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Pavement Damage Functions for Cost Allocation: Executive Summary

Rauhut (Brent) Engineering, Inc., Austin, TX

Prepared for

Federal Highway Administration, McLean, VA

Jun 84

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PAVEMENT DAMAGE FUNCTIONS FOR COST ALLOCATION

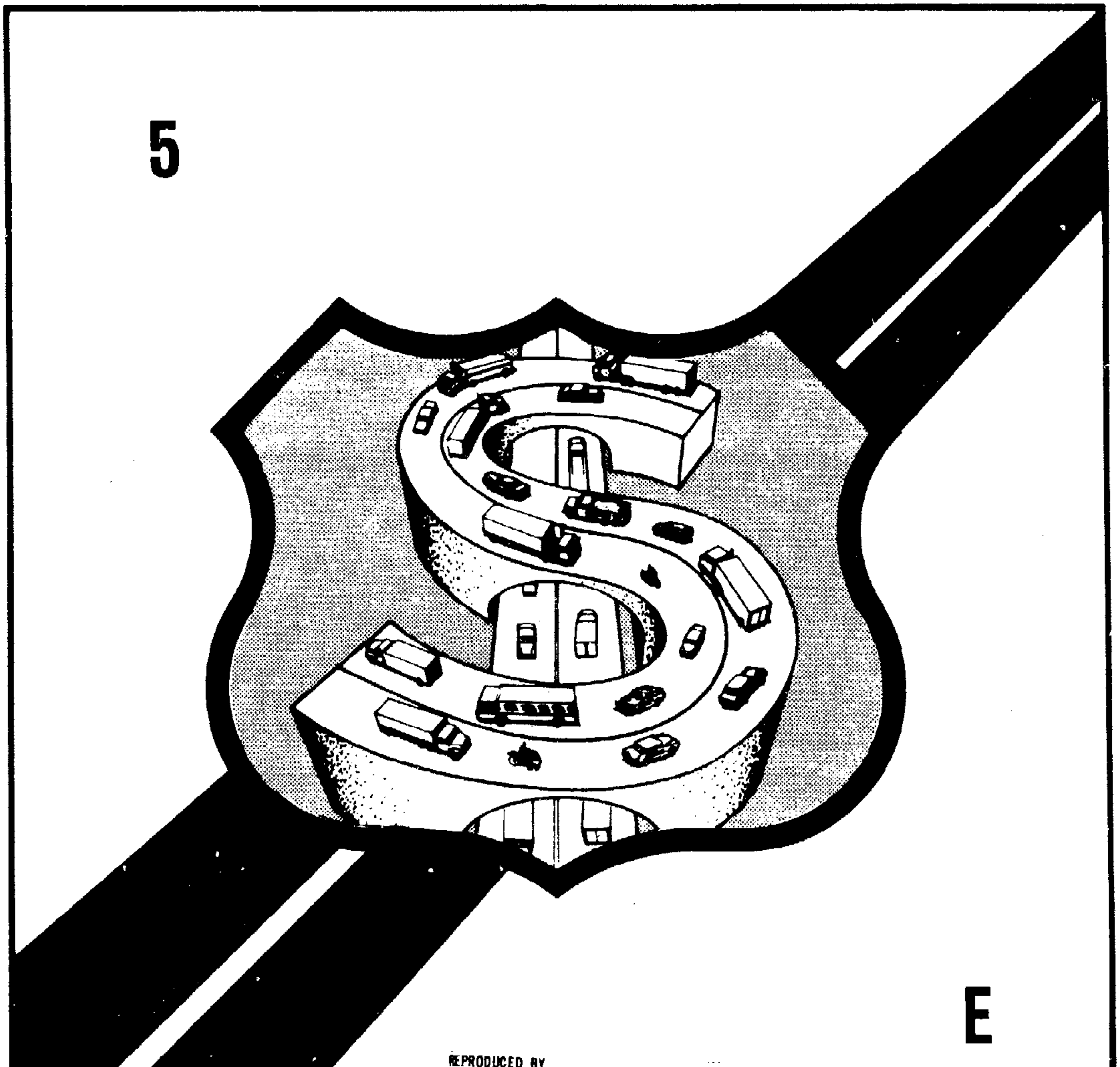
EXECUTIVE SUMMARY

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101

Report No.
FHWA/RD-84/017

June 1984



FOREWORD

This report is a summary of research conducted to develop pavement damage functions that predict repair or rehabilitation needs from distresses. Distress occurs from traffic loadings and environmental factors. These predictions are more general than the AASHO Road Test results.

Richard E. Hay, Director
Office of Engineering and Highway
Operations Research and Development

NOTICE

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16. Abstract

Pavement damage functions were developed for both flexible and rigid pavement distresses that were considered significant as generators of major repair or rehabilitation. These damage function s were then used to develop load equivalence factors for each of these significant distresses. The result of this is a family of damage functions or distress models for broad application for pavement management and other uses as well as for cost allocations. Two classes of damage functions were produced, those that predict load-induced damage and those that predict damage caused by the environment with general independence of axle loads.

A computer program called program DAMAGE was developed to use these damage functions in the calculation of load equivalence factors, and the distribution of the various types of damage to specific axle load classes. Deduct points are used to weigh the damage in terms of their relative importance and to thus generate distributions of overall responsibility to be ascribed to the various axle load classes.

All the damage functions and performance models used in this work effort were either developed during this work effort or have resulted from improvements to existing models.

