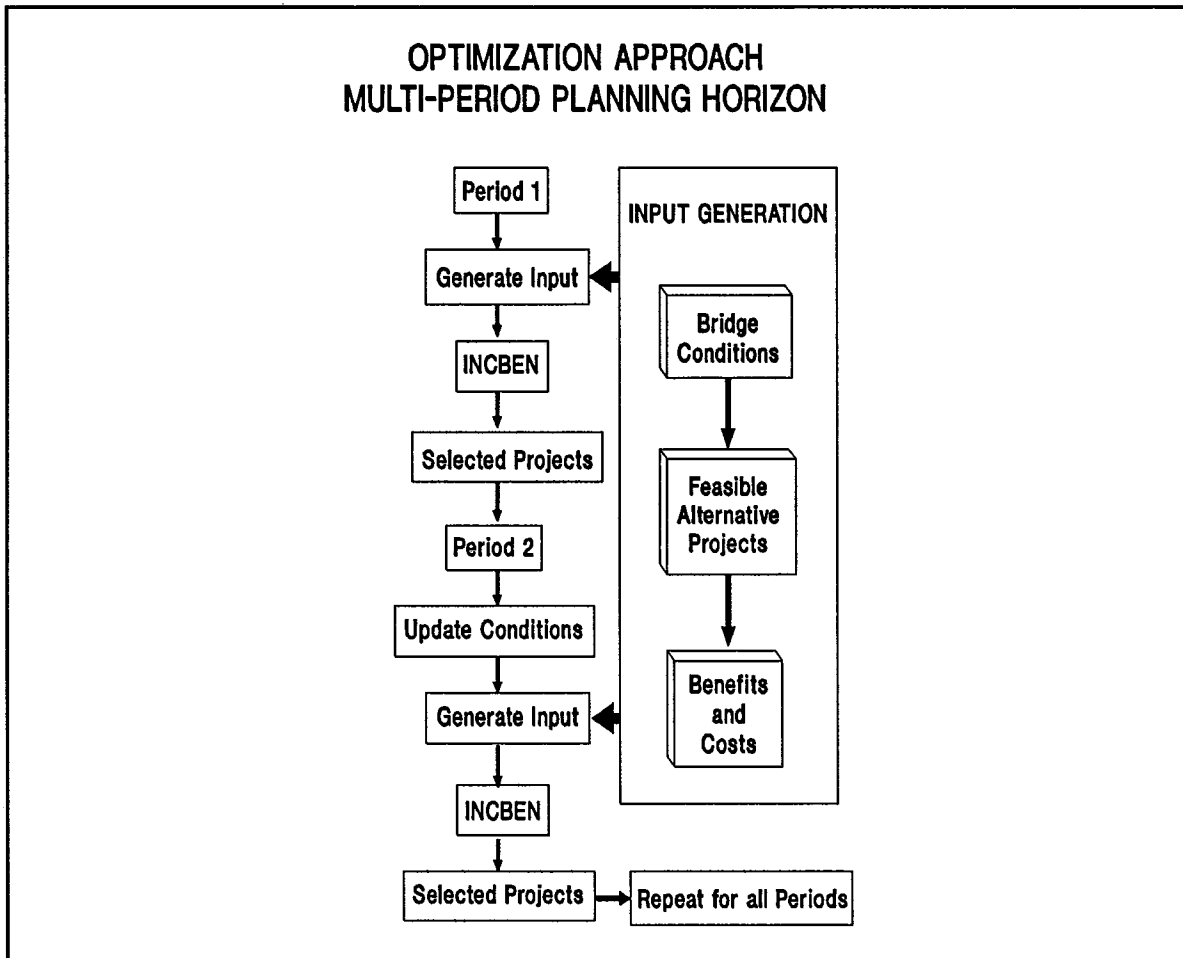
Figure 12. Sequential Optimization

fundamental logic of the dynamic programming approach to analyze a multi-period planning horizon has been previously presented in Report 1212-1F.

In this multi-stage optimization problem, the stages correspond to periods, the state variables to funds available before each period, and the decision variables are binary variables indicating which strategy should be selected for each bridge in each period of the planning horizon. Since the condition of a bridge changes from period to period, the bridge condition deterioration process must be used within the optimization methodology to take into consideration the effect of selecting or not selecting improvement projects for each bridge.

The following notation was used in Report 1212-1F for the formulation of the dynamic programming recursive relationship for a multi-period optimization model:

A_t Amount available at the beginning of period t,

X_t Set of projects to choose from in period t,

$b(X_t)$ Total benefit for period t,

$c(X_t)$ Total cost for period t,

R_t Bridge conditions at the beginning of period t, and

P_t Set of feasible projects for period t, $P_t = d(R_t)$.

As indicated in Report 1212-1F, the subproblem for period t can be formulated as follows:

$$g_t(B_t) = \text{maximize } \{f_t(A_t) + g_{t-1}(A_t + c(X_{t-1})\}$$
$$0 \leq A_t \leq B_t$$

where X_{t-1} is the optimal project list at Period t-1 and $f(A_t)$ is found using the INCBEN methodology to solve the model formulated below:

$$f(A_t) = \text{maximize } b(X_t)$$

subject to $c(X_t) \leq A_t$

$$X_t \in P_t$$

The alternatives selected by the FAS for consideration by the optimization model are based on the existing or predicted conditions of the bridge. Since the condition of a bridge may change from period to period within the planning horizon, the project listing should somehow reflect the bridge deterioration process. This can be accomplished in one of two ways.

The first way is to simply list the feasible projects for each bridge, along with their corresponding costs and benefits, at the beginning of the entire planning horizon. These alternatives would reflect the existing conditions of the bridge and thus could be used directly in the first period analysis. For subsequent periods, the cost and benefit data for each alternative can be updated by means of predetermined factors to account for bridge deterioration or other variables. The second way is to specify the appropriate cost and benefit information for each alternative for each period using the appropriate deterioration and life-cycle cost models.

One limitation of the dynamic programming option is that the project list for each bridge must be predetermined at the beginning of the entire analysis period. New alternatives cannot be incorporated into the analysis in later periods after which time the bridge has experienced further deterioration. That is, although the costs and benefits of existing alternatives can be updated through the use of multiplying factors, new alternatives reflecting the increased deterioration of the structure cannot be introduced. For example, assume that based on the existing condition of a bridge, the FAS recommended deck rehabilitation but not deck replacement. The rehabilitation option can be considered in every period of the planning horizon through the use of updating factors to adjust the benefits and costs. However, even if the replacement alternative becomes feasible in a later period

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due to continued deterioration of the structure, it cannot be considered by the optimization model since it was not in the original list of projects.

It is also possible to include all feasible alternatives during the analysis period by running the FAS for conditions corresponding to the end of the analysis period and adding the projects to the initial list obtained using existing conditions. Since the costs and benefits associated with these additional alternatives would correspond to some future time period, multiplying factors would have to be used to estimate this information for previous periods.

Another limitation of this option is that at most one alternative can be selected per bridge during the planning horizon. This limitation is not likely to be significant since the anticipated planning horizon for the investment analysis is greater that the minimum service life extension predicted for the activities presently considered by the FAS.

Needs Analysis

The objective of the needs analysis is to estimate the funding level required to attain (or maintain) a specified level of service (LOS). More formally, the optimization problem can be defined as minimizing cost subject to a specified minimum level of benefits (i.e., level of service). In this type of analysis, the level-of-service goals should be attained locally for every bridge on the network rather than in a global, average, or cumulative fashion. For this reason, it is very difficult to think of benefits in terms of dollars as is done in the investment analysis. It is more appropriate to define benefits in terms of tangible level-of-service goals for the bridge structure itself. These would take the form of both structural and functional goals such as minimum acceptable condition ratings, deck width, vertical clearance, load capacity, etc. In this manner, a direct comparison of the level-of-service goals can be made on a bridge-by-bridge basis. The cost required to achieve different benefit levels can then be investigated by defining various sets of LOS guidelines. For example, a minimum acceptable LOS and a desirable LOS for various functional classifications could be established. The BMS could then be run to determine the minimum cost required to achieve the desirable level of service for all bridges in the specified network. If the cost appears to be higher than the anticipated funding level, the problem could be rerun using the minimum acceptable LOS to establish a lower bound on cost.

In the needs analysis the LOS guidelines are enforced by the feasible alternatives synthesizer (FAS). Only alternatives that will provide the desired level of service will be selected for consideration by the FAS. Assume, for example, that deck rehabilitation raises the existing condition of the deck three rating points, and deck replacement raises the condition rating to 9 (i.e. new). If the existing deck condition rating of an interstate bridge is 4 and the desired LOS for this functional classification is 6, then the FAS could select either deck rehabilitation or replacement as feasible alternatives. However, if the existing condition rating of the deck was 2, the only alternative the FAS could select would be deck replacement, since deck rehabilitation would only provide a condition rating of 5 which is below the desired level of service. In this fashion it is assured that every alternative selected

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by the FAS will provide the desired level of service. It then becomes a matter of selecting the projects that will minimize cost over the planning horizon.

The simplest approach for minimizing the cost of alternatives is to calculate the life-cycle cost of each alternative and select the alternative that minimizes the life-cycle cost of each bridge. Thus, rather than calculate a separate cost and benefit for each alternative as in the investment analysis, the initial cost, agency costs, and user costs associated with the alternative are used to calculate an overall life-cycle cost.

Since it is desired that all bridges on the network be at or above the selected LOS and since only deficient bridges are considered by the FAS, it stands to reason that at least one project must be selected for each bridge. It is conceivable, however, that if a bridge has more than one deficiency, more than one alternative might have to be selected for that particular bridge to bring it up the required LOS. This could be accomplished by keeping track of which rules (i.e., alternatives) were "fired" due a particular deficiency and by constraining the model to select one project from each group of alternatives for a given bridge.

The planning horizon for the needs analysis is typically much longer (20-25 years) than for the investment analysis. Therefore, bridge deterioration can be a significant factor in the analysis as can the timing of projects within the planning horizon. Deterioration or upgrading of bridge conditions can be handled in a manner similar to that described for the successive single-period investment analysis. Projects would initially be selected by the FAS based on the existing conditions of the bridge. Thereafter, the bridge conditions could be updated to a prescribed time later in the planning horizon, at which point the FAS could select another set of feasible alternatives which meet or exceed the defined level of service. In this way bridges and/or projects which were not initially considered by the FAS could be considered at later stages within the planning horizon as the bridges continue to deteriorate.

This approach would also allow for multiple projects to be selected for each bridge if, after some project has been selected, the bridge or one of its components once again drops below the LOS guidelines. This feature of the proposed procedure can be advantageous when considering planning periods of 20 years or more as is typical for a needs analysis.

One disadvantage of this approach is that it does not, in the true sense, consider the timing of projects within the planning horizon. It will list the projects selected for each period and the corresponding budget requirements. However, once a particular project is selected for a bridge, the bridge condition will be updated and that same project will not be considered in subsequent periods.

If the analysis is restricted to the selection of only one major capital expenditure during the planning horizon, a modified approach similar to the one described above can be applied to the needs analysis problem. First, the planning horizon is subdivided into several periods. For each period, the bridge condition is deteriorated the appropriate amount, and the FAS selects alternatives which satisfy the LOS guidelines. Thus, an independent list of alternatives is generated for each period. For a given bridge, these lists may include different numbers and

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types of projects from one period to the next. Additionally, as conditions deteriorate throughout the planning horizon, the number of bridges being considered by the FAS may increase.

The next step is to calculate the life-cycle cost, including initial, agency, and user costs, for each alternative in each period. For each period, the minimum life-cycle cost alternative is kept for each bridge under consideration. If more than one deficiency exists for a particular bridge, the model may be constrained to selecting more than one alternative for that bridge, but they would be considered together as a single alternative in order to obtain a single life-cycle cost for the bridge.

After the minimum cost alternatives have been selected for each period, the periods are compared on a bridge-by-bridge basis to select the alternative which provides the overall minimum life-cycle costs for a particular bridge over the entire planning horizon. One project (or set of projects) must be selected for each bridge. In this manner, the timing of a project can be considered, as well as a comparison between different projects in different periods. Once the overall list of projects has been selected, they can be grouped by period, and the initial costs of the alternatives can be used to determine budgetary needs.

Computerization Suggestions for the Dynamic Programming Investment Analysis

In the following discussion, a level of funding corresponds to a specified percent of a maximum available value. In general, the program should allow for the consideration of an arbitrary number of funding levels, s. For instance, if s=3 and the available budget is $1,000,000, the first level of funding could be 85 percent or $850,000; similarly, the second level of funding could be 95 percent or $950,000; and the third level of funding could be 100 percent or $1,000,000. The main purpose of the dynamic programming procedure is to select the combination of funding levels that will maximize the total benefits for a specified planning horizon and to identify the corresponding bridge project schedule.

The fundamental logic of the dynamic programming procedure will be described in terms of an example. The example considers four stages (T=4) and five specified values (s=5) for the state variable at each stage. Figure 13 illustrates the procedure followed for the first three stages. Figure 14 shows the procedure followed for the last stage, that is, Stage 4. Each project set X_t^j selected in Period t, under the jth (j=1,2,...,s) funding level, is associated with a number indicating the rank in magnitude (that is, the number 1,2,3,4 or 5) of the funding level selected in the preceding period. This selection number for each stage can be organized into a vector which will be referred to as the "summary vector."

The procedure starts at Stage 1 where a set of projects is selected for each of the five different values of the state variable in such a way that the benefit is maximized. Figure 13 assumes that for the state value S_1^1 the set of projects X_1^1 was chosen. Similarly, for the state value S_1^2, the set of projects X_1^2 was chosen, and so on. Each of these selected projects has its corresponding cost and benefit.

Stage 1

S_1^1	X_1^1	1
S_1^2	X_1^2	2
S_1^3	X_1^3	3
S_1^4	X_1^4	4
S_1^5	X_1^5	5

Stage 2

	1	2	3	4	5	
S_2^1		X_2^1				2
S_2^2			X_2^2			3
S_2^3					X_2^3	5
S_2^4	X_2^4					1
S_2^5	X_2^5					1

Stage 3

	2	3	5	1	1	
S_3^1	X_3^1					1
S_3^2				X_3^2		4
S_3^3					X_3^3	5
S_3^4	X_3^4					1
S_3^5		X_3^5				2

Figure 13. Dynamic Programming Process for Stages 1,2,3

As indicated in Figure 13, the preferred selections are organized into a summary vector containing numbers 1,2,...5. These numbers are shown in the last column of the decision table. In subsequent stages a similar analysis is repeated.

In Stage 2, a set of projects is also selected for each one of the five different values of the state variable, in such a way that the combined benefit from Period 1 and Period 2 is maximized. In this case, the X_2^j sets are selected considering all possible choices for X_1^k (k=1,...5) in the preceding stage. Of all the five different sets X_2^j selected for each value of S_2^j (j=1,...5) the one that yields the maximum benefit is chosen as the best selection of projects, and the corresponding value of the index k is stored in the summary vector.

To facilitate the discussion of Stage 2, the summary vector of the preceding stage is placed across the top of the decision table, as shown in Figure 13. The row corresponding to the first funding level in the decision table for Stage 2 indicates that the best selection of projects for the state value S_2^1 is that corresponding to k = 2. The procedure is repeated for the remaining values of S_2^j as well, and the results are stored in the summary vector. As illustrated, the summary vector for Stage 2 contains selection numbers k = 2, 3, 5, 1 and 1.

The first value k = 2 indicates that the selection of projects $X_2^1(S_2^1)$ in Period 2 corresponds to a funding level $S_1^k = S_1^2$ in Period 1. Similarly, from the second entry k = 3 in the summary vector, we can determine that the selection of projects $X_2^2(S_2^2)$ corresponds to a funding level S_1^3 in Period 1 and so on.

In the analysis of the following stages and based on the principle of optimality of dynamic programming, the procedure considers for each funding level only the solutions corresponding to the summary vector of the previous stage. After considering these solutions, the one maximizing total combined benefits is selected. The methodology described above is then applied to the current stage and a new summary vector is obtained.

Figure 14. Dynamic Programming Process for Stage 4

Figure 13 shows that the summary vector for Stage 3 contains the selection numbers k = 1, 4, 5, 1 and 2. This means that the selection of projects $X_3^1(S_3^1)$ in Period 3 corresponds to a funding level S_2^1 in Period 2. Similarly, the selection of projects $X_3^2(S_3^2)$ that yields maximum benefit is obtained with S_2^4. The same discussion applies to the remaining values of S_3^j.

As shown in Figure 14 for this example, in Stage 4 only the value of S_4^5 is considered assuming that all the available budget must be spent at the end of the planning horizon. Thus, state values S_4^1, S_4^2, S_4^3, and S_4^4 are disregarded. The summary vector contains only one entry, which would indicate that the best selection of projects $X_4^5(S_4^5)$ in Period 4 corresponds to a funding level S_3^4 in Period 3.

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Once all the stages have been analyzed, a backtracking procedure is used to obtain the preferred selection of alternatives that maximizes benefit along the four-period planning horizon. Only the summary vectors of all four stages need to be considered, starting with the last stage.

Since the best selection of projects in Stage 4, $X_4^5(S_4^5)$, was computed from state value S_3^4 of Stage 3, $X_3^4(S_3^4)$ is chosen as the best selection of projects for Stage 3. Since $X_3^4(S_3^4)$ was selected for a state value S_2^1 in Stage 2, $X_2^1(S_2^1)$ is chosen as the best selection of projects for Stage 2. Finally, since $X_2^1(S_2^1)$ was selected for a state value S_1^2 in Stage 1, $X_1^2(S_1^2)$ is chosen as the best selection of projects for Stage 1. In summary, the preferred selection of alternatives that yields the maximum benefit on a time horizon of four periods, given five possible values for the state variable, is the following:

in Stage 1 select projects $X_1^2(S_1^2)$,

in Stage 2 select projects $X_2^1(S_2^1)$,

in Stage 3 select projects $X_3^4(S_3^4)$, and

in Stage 4 select projects $X_4^5(S_4^5)$.

The run time of the procedure to be computerized is a function of the number of periods or stages (T) of the planning horizon, the number of state values (s) defined per stage, and the number of bridges in the system. It is suggested to consider five state values (s=5) in each stage of the dynamic programming algorithm. These five values can represent percentages of a period's initial total funding, such as 80 percent, 85 percent, 90 percent, 95 percent, and 100 percent. It is assumed that any excess budget from one stage can be carried over to the next stage and, therefore, the investments of the two periods become interrelated. The task of dynamic programming is to determine the best possible combination of spendings from periods 1 to T.

In addition, cost and benefit figures are updated in every stage of the analysis utilizing user defined factors read from an external file. The INCBEN code (McFarland et al. 1983) should be implemented as a subroutine of the main code. The basic steps involved in the development of a code for solving the multi-period budget allocation problem on a system of bridges are summarized in Figure 14 which is discussed in the following paragraphs.

Step 1: Read the input data from a data file. These data include the number of planning periods, the total number of bridges to be analyzed, the amount of budget assigned at the beginning of each period, the number of alternative projects at any particular bridge, and the coded name of each of these replacement or rehabilitation alternatives along with their corresponding cost and benefit figures. Also, user-defined factors to update cost and benefit figures are read from an additional external data file.

Step 2: Call Subroutine INCBEN to solve the maximization problem for each value of the state variable in Stage 1. Five funding levels are recommended (such as 80 percent, 85 percent, 90 percent, 95 percent, and 100 percent of a period's budget). Store the optimal project lists.

DYNAMIC PROGRAMMING OPTIMIZATION MODEL
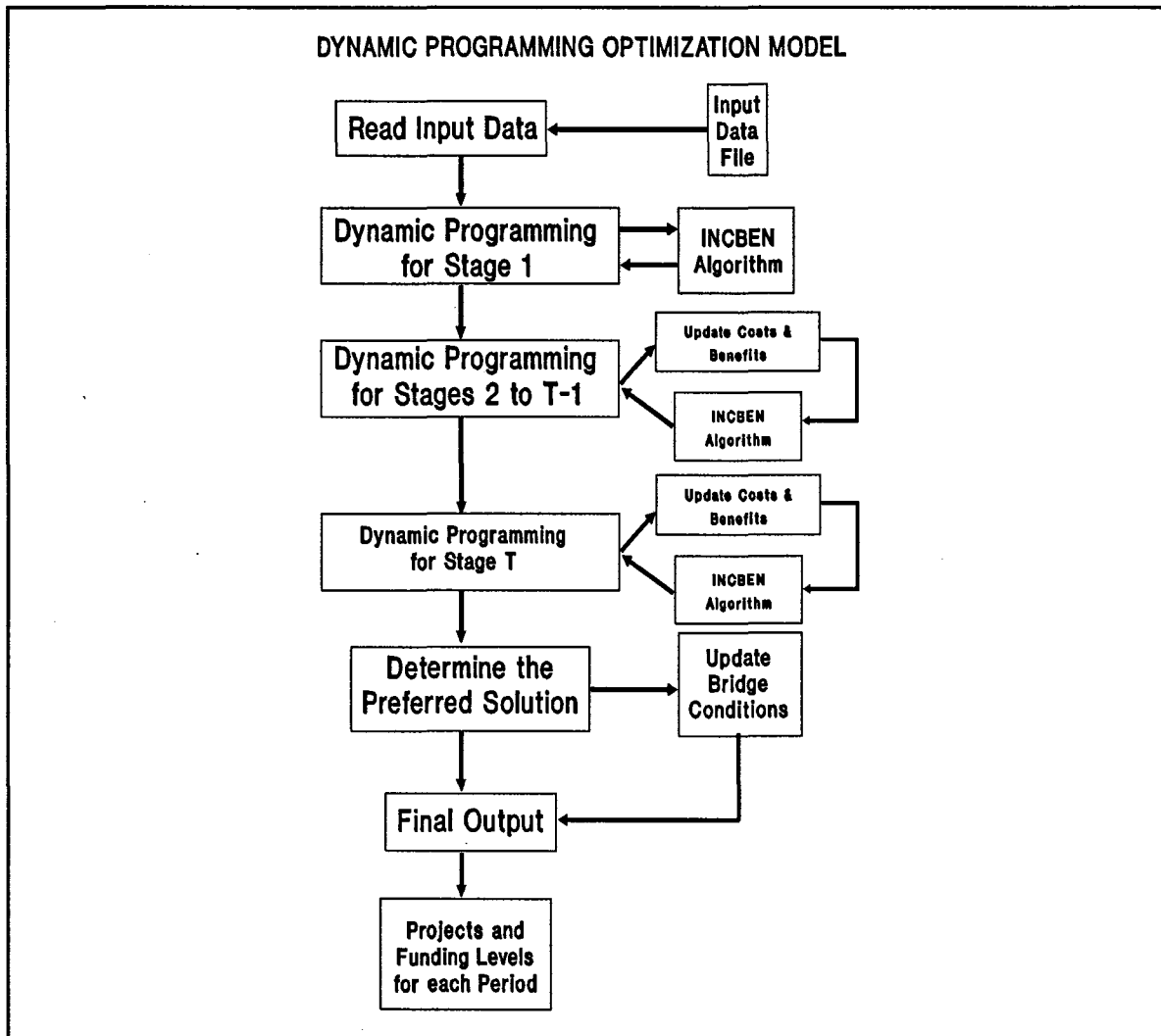
Figure 15. Dynamic Programming Procedure

Step 3: Call Subroutine INCBEN to solve the maximization problem for each value of the state variable in Stages 2 through T-1 using in each stage the information concerning the best solution of the immediately preceding stage. At the beginning of each stage, update the cost and benefit figures utilizing the user-defined updating factors. Auxiliary arrays should be used in order not to include in a stage's list of selected projects those alternatives chosen in previous stages. The optimal project list resulting from the DP analysis at each stage (period) should be stored.

Step 4: Solve the maximization problem in Stage T considering only the last value of the state variable since it is assumed that in the last period of the analysis, the total budgeted amount must be spent. Costs and benefits should be updated, and the procedure mentioned in Step 3 should be repeated to avoid choosing projects already selected in previous stages.

Step 5: Considering the stages in backward order. That is, from the last period to the first one, determine the preferred solution. This solution is the one that maximizes the net benefits of the overall system of bridges.

Step 6: Update the condition ratings of the bridges according to the projects selected in the analysis.

Step 7: Send the best solution to an output file. The output consists of the number of periods and bridges analyzed, the amount of budget assigned for each period, and a list of the selected projects with corresponding cost and benefit figures for each period. Additionally, the total cost, cumulative benefit, and excess budget could be indicated for each period.

Inspection

Inventory Inspection

Inventory inspection can be coordinated easily into the proposed BMS. The present practice in some districts is to contract inspection of all bridges in the district at the first of every other year. All bridges in the district then have the same inspection anniversary, and coordination of such inspection is trivial. A report listing the status of the inspection can be provided to assure completion of the contracts. Districts which perform some or all of their own inventory inspections can choose to perform required biannual inspections throughout the two-year period to allow inspection teams to work steadily throughout the period. In such a case, the various bridges will have inspection anniversaries scattered more or less uniformly throughout the two-year period, and the coordination is not such a trivial problem. In either case, the BMS can include a report procedure which lists the bridges for which inspection is due in the next few months to allow scheduling of inspections.

Maintenance Inspection

Maintenance inspection should be coordinated with the other elements of a bridge inspection program. The existing (BRINSAP) biannual inspection could be expanded to address preventive maintenance conditions and needs which, if not corrected, will develop into more serious problems. Alternatively, separate maintenance inspection training and procedures could be developed, but the former solution of integrating maintenance inspection with other inventory inspection is preferred for the reason that maintenance is included in the same database as other related data. The same personnel could perform both inspections.

Many states have already included additional items related to maintenance on their inspection forms, while others require supplemental forms or narratives to document maintenance. The general information to be provided should include needs, priority of accomplishment, and resources. The report by Kruegler et al. (1986) states that the maintenance inspection interval should not exceed six months for most bridges. It is recommended to perform more frequent inspections on bridges with unusual problems, such as high water, accidents, leaking joints, and frozen bearings.

Documentation should include not only deficiencies, but also practical recommendations on suggested courses of action to preclude more serious problems. The existing BRINSAP data does not meet the need for determining maintenance actions. The reason for this is that condition ratings are used to evaluate the effect that elements have on the ratings of the components: deck, superstructure, substructure, channel, and approaches. The inspector determines the effect that deterioration or damage of each separate element has on the components. This focuses the ratings on only those elements that affect condition ratings, rather than listing the levels of required maintenance activities, such as those discussed earlier. Although the narrative portion explaining the condition rating may describe in detail the condition of elements of the component, this information must be entered manually and is not readily retrievable for the purpose of maintenance needs.

An expanded rating sheet appears to be needed indicating the urgency of maintenance of elements such as joints and bearings. This would help define the problem but may require much more work than reporting only the overall condition. These additional difficulties with the existing reporting system are discussed in Kruegler (1986). The condition rating does not indicate the level of urgency of maintenance and inspection. For example, the inspector may note that the item needs to be worked on in the near future, but the particular work needed may not be sufficient cause to lower the condition of the bridge component. This is in consonance with the overall need for preventive maintenance: that is, to preserve the structure, but not to raise its condition. Report 1212-1F listed bridge maintenance work items that are being added to the MMIS as of September 1989 and recommended work items to be accomplished on a periodic basis. These lists, plus those shown in the section entitled *Scope of Bridge Maintenance Activities*, are the functions that should be included in the maintenance portion of the inventory inspection and appraisal report. These are discussed in another section of this report.

In summary:

1. It is desirable to include a bridge maintenance inventory inspection and appraisal in the existing BRINSAP to preclude a separate database and reporting system.

2. The existing BRINSAP inspection reports are not adequate for reporting maintenance needs.

3. Maintenance inventory and appraisal reports should relate to maintenance needs already identified.

MINIMUM AND DESIRABLE ENGINEERING INFORMATION REQUIREMENTS

Task 2 of the study was to establish minimum and desirable engineering information requirements for the BMS. This task was accomplished by reviewing other existing and developing bridge management systems, reviewing the existing procedures used within TxDOT for accomplishing bridge management tasks, reviewing the data and data collection procedures used at present by TxDOT, and reviewing the data reporting requirements of FHWA. The data required by each of the identified models or processes is identified in the following paragraphs.

Data Required by the Deterioration Model

The deterioration model requires several parameters, identified as β_i. Some parameters, having units of years, represent the deterioration rate either before or after rehabilitation. Other parameters in the model proposed by West et al. are integer-valued parameters, in the same range as the condition rating model. All parameters can be determined by regression to historical condition data. Present efforts have resulted in the calculation of most of these parameters.

As much as possible, these bridge deterioration models were developed and classified by various categories of bridges: bridge material type (steel, concrete, timber, etc.), highway classification (interstate, US, SH, FM, etc.), and geographical location. The effects of previous maintenance done on the bridge could not be adequately reflected in the deterioration models because the available bridge condition data do not indicate these maintenance efforts. It is therefore recommended that the bridge deterioration rates estimated in this study, especially the rates based on expert opinion, be adjusted with a user-provided multiplier factor when appropriate. These multiplier factors are not intended to be used to change the default deterioration coefficients for all bridges within the state, region, or district, but rather are planned to be used on an individual bridge basis based on the user's experience and expertise. The purpose of the multiplier is to account for significant variations in deterioration rates among bridges in a similar classification. The deterioration coefficients reported in Table 1 through Table 5 assume no maintenance or rehabilitation has been performed on a bridge. If a particular bridge is known to be deteriorating at a slower rate than other bridges in its category, perhaps due to preventative maintenance, etc., a predetermined multiplier can be applied to the bridge to reflect this difference. Similarly, if poor construction materials and/or techniques has caused a particular bridge within a particular category to deteriorate more rapidly than the average bridge in that same category, a predetermined multiplier can be applied to the default deterioration rates for that bridge to account for the difference. Those persons knowledgeable about the condition of individual bridges under their authority, such as district bridge and maintenance engineers, would be responsible for determining which bridges warrant such changes and for providing some form of documentation or evidence supporting such action.

The data input required for use of these bridge deterioration models will be primarily the age of the bridge and the condition ratings of its structural components. To predict the future condition at a specified age, the

equations of deterioration models can be used to compute the expected condition ratings. In some cases the geographical location of the bridge and the highway system may be required to apply a specific deterioration model.

After the bridge management system is implemented and future statistical data becomes available, the effects of maintenance and rehabilitation on the bridges can be better quantified and the initial default deterioration coefficients can be updated with more accurate numbers. In this fashion the BMS will continually improve upon itself as better data is collected. Although this updating procedure can be accomplished in several ways, an automated updating system such as that proposed in the PONTIS bridge management system would be desirable. The PONTIS system was only recently completed and details of the system were not available during the conduct of this research. However, it is anticipated that with a little additional study, the updating algorithms used in this system can be incorporated into the proposed BMS for Texas. It is recommended that this be investigated during the computerization and implementation phases of the BMS.

Data Required by Feasible Alternatives Synthesizer

The above approach requires certain data, most of which is available in the BRINSAP file. Data items needed, along with BRINSAP identification (item number, as listed in 1990 Supplement to the BRINSAP Manual of Procedures) are listed below.

Roadway

        Type of construction: Item 107.1 -- Deck Structure Type, Main Span

                1 implies cast-in-place RC decks

                2 implies precast concrete panels

        Presence of overlay: Item 108.1 -- Wearing Surface/Protective System, Main Span

                0, 1, 2, 3, or 4 implies concrete wearing surface (or no wearing surface)

                5 or 6 implies epoxy or bituminous overlay

                7, 8, 9, 0, or N are other cases not applicable here

        Length: Item 49 -- Structure Length

        Width: Item 51 -- Bridge Roadway Width, Curb-to-curb

        Number of Spans: Item 46 -- Total Number of Spans

        Number of sealed joints present: this item does not appear to be documented in BRINSAP

Superstructure

        Type of construction: Item 43.1 -- Structure Type, Main Span

                Second digit denotes through or deck when trusses: 1 implies deck, 2-7 implies through or partly through.

                Third digit denotes type of construction:

31-34, 39 implies PS concrete,

21-25, 29 implies reinforced concrete,

01-19 implies steel, and

65-98 implies truss.

Waterway beneath: Item 42 -- Type Service. Second digit denotes waterway beneath.

Certain condition data and appraisal ratings are important to the "rules" that are presently available. DCIS interaction also needs to be analyzed.

Information Requirements for Incorporation of Maintenance into BMS

In addition to discussing the state of the bridge maintenance program in Texas, Report 1212-1F also discussed maintenance needs and priorities. Work items and a set of recommendations for a maintenance program were included in that study.   These work items were defined previously in **Incorporation of Maintenance into a BMS.**

Bridge Maintenance Needs and Priorities

District bridge managers need a decision-support tool for maintenance to aid the bridge and maintenance engineers in making decisions and defining inspection requirements. It is also important that maintenance considerations be emphasized during the design phase of bridge projects. Based on personal interviews with various TxDOT bridge personnel, it seems that bridge painting and joint repairs are the bridge maintenance activities of highest priorities. A survey of districts, discussed in the section referred to above, provided more descriptive and detailed data on these and other bridge maintenance activities. For each of these work items there is a need to define the level of maintenance needs, required activity, frequency of occurrence, expected extension in service life, cost, and benefit(s). Since there is no database that could be used to analyze this information, the researchers proposed a survey that BMS users would provide when using the bridge management system. The questionnaire was assembled from responses that bridge engineers provided in Report 1212-1F and an additional survey using the key levels of distress/deterioration previously identified in this report.

Bridge Maintenance and Service Life

One of the objectives of this study was to incorporate maintenance considerations into the life-cycle-cost model. This would assist in defining the role that maintenance plays in the bridge management system. To achieve this objective, given the lack of definitive maintenance data, an additional survey of experienced bridge maintenance engineers was used to provide the essential information. The questionnaire was designed to:

1. Recommend level of service criteria for bridge maintenance.

2. Provide realistic tradeoffs and estimates of extensions in service life for each level of service.

3. Provide recommendations for districts to set their own levels of service and their own estimates of cost and extension of service life.

4. Provide some basis for judging the adequacy of budgets for maintenance statewide.

This survey relied on data produced in the previous survey (Appendices B, C, and G of Report 1212-1F) which showed the most significant bridge maintenance items and frequency of application. This information was summarized previously in this report in the section entitled Selected Levels of Distress/Deterioration for Various Bridge Maintenance Conditions. The information was reviewed and edited by TxDOT personnel prior to sending out the survey.

There were two distinct parts to this follow-on survey. Part A was designed to determine the extension in service life achieved by correcting various levels of distress/deterioration that might exist due to a particular maintenance condition on the bridge. The respondents were provided a complete list of all the maintenance conditions with parameters and suggested levels of need (e.g. when 10 percent of the bridge deck showed cracks). The idea of using conditions, parameters, and corresponding levels of need was introduced in the North Carolina study by Nash and Johnston (1985). Part B of the survey was designed to determine the cost of these corrective maintenance actions.

Seven engineers responded to the survey on bridge maintenance conditions. However, only one of the respondents was able to provide an estimate for the costs of the various treatments, and an attempt to predict costs was not successful. However, this information is being collected in aggregated form in the Maintenance Management Information System as discussed in Report 1212-1F. Repair and replacement costs are discussed in the section entitled **Initial Costs Model**.

The results obtained from part A of this follow-on survey are summarized in Appendix A, Levels of Distress/Deterioration on Bridge Elements. Part B has been omitted because of insufficient data.

Examples Using Survey Results

The following examples summarize the information furnished in the appendices of Report 1212-1F, as well as the default initial cost values identified earlier and the levels of distress/deterioration on bridge elements.

The initial criterion for maintaining the deck is when there are cracks over 20 percent of the surface area. For cracks over 10 percent of the deck area, the respondents were divided as to whether work would be effective or warranted. Sealing a deck with a condition rating of 7 and cracks over 20 percent of the deck area would, on the average, provide a 10 percent extension of service, which equates to approximately 4 years for a reinforced concrete deck (see p. 171 Report 1212-1F). The cost of sealing would be approximately $7 per square foot of deck. Rehabilitation (e.g overlay) of a deck at a condition rating of 5 would cost approximately $15 per square foot, and would yield an increase in service life of about 10 years (see p. 177 Report 1212-1F).

Reconstruction, performed at a condition rating of 2, would cost about $25 per SF generating an extension in service life of 26 years.

The tables in Appendix A show that a bituminous overlay would probably be required when 30 percent or more of the surface has cracks or spalls which expose rebar. An overlay, which might be properly classified as *limited rehabilitation*, would increase the service life of the deck by about 20 percent. At an initial condition rating of 5, this would equate to an extension in service life of 4 years and would upgrade the condition to 7. Note that the deck now has a remaining life of 22 years, even though the data on page 171 of Report 1212-1F shows an expected 32 year life at a condition of 7.

Life-Cycle Cost Comparison with Maintenance and Rehabilitation

The information collected in the surveys must be used to determine whether the life-cycle costs of some component of the bridge can be reduced using maintenance and/or rehabilitation to postpone eventual replacement. The example below provides such a comparison for the bridge deck using survey information discussed above. In this example, the agency net benefit will be calculated as the difference between the life-cycle cost of the replacement alternative, LCC_0, and the extended life case, LCC_1, which includes maintenance and rehabilitation. Some reasonable assumptions will be made to demonstrate the effectiveness of this model:

1. A new bridge has a life of 60 years.
2. Deck replacement cost is $35 per SF yielding a service life of 40 years
3. Sealing costs are $0.70 per square foot of the total deck surface area. Only 20 percent has cracks needing sealant. Sealing is performed every four years and the effort increases the equivalent of $0.20/SF each four years after replacement or rehabilitation. Sealing increases the bridge deck life (time to replace deck) by three years. Sealing acts to defer rehabilitation by two years ($e_1 = 2$).
4. A 4" overlay is considered rehabilitation and costs $6 per square foot over the entire bridge, performed when the deck deteriorates to condition 4 or 5. The first overlay on a new deck is at year 20, but maintenance will postpone this three years. This treatment increases service life eight years ($e_2 = 8$).
5. The bridge deck has reached condition 5 at time zero. The first replacement cycle in the base case starts in 10 years. In the extended life case, an overlay rather than the first replacement must be done in four years to prevent further deterioration. Maintenance has been performed up to the present time.
6. $i = 6$ percent and there is no differential cost escalation and no widening or other improvements.

The cost estimates and service lives are approximate but are extrapolated from data within the report.
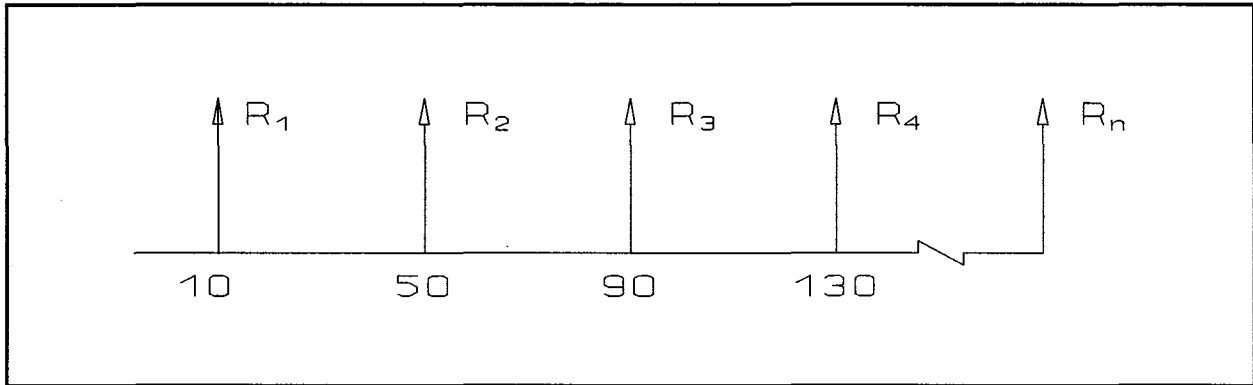
Figure 16. Life-Cycle Profile for Replacement Alternative

A. The replacement cycle, shown in Figure 16, has no maintenance nor rehabilitation. Calculate LCC_0 from the following with R denoting replacement cost.

Then $R_1 = R_2 = R_3 = ...R_n = \$35/SF$

$i_{effective} = (1.06)^{40} - 1 = 9.286$

$LCC_0 = 35/(1.06)^{10} [1 + 1/9.286] = \$21.60/SF$

B. LCC_1 is the life-cycle cost of the alternative in which there is maintenance (sealing) and rehabilitation (overlay). The first replacement occurs at year 20 (10 + 8 + 2). The next replacement occurs in year 70 (20 + 40 + 8 + 2). Each successive life cycle is 50 years. The cash flow diagram shown in Figure 17 illustrates this case. S=sealant, O=overlay.
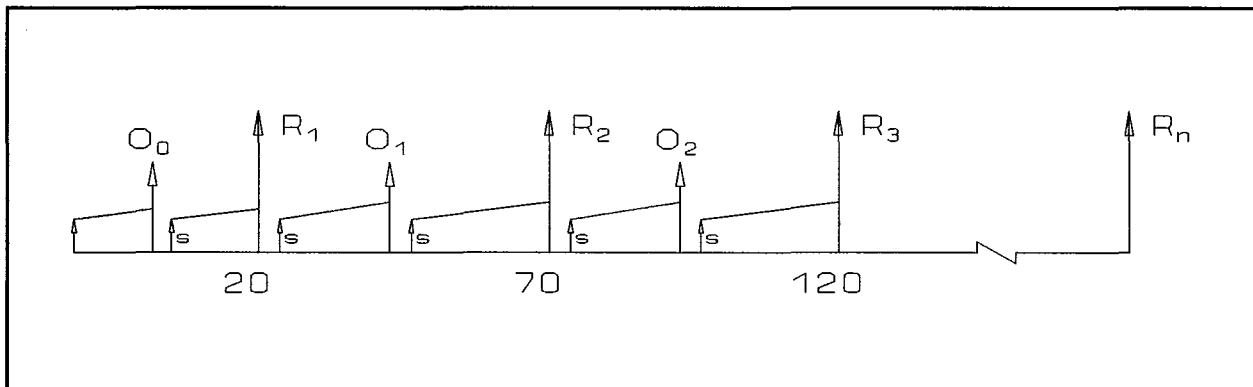
Figure 17. Life-Cycle Profile for Maintenance/Rehabilitation Alternative

(1) There are two effective interest rates: one over the replacement cycle

$i_{eff\ repl} = (1.06)^{50} - 1 = 17.42$

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and one for the four year cycle between seal coats

$$i_{\text{eff maint}} = (1.06)^4 - 1 = 0.263.$$

(2) The present value of one life cycle is computed as follows.

Sealing cost $= (.7)(P/A,26.3,12) + (.2)[(P/G,26.3,5) + (P/G,26.3,6)(P/F,6,23)]\}$

$= (.7)(3.57) + .2[4.05 + 5.29(.26)]$

$= \$ 3.58/SF$

Overlay cost $= 6(1/(1.06)^{23})$

$= \$1.57/SF$

$P_1 = 35 + 3.58 + 1.57$

$= \$40.15/SF$

(3) An infinite number of these cycles has the present value

$P_2 = 40.15/17.42 = \$ 2.30/SF$ at EOY_{20}.

(4) The present value of one complete cycle at time zero is

$P_0 = (40.15 + 2.30)(P/F,6,20)$

$= \$ 13.23/SF.$

(5) $LCC_1 = 13.23 + (.7)(P/A,26.3,4) + (.2)(P/G,26.3,4) + 6(P/F,6,4)$

$= 13.23 + 1.62 + .54 + 4.75$

$= \$20.14/SF$

So the agency net benefit of maintenance and rehabilitation of the deck in this case is:

$B_a = LCC_0 - LCC_1$

$= \$1.46/SF$ over the bridge deck.

Similar examples could be used for other maintenance work items. A more generalized life-cycle cost model could be constructed in which the extensions in life of the components can be approximated from the tables in Appendix A. The significance of this model is that maintenance is included as an element in the generalized agency cost model. This is the only reasonable method of justifying maintenance budgets. If maintenance were not included in this particular model, LCC_1 would have been greater, because the overlay and replacement would have occurred earlier.

This model is very sensitive to the cost of the sealant application, the overlay, and the selected interest rate. It should also be noted that other maintenance items have a major effect on the life of the deck, but these are not included in the model. Combining all these factors and determining the range of costs and other parameters that affect the solution requires a computer program which is beyond the scope of this study. Such a program would yield very important guidelines for performing maintenance and rehabilitation.

Required Initial Costs Data

The minimum required initial costs data for the BMS was summarized in tables presented in the section entitled "Suggested Default Initial Costs Data." The level of detail provided in these tables corresponds to the current level of sophistication of the rules within the feasible alternatives synthesizer (FAS) and the alternatives they recommend. It should be noted that, if desired, the proposed bridge breakdown structure (BBS) could be used to support a more detailed cost structure on an element by element basis. Shown in the following tables is a suggested method for collecting and storing this comprehensive data. Once completed, this database could be used to combine costs at several levels to arrive at unit aggregate costs for the FAS alternatives. This approach would also be useful if, in the future, the department expands its inventory and appraisal data to allow the BMS to perform a more detailed analysis.

BRIDGE ELEMENT			ACTIVITY	CODE	UNIT	COST
ROADWAY	DECK	P/S FLAT SLAB (PC)	Patch spalls	11011	SF	
			Replace deck	11014	SF	
			Overlay	11015	SF	
		REINFORCED SLAB (CIP)	Patch spalls	11021	SF	
			Replace deck	11024	SF	
			Overlay	11025	SF	
		REINFORCED SLAB (PC)	Patch spalls	11031	SF	
			Replace deck	11034	SF	
			Overlay	11035	SF	
		VOIDED SLAB (CIP)	Patch spalls	11041	SF	
			Replace deck	11044	SF	
			Overlay	11045	SF	
		RC DECK + AC OVERLAY	Patch spalls	11051	SF	
			Replace deck	11054	SF	
			Overlay	11055	SF	
		POST-TENSIONED RIB SLAB	Patch spalls	11061	SF	
			Replace deck	11064	SF	
			Overlay	11065	SF	
	WEARING SURFACE		Seal cracks	12001	SF	
			Patch overlay	12002	SF	
			New overlay	12003	SF	
	JOINTS	OPEN	clean	13011	LF	
			replace	13014	LF	
		SEALED	clean	13201	LF	
			repair	13022	LF	
			replace	13024	LF	
	DRAINAGE		clean	14001	LF	

BRIDGE ELEMENT			ACTIVITY	CODE	UNIT	COST
SUPER-STRUCTURE	MAIN MEMBER	STEEL I-BEAM	Replace member	21014	Ton	
			Clean and Paint	21011	SF	
			Strengthen(add member or strut)	21015	Ton	
		STEEL I-BEAM GIRDER	Replace member	21024	Ton	
			Clean and Paint	21021	SF	
			Strengthen(add member or strut)	21025	Ton	
		STEEL PLATE GIRDER	Replace member	21034	Ton	
			Clean and Paint	21031	SF	
			Strengthen(add member or strut)	21035	Ton	
		STEEL TRUSS (DECK)	Replace member	21044	Ton	
			Clean and Paint	21041	SF	
			Strengthen(add member or strut)	21045	Ton	
		STEEL TRUSS (THROUGH)	Replace member	21054	Ton	
			Clean and Paint	21051	SF	
			Strengthen(add member or strut)	21055	Ton	
		STEEL ARCH	Replace member	21064	Ton	
			Clean and Paint	21061	SF	
			Strengthen(add member or strut)	21065	Ton	
		PRESTRESSED I-BEAM (PC)	Replace member	21074	Ton	
			Clean debris	21071	SF	
		CONCRETE I-BEAM (CIP)	Replace member	21084	Ton	
			Clean debris	21081	SF	
			Patch spalls	21085	Ton	
		CONCRETE (PS) SINGLE T (PC)	Replace member	21094	Ton	
			Clean debris	21091	SF	
			Patch spalls	21095	Ton	
		CONCRETE T-BEAM (CIP)	Replace member	21104	Ton	
			Clean debris	21101	SF	

BRIDGE ELEMENT			ACTIVITY	CODE	UNIT	COST
SUPER-STRUCTURE	MAIN MEMBER	CONCRETE T-BEAM (cont.)	Patch spalls	21105	Ton	
		CONCRETE BOX GIRDER (CIP)	Replace member	21114	Ton	
			Clean debris	21111	SF	
			Patch spalls	21115	Ton	
		PRESTRESSED BOX BEAM (PC)	Replace member	21124	Ton	
			Clean Debris	21121	SF	
		CONCRETE SEGMENTAL BOX (CIP)	Replace member	21134	Ton	
			Clean Debris	21131	SF	
			Patch spalls	21135	Ton	
		REINFORCED GIRDER WITH CIP SLAB	Replace member	21144	Ton	
			Clean Debris	21141	SF	
			Reinforce and patch spalls	21145	Ton	
		TIMBER	Replace member	21154	Ton	
			Clean Debris	21151	SF	
			Strengthen(add member or strut)	21155	Ton	
	FLOOR SYSTEM		Clean Joint	22001	LF	
	SECONDARY MEMBER		Clean	23001	LF	
			Repair	23003	SF	
	BEARING		Clean	24001	LF	
	CONNECTION		Repair	25002	LF	
	STEEL COATING		Spot Paint	26001	SF	
			Clean and Paint	26002	SF	

BRIDGE ELEMENT			ACTIVITY	CODE	UNIT	COST
SUBSTRUCTURE	ABUTMENT		Wash Cap and remove Debris	31001	EACH	
	INTERMEDIATE SUPPORT	PILING - TIMBER	Repair	32012	LF	
			Replace	32014	EACH	
		PILING - DRILLED SHAFTS (Caissons)	Repair (Reinforce)	32022	LF	
			Replace	32024	EACH	
		PILING - PS CONCRETE (driven)	Repair	32032	CY	
			Replace	32034	EACH	
		PILING - (RC) with footing	Repair (Reinforce)	32042	CY	
			Replace	32044	EACH	
		PILING - STEEL H	Clean and Paint	32051	SF	
			Repair	32052	SF	
			Replace	32054	EACH	
		PILING - METAL SHIELD (Concrete filled)	Repair (Shield)	32062	SF	
			Replace	32064	EACH	
		SPREAD FOOTING	Repair	32072	CY	
			Replace	32074	EACH	
		CAPS including SHORING	Repair	32081	EACH	
			Replace	32082	CY	
	COLLISION PROTECTION		Repair	33002	LF	
			Replace	33004	LF	

BRIDGE ELEMENT			ACTIVITY	CODE	UNIT	COST
CHANNEL	RIP RAP		Repair	41002	SF	
			Add Rip Rap	41005	SF	
			Remove Debris	40001	EACH	
			Cut Channel	40005	CY	
RETAINING WALL			Repair	50002	SF	
APPROACH	EMBANKMENT		Raise and Widen	61005	CF	
	PAVEMENT		Patch Potholes, seal cracks	62002	SF	
			Bituminous Overlay	62003	SF	
	DRAINAGE		Clean and remove Debris	63001	EACH	

Required Agency/User Benefits Data

Most of the data needed for estimating agency and user benefits (costs) is available in the literature or in the BRINSAP file. The principal variables needed are:

1. Length of detour for detoured traffic. This item is used to estimate the extra cost of vehicles that must detour because of bridge weight or height restrictions and is available in the BRINSAP file. However, it would be possible to do a more detailed calculation of user costs from detours if more detailed data were provided on the precise design characteristics of the detour, by highway segment for the detour route, such as number of lanes, ADT on the bypass route, number of intersections, etc. There also is the possibility of estimating the extra damage to pavements on the detour route, a cost that is not considered at this time in known models. This cost is offset by reduced cost on the route being considered, and this may be the reason that this cost is currently ignored. At this time, it is recommended that the BRINSAP data item on detour distance be used.

2. Vertical underclearance/overclearance. These items are required to determine if a vertical clearance deficiency exists and, if so, how many vehicles will be detoured as a result. These items are available in the BRINSAP file.

3. Design load. The design load of a bridge is used in the determination of load capacity deficiencies. This item is stored in the BRINSAP file.

4. Operating/inventory rating. This item indicates the load posting of a bridge based on the condition of the bridge at the time of the last inspection. It can be used directly in short-term analysis to determine the number of vehicles detoured due to a load capacity deficiency. In a long-term analysis, the future load capacity is determined using the existing load capacity and a suitable deterioration model. This item is available in the BRINSAP file.

5. Functional classification. This item indicates the functional classification (i.e., interstate, U.S. highway, state highway, primary, etc.) of the roadway on which the bridge exists. This information is used to select the appropriate vehicle distribution for the bridge for the detour analyses. That is, the percent of vehicles detoured due to load capacity or clearance deficiencies. This item is stored in the BRINSAP file.

6. Deck/bridge width. This item is used to estimate accident costs for bridges and is available in the BRINSAP files.

7. Roadway width. This item is used to estimate accidents at bridges due to width restrictions. It is available in the BRINSAP file.

8. Highway geometrics near the bridge (geometric appraisal). This data item can be used to calculate accident costs and is available in the BRINSAP file. The possibility of using this item for calculating vehicle and time costs of poor geometrics is being considered.

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9. Approach alignment appraisal. This item is used to calculate accident rates due to poor approach alignment. It is available in the BRINSAP file.

10. Structure length. This item can be used to calculate extra vehicle costs on narrow bridges. On a narrow bridge, a vehicle typically moves toward the center of the bridge and travels at a reduced speed along the length of the bridge. This item is available in the BRINSAP file.

11. Annual average daily traffic (ADT), initial and over the analysis period. It is recommended that ADT for the bridge be taken from the HPMS data tapes developed by D-10 on an annual basis. These ADT forecasts are available for each roadway section, and each bridge on each section is given the same ID used in BRINSAP.

12. Vehicle distribution by classification (percent trucks). This is needed (for various functional classifications) for estimating the percent of vehicles that will be detoured and also for calculating time costs and vehicle operating costs. This information is available from traffic maps developed by TxDOT and in the literature.

13. Vehicle distribution by weight and height. This information is needed for determining the number and type of vehicles that will be detoured due to load capacity and vertical clearance deficiencies, respectively. Due to the lack of available data, this information will be adopted from previous studies and other literature sources. As more accurate data is made available, the information can be readily updated in the BMS.

14. Average accident costs. Data are needed for calculating accident costs as related to roadway geometrics near the bridge and as related to bridge width. These are available from existing studies but will need to be updated periodically in the future with special studies.

15. Time costs for passenger vehicles and trucks. Time costs are needed for calculating the time costs of detouring and the costs of slowing down because of narrow bridges or for rough bridge decks.

16. Vehicle operating cost equations. These are needed for calculating the cost of detours, bridge deck roughness, and slowing down for narrow bridges or rough bridge decks. These are available from secondary sources but will need to be updated periodically in special studies.

17. Roughness of the bridge deck and pavement near the bridge. It is recommended that time and vehicle operating costs of rough bridge decks be calculated. These costs are usually related to the serviceability index (SI) in pavement analyses, and user costs are available as related to the serviceability index. The SI for the bridge deck is not included in the BRINSAP data at this time, but it may be possible to assume a value based on the rating of the bridge deck deterioration. Otherwise, a rating will have to be provided either by measurement using a Maysmeter or similar equipment or through using a visual rating. For modeling purposes, it will be required to have this value initially and also over time for different improvement strategies. Therefore, the best approach may be to assume that the bridge deck SI is directly related to bridge deck condition.

The roughness of the pavement near the bridge can be compared to the roughness of the bridge deck to estimate the cost of slowing down at the bridge (assuming the bridge deck is rougher than the pavement near the bridge). This item is not included in BRINSAP, so inclusion of this type of calculation would necessitate a new data item. This item needs to be studied to determine whether it is worthwhile to include it.

Data Required by Optimization Procedures

The proposed optimization methodology requires that a set of bridge projects, along with the corresponding benefits and costs, be available at the beginning of each period. In addition, it is assumed that budgets are specified for each period. The optimization procedure performs an analysis of funding levels which allows the identification of the most effective expenditures along the planning horizon under the assumption that any money not used in one period can be carried over to the next period. It is anticipated that the following two options of the optimization methodology will have some potential as decision-making aids:

Option 1:   Any bridge can be rehabilitated or replaced, at most, once in the specified planning horizon.

Option 2:   Some bridges can be rehabilitated one or more times in the specified planning horizon.

Option 3:   The planning horizon can be analyzed in terms of a forward sequence of single-period runs, without using the dynamic programming recursive relationship.

For the application of the first option, the model requires that at the beginning of the entire planning horizon the list of feasible projects for each bridge be known along with the corresponding benefit/cost data for the first period. For each of the remaining periods, the cost and benefit data can be updated by means of specified predetermined factors. If the use of the updating factors is not desired, the appropriate cost/benefit information for each period must be specified. This option can be recommended for those cases in which only a few rehabilitation or replacement activities are considered for each bridge and when it is anticipated that a bridge will not require more than one major capital expenditure during the specified planning horizon.

The second option, as indicated before, requires that each bridge project list will be specified in advance. This is a meaningful option only when a bridge may be assigned rehabilitation activities more than once. For example, it can be recommended when the alternatives under consideration have service lives significantly shorter than the length of the planning period.

The third option allows the updating of bridge conditions and the list of feasible bridge projects at the end of each period of the planning horizon. In this case, the budget for each period is assumed to be known.

In all of these cases the required inputs to this optimization model are the outputs of the FAS and the costs and benefits calculated by the BMS procedures. External data is not required, although plans to incorporate user input as overrides to input to the optimization model are being evaluated. Examples of user input which are being discussed among the researchers include "forcing" certain alternatives as the only alternative for a certain bridge,

elimination of one or more of the feasible alternatives, and adjusting costs or benefits to reflect user knowledge not available to the costs and benefits models.

Data Required for Maintenance Inspection

Bridge maintenance inspection reports should reflect the following:

1. Description of the maintenance condition: The abbreviated description (e.g., clean drainage drain at_____).

2. Level of maintenance needs: Percentage of area affected, amount of section loss, etc.

3. Maintenance priority rating: The priority of maintenance work based on the observed condition and the current schedule of work to be done. Ratings are needed to indicate whether regular preventive actions will suffice, whether some higher level of maintenance is needed, or perhaps, whether rehabilitation or replacement is the only alternative.

4. Units (SF, EA, etc.).

5. Estimated quantity of work.

Based on the list of important bridge activities identified earlier, maintenance inspection should be performed according to the following schedule.

ELEMENTS/COMPONENTS	FREQUENCY OF INSPECTION
Joints, deck	Annual
Drainage system, deck	Annual
Wearing surface, deck	Semiannual
Expansion bearings, superstructure	Annual
Fixed bearings, superstructure	Annual
Steel main members, superstructure	Annual
Abutments, substructure	Semiannual
Intermediate supports, substructure	Semiannual
Banks and riprap, channel	Annual
Joints and drainage, approaches	Annual

Recommended Organization of Databases

Several databases or files are needed to support the BMS calculations. Among these are the following:

1. DB1 is an inventory and condition database extracted from the BRINSAP file. This database will be written at appropriate intervals by the use of an interpreter program which will read the BRINSAP file, identify and extract desired data, and write the data in a prescribed format in the DB1 database.

2. DB2 is an initial costs database which is intended to be developed and maintained by the district level user. This database includes unit cost information for each of the identified alternatives which can be used within the BMS to calculate the total initial cost of any alternative for a given bridge. Since costs may vary regionally, it is planned for each district to maintain a cost database; but a default database, reflecting data discussed elsewhere in this report, will be prepared for initial implementation.

3. DB3 is a user benefits database which includes unit cost data associated with various aspects of bridge deficiencies, such as reduced visibility or curved approaches, narrow widths, etc. This database will allow the calculation of the user benefits (reduction in user costs) associated with any considered alternative.

4. DB4 is a default LOS (level of service) database, which includes the LOS goals identified by FHWA or as identified by the TxDOT administration. These goals will be statewide, with exceptions noted in DB7, as addressed below.

5. DB5 includes the default deterioration data.

6. DB6 includes the data extracted from the DCIS database when bridge alternatives have already been programmed.

7. DB7 is an optional user input database which can contain many different types of information. Some types of information to be included are:

a. Improved estimates of deterioration rates -- a specific bridge can be identified by an engineer familiar with its performance as "significantly above average," "above average," "average," "below average," or "significantly below average" with respect to its deterioration rate in comparison to bridges of similar material and type in similar geographic regions. Also, the expected level of maintenance, when different from "normal" maintenance, can be reflected in this database. Two other maintenance levels are identified: high or deferred. These different maintenance levels will cause fractional changes in the deterioration rates.

b. Improved estimates of initial costs -- the estimated cost of a specific alternative is generated by unit costs data to allow identification of alternatives which are most likely to be programmed. When a specific bridge is identified as requiring attention, a bridge engineer makes an estimate of the cost of a proposed activity such as major rehabilitation. This estimate will be much better than the estimate generated from the initial costs data of DB2. By including the bridge identification number, a code identifying the alternative considered, and the estimate of initial cost, the improved estimate can be used in further application of the BMS.

c. Special measures of user costs may be noted by district engineers. If the accident rate is noticeably higher or if a posted or width restricted bridge is creating user costs that can be quantified by a district bridge engineer, this data can be used to reflect the higher user benefits associated with the improvement of that bridge. ADTs or truck traffic different from the data in the BRINSAP file can

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be noted in the DB7 database, for instance. Higher accident rates, accident costs, or vehicle operating costs may also be noted.

d. Special level of service (LOS) criteria may be justified for special bridges. The default LOS criteria is used by the feasible alternatives synthesizer (FAS) to generate alternatives which meet the predefined LOS criteria. For some bridges, it may be that the district bridge engineer may choose to identify LOS criteria differently (more or less stringent) than the default criteria. Less stringent criteria can be specified to allow a specific deficient bridge to remain in service longer when other factors allow. More stringent criteria can be specified for selected routes or areas when either practical considerations or political factors dictate. (It is noted that the LOS criteria did not appear in the new Intermodal Surface Transportation Efficiency Act of 1991, but the concept of the LOS criteria is sound and is recommended for the proposed BMS.)

e. The maximum possible component condition rating after major rehabilitation may be selected if the default value is not appropriate.

f. Feasible alternatives may be user specified in one of two methods -- alternatives may be specified to supplement automatically generated alternatives, or alternatives may be specified to override all lower rank (i.e., "the minimum required activity is minor rehabilitation").

Items a-e may be entered on a bridge-by-bridge basis to reflect special knowledge about specific bridges or for a group of bridges (by region, district, county, class, material, or age). Item f is entered on a bridge-by-bridge basis only.

Also needed are two interpreters -- programs which read existing databases and create new, usually smaller, databases. The more important of these is required to create the DB1 file from the existing BRINSAP file. In addition to the obvious task of reading the BRINSAP file and writing the DB1 file, the interpreter is required to detect incomplete data and obviously erroneous data. When incomplete or obviously erroneous data is detected, a BRINSAP problems report is written for the attention of the D-5 BRINSAP engineer. This code can be conveniently written in SAS language. The second data interpreter is needed to search the existing DCIS file for indication that the bridge under consideration by the BMS has already been programmed for work. When such is the case, that bridge ID is flagged and no alternatives will be considered for that bridge.

RECOMMENDED PROCESSES AND PLATFORMS FOR IMPLEMENTATION OF PROPOSED BMS

Task 4 of the present study was to develop the engineering processes for integrating the submodel processes into an overall bridge management system (BMS). The recommendations resulting from this task address computer programming, hardware platform and software language choices, and implementation. First, it is strongly recommended that computer programming be performed with direct and robust interaction with,and preferably supervision by, representatives of the present project staff. Practical problems associated with the proposed plan will first arise during programming, and prompt attention at that time can minimize subsequent lost time and effort.

The second recommendation of Task 4 concerns recommendations about hardware and software choices. Decisions fixing these choices must be made early in the programming phase. These decisions should be addressed in meetings including personnel from D-19, D-5, representative district bridge engineers, and members of the TTI Study Staff. During the course of this study of the engineering aspects of a BMS for Texas, several factors were recognized as impacting the recommendations for hardware and software platforms for future implementation of the recommended BMS. These factors are briefly mentioned here. First, TxDOT's investment in the existing mainframe hardware and networks linking the various district offices suggests that a logical hardware platform for the recommended BMS be a central mainframe computer with access by the districts through existing network links. While it is expected that some and probably all individual district utilization of the BMS software could be accomplished on desktop computers, central utilization for statewide applications appears to be impractically cumbersome for the present generations of such microcomputers (including the 80486 CPU). Also, maintenance of the software by the automation division, D-19, will be facilitated if such a mainframe platform is chosen. Pre- and post-processing of input and output data can probably be most efficiently accomplished on microcomputer platforms, however. Such pre- and post-processing tasks may eventually involve a GIS (geographic information system), but the Department has not yet made a commitment about adoption or development of specific GIS software. When a decision is reached about the platform and software for a GIS, the platform for pre- and post-processing of BMS activities should be reevaluated. These observations about hardware and software also figure in the third recommendation.

Partly in recognition of the above factors, the third recommendation of this section is that initial implementation of the BMS be carried out on a central mainframe computer and that pre- and post-processing tools development be deferred until the basic BMS is implemented. Programmers should retain the option of portability (to microcomputers) of the end product during development for the mainframe, however. Figure 18 indicates a recommended scheme for this phased implementation. This will result in a more rapid implementation of a basic BMS system with basic reporting capabilities. Pre-processing of data can be accomplished in the mainframe environment with existing text editing tools, or more likely, on remote microcomputers. As shown in Figure 18, the initial implementation of the proposed BMS will involve some databases (DB1 and DB6) which are developed

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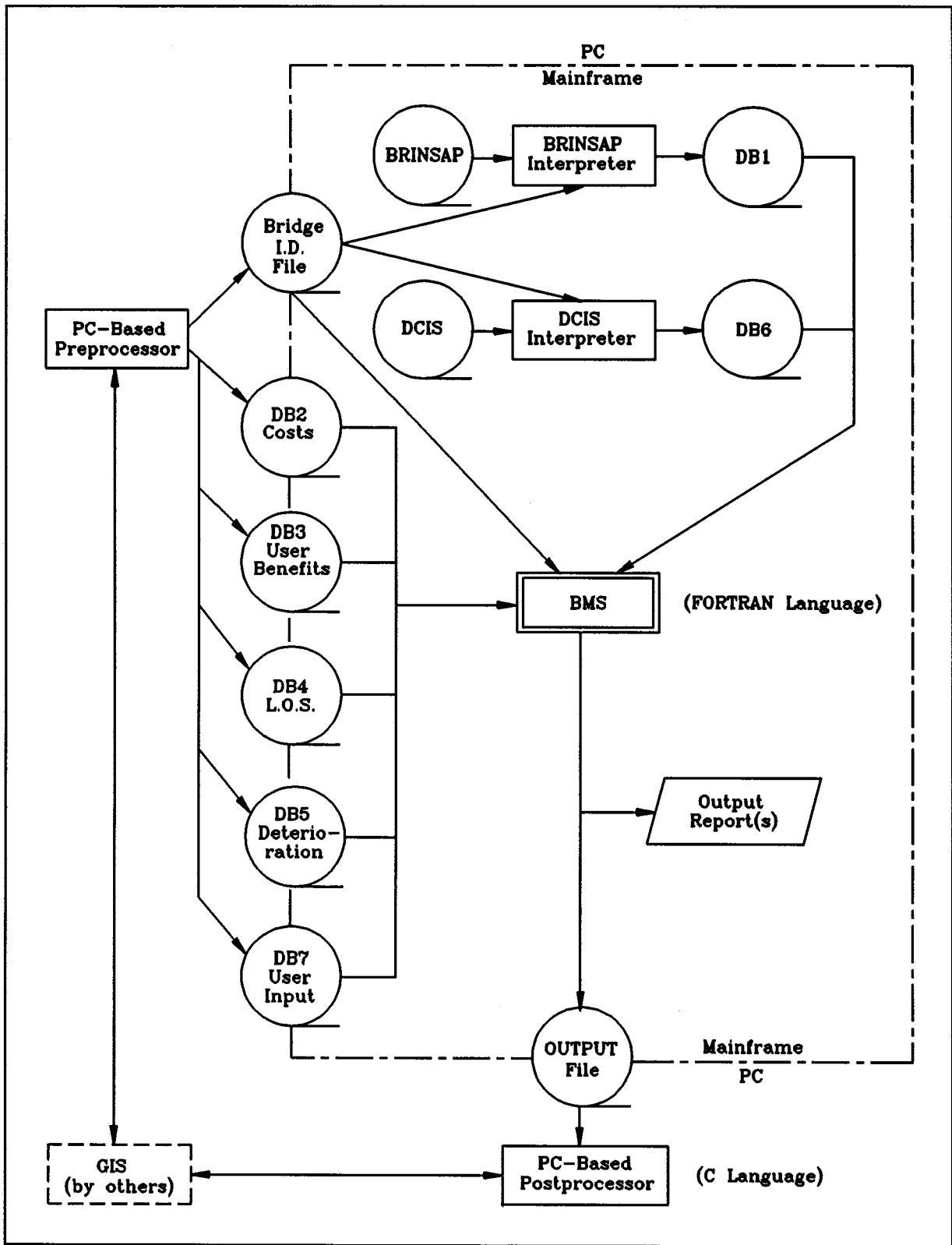
Figure 18. Databases and Suggested Platforms for Proposed BMS Implementation

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on a mainframe platform from existing databases. Databases DB2-DB5 can be developed on either a mainframe or, if more convenient, on a microcomputer and uploaded to a mainframe. Initially, DB7 does not have to be implemented, and user input can be omitted in the first phase of the implementation. In the initial implementation, the output reports will be listings of bridges considered, alternatives considered, costs and benefits used in optimization, and recommended action listings. Later development of a PC-based postprocessor will allow more sophisticated reports modules, and linkage to eventual GIS packages will provide more versatility in pre- and post-processing packages. As proposed, eventual enhancements will include user-friendly, GIS-linked, PC-based, user-customized pre-processor modules which will facilitate development of the bridge ID file and the various required databases DB2-DB5 and DB7. Not shown, but also recommended, is a user-input module which will allow review and editing, if desired, of the DB1 and DB6 databases.

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APPENDIX A. Expert Opinion on Recommended Maintenance Activity and Expected Effectiveness --
Summary of Seven TxDOT Expert Engineer Responses

A. Levels of Distress/Deterioration on Bridge Elements (Maintenance Conditions)

A. Bridge decks:

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level and its Respective Expected percent Extension in Service life					
			none	seal	patch	overlay	mill	NA
CRACKS	Percent of surface area affected	10 percent of Bridge deck	3-0 percent	3-5 percent 1-40 percent				
		20 percent of Bridge deck	1-0 percent	1-5 percent 2-10 percent 2-20 percent	1-10 percent			
		30 percent of Bridge deck		1-5% 1-10% 1-30%		2-10% 1-20% 1-25%		
SPALLING	Depth of Spall	Less than 1" spalls	1-0%	1-5% 1-30%	1-NA 1-5% 2-10%			
		1" spalls			2-5% 4-10% 1-25%			
		Rebars are visible			1-5% 2-10% 1-20%	3-20%		
SKID RESISTANCE	Skid Number	Mill					1-NA 2-5% 1-10% 1-15% 1-35%	NA
		Overlay				3-10% 1-15% 2-20% 1-35%		

B. Joint:

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level				
			nothing	clean	reseal	clean & seal	replace
Presence of foreign material blocking joint	Percent of length affected	10% of joint	2-0%	1-NA 1-2% 1-10% 1-20%		1-25%	
		50% of joint		1-NA 1-2% 1-5% 2-10% 1-15%		1-15%	
		100% of joint		1-2% 3-10% 2-20%		1-10%	
Loss of seal	Percent of area affected	25% of length	1-0%		1-NA 1-3% 1-5%	3-10%	
		50% of length			1-NA 1-5% 1-10% 1-37%	1-10% 1-15% 1-20%	
		100% of length			1-10% 1-20% 1-62%	1-10% 1-40%	1-20% 1-100%

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C. Drain Opening:

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level	
			nothing	clean
Presence of foreign material blocking drain	Percent of area affected	10% of drain	1-0%	1-0% 1-2% 1-3% 2-10% 1-60%
		50% of drain		1-0% 1-4% 2-10% 1-20% 1-30% 1-40%
		100% of drain		1-0% 1-5% 2-10% 1-25% 1-30% 1-80%

D. Structural Steel (Superstructure):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level			
			nothing	spot paint	No-ans	clean & paint
COATING (Paint) FAILURE	Percent of surface area affected	5% of area	3-0%	1-5% 1-10% 1-30%	1-NA	
		10% of area		1-5% 1-8% 1-10% 1-15% 1-20% 1-30%		1-20%
		20% of area				2-10% 1-20% 1-25% 1-30% 1-40% 1-100%

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D. Structural Steel (Superstructure)- II

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level					
			no-ans	clean	clean & paint	clean & repair	rehab	replace
CORROSION	Degree of section loss	Limited	1-NA	1-5% 1-10%	1-5% 1-10% 2-30%			
		Moderate	1-NA		1-15% 2-20%	1-10% 1-25% 1-30%		
		Extreme			1-10%	1-25%	1-25%	1-10% 1-60% 2-100%

D. Structural Steel (Superstructure)- III

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level				
			none	No-ans	clean	repair	replace
BEARING DAMAGE	Degree of Distress	Limited/Minor	1-0%	1-NA	1-NA 2-10% 1-20% 1-40%		
		Moderate		1-NA	1-5%	1-NA 2-15% 2-30%	
		Severe/Extensive		1-NA			1-10% 2-20% 1-25% 1-40% 1-100%
CONNECTION DAMAGE (Rust on hanger plates,etc...)	Degree of Distress	Limited/Minor			1-NA 2-5% 1-10% 2-20% 1-30%		
		Moderate				1-5% 2-10% 2-15% 1-20%	1-30%
		Extensive/Severe				1-10%	1-15% 1-20% 1-25% 1-30% 1-40% 1-100%

E. Cast-In-Place or Prestressed Concrete (Superstructure):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level					
			no-ans	none	clean	repair/seal	replace	reset/maint
BEARING DAMAGE	Degree of Distress	Limited/Minor		1-0%	1-NA 1-5% 1-10% 1-20% 1-30%	1-5%		
		Moderate			1-5%	1-10% 1-15% 1-20%		2-10% 1-15%
		Severe/Extensive				1-10% 1-15%	1-15% 2-20% 1-25% 1-100%	
BEAM DAMAGE	Spalls or Cracks	Limited/Minor	1-NA	2-0%	1-30%	1-5% 2-10%		
		Moderate				2-10% 3-20% 1-25% 1-30%		
		Severe/Extensive				1-10% 1-20%	1-20% 2-40% 2-100%	
BEAM DETERIORATION	Salt damage /Corroded steel	Limited/Minor	1-NA	1-0%	2-5% 1-20% 1-40%	1-10%		
		Moderate			1-25%	2-10% 1-15% 2-20% 1-30%		
		Severe/Extensive				1-10% 1-20%	1-25% 2-40% 2-100%	

F. Pile Cap (Concrete):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level					
			no-ans	none	clean	patch repair	seal maint	replace
SILT ACCUMULATION	Degree of accumulation	Light		3-0%	1-NA 1-2% 2-10%			
		Moderate		1-0%	1-NA 1-4% 2-10% 1-20% 1-30%			
		Heavy			1-0% 2-5% 1-6% 1-10% 1-20% 1-25%			
CONCRETE DAMAGE	Spalls or Cracks	Light	1-NA	2-0%	1-30%	1-10%	2-5%	
		Moderate				1-5% 1-8% 1-10% 3-20% 1-30%		
		Heavy				3-10% 1-20% 1-50%		1-40% 1-100%
CONCRETE DETERIORATION	Salt damage /Corroded steel	Light	1-NA	1-0%	1-30% 1-40%	1-10%	1-5% 1-8%	
		Moderate				3-10% 1-20% 1-25% 1-30%	1-10%	
		Heavy				1-10% 2-20%	1-15%	1-25% 1-40% 1-100%

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G. Piling (Steel):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level					
			none	clean	paint maint	complete repair	rehab	replace
COATING (Paint) FAILURE	Percent of surface area	5% of area	1-NA 3-0%		1-5% 1-30%	1-5%		
		10% of area	1-NA 1-0%	1-5%	1-10% 1-25%	1-8% 1-25%		
		20% of area	1-NA	1-10%	1-5% 1-20%	1-10% 1-20% 1-100%		
		>20% of area	1-NA			1-10% 2-15% 1-20% 1-40% 1-100%		
CORROSION	Loss of section	5% of section	1-NA 2-0%		2-5% 2-30%			
		10% of section	1-NA 1-0%	1-5%	1-5% 1-10% 1-25%	1-20%		
		20% of section	1-NA			3-10% 1-25% 1-30%	1-15%	
		>20% of section	1-NA			2-5%	1-20% 1-25% 1-50%	1-60% 1-100%

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H. Piling (Concrete):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level				
			none	seal/maint	patch/repair	rehab	replace
CRACKS	Percent of surface area affected	10% of area	1-NA 3-0%	1-5% 1-10% 1-30%			
		20% of area	1-NA	1-5% 2-10% 2-20%	1-20%		
		30% of area		1-10%	1-10% 1-20% 1-40%	1-25%	1-40%
SPALLING	Depth of spall	Less than 1" spalls	1-NA 2-0% 1-10%	1-5%	1-5% 1-40%		
		1" spalls	1-NA		3-10% 1-15% 1-25% 1-30%		
		Rebars are visible	1-NA		3-20%	1-20% 1-25%	1-20%

I. Columns (Concrete):

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level				
			none	seal/maint	patch/repair	rehab	replace
CRACKS	Percent of surface area affected	10% of Bridge deck	3-0%	2-10% 1-30%	1-NA		
		20% of Bridge deck		1-5% 1-10% 1-15% 1-20% 1-30%	1-10% 1-20%		
		30% of Bridge deck		1-10% 1-20%	1-10% 1-40%	2-20%	1-40%
SPALLING	Depth of spall	Less than 1" spalls	2-0% 1-10%	1-5%	1-NA 1-10% 1-40%		
		1" spalls			4-10% 1-15% 1-25% 1-30%		
		Rebars are visible			4-20%	2-25%	1-20%

J. Channel:

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level	
			none	clean
PRESENCE OF DEBRIS	Percent of area affected	25% of channel	2-0%	1-0% 2-5% 2-10%
		50% of channel		3-5% 1-10% 2-20% 1-50%
		100% of channel		1-5% 2-10% 1-15% 1-30% 1-40% 1-100%

K. Abutment Drainage:

Maintenance Condition	Parameter	Suggested Level of Maintenance Needs	Required Activity at Maintenance Level		
			none	no-ans	clean
PRESENCE OF FOREIGN MATERIAL BLOCKING DRAIN	Percent of area affected	25% of Drain	3-0%	1-Na	2-5% 1-10%
		50% of Drain	1-0%	1-NA	1-5% 2-10% 1-20% 1-30%
		100% of Drain		2-NA	1-10% 2-15% 1-30% 1-100%