This Executive Summary briefly describes this study and its results. Detailed descriptions are to be found in:

Vol. 1. Damage Functions and Load Equivalence Factors, FHWA/RD-84/018
Vol. 2. Descriptions of Detailed Studies, FHWA/RD-84/019

17. Key Words
Pavement distress, pavement performance, damage functions, load equivalence factors, mathematical distress models

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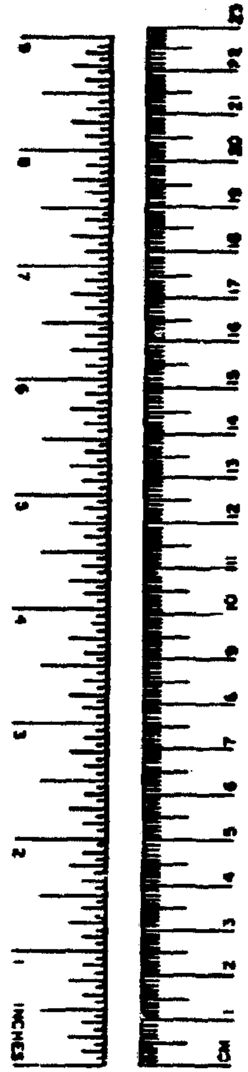
METRIC CONVERSION FACTORS

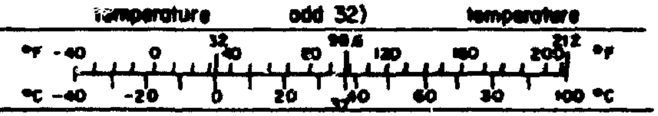
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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CHAPTER 1

INTRODUCTION

BACKGROUND

The AASHO Road Test produced information for highway cost allocation studies required by the Federal Highway Act of 1956, including extra thicknesses of pavements needed to accommodate heavy trucks and relative amounts of pavement wear attributable to various types of vehicles. However, these tests were generally conducted for controlled traffic loadings to failure over a very short time period with little maintenance, and were only representative of one environment. Thus, their applicability to typical highway pavements with variability in traffic loading and with contemporary rehabilitation and maintenance policies is questionable. Because of this uncertainty and the necessity for fair allocation of pavement construction and maintenance costs, the Federal-Aid Highway Act of 1978 required that new cost allocation studies be conducted and that the results of these studies be reported back to Congress by January 15, 1982. This study was the responsibility of the Secretary of Transportation, with the Congressional Budget Office also responsible for evaluating DOT's plans for conducting these studies.

The Congressional Budget Office published guidelines in February 1979 for conducting these studies, requiring that 1) the fraction of highway deterioration attributable to environmental factors and that to traffic be defined, 2) the reliability of the axle-load equivalents from the AASHO Road Test for all climatic conditions and for today's construction practices be determined, and 3) the fraction of new pavement costs that depreciate over time be determined. The studies described in this report contribute to Items 1 and 2 above.

As the development of the necessary information through field tests would have required several times the time available for completion of these studies, and would not be economically feasible, the FHWA selected another logical approach, apparently the only feasible one available. Numerous mechanistic and empirical mathematical models have been developed to predict distress and performance of the various types of highway pavements, and these models may be economically exercised in a short period of time over a range of parametric input representing a variety of conditions. The approach adopted was to utilize suitable models and to "calibrate" them to obtain sufficiently accurate predictions for the studies required.

BRIEF DESCRIPTION OF PROJECT

The broad objectives defined for this project were "1) to compare damage predicted by existing pavement damage models with the damage that has actually occurred on selected test sections of highways, 2) to modify the damage functions and other aspects of the models to more closely match the observed damage, and 3) to provide a procedure that can be used to evaluate the costs of pavement damage as a function of vehicle class, using the modified models."

ORGANIZATION OF REPORT

The scope of this research project was sufficiently large and detailed that it was decided to separate the report into two volumes. Volume I contains the results of the various phases of the study with descriptions of how the research was conducted, Volume II provides much more detailed information on specific supporting studies, and this Executive Summary provides the primary results from the study and a brief description as to how they were derived.

CHAPTER 2

INDIVIDUAL STUDY REQUIREMENTS AND ORGANIZATION OF RESEARCH EFFORT

The broad scope and expedited nature of this project necessitated participation of four separate organizational groups as discussed in the preface. The prime contractor was Brent Rauhut Engineering Inc. and the primary responsibility for the project rested with Dr. J. Brent Rauhut, the Principal Investigator. The BRE staff was also responsible for all work activities related to models for load-induced damage for flexible pavements. ERES Consultants, Inc., with Dr. Michael I. Darter as Co-Principal Investigator, were responsible for all work effort leading to rigid pavement distress and damage models. The Texas A&M Research Foundation under the leadership of Dr. Robert L. Lytton, Co-Principal Investigator, was responsible for environmental damage models for flexible pavements, statistical multiple regression analyses to develop flexible pavement damage models, and the development of computer programs to calculate load equivalence factors for various axle loads and to distinguish between load-induced and environmentally caused damage. Hamilton Drilling and Engineering Testing, Inc. was responsible for the repetitive-load testing for asphalt concrete cores and subgrade samples for the flexible test sections.

The following is a detailed list of separate identifiable major tasks or subtasks that were accomplished to satisfy the objectives of this project:

1. Select significant pavement types to be considered.

2. Select significant types of distress and performance measures for each type of pavement.

3. Identify State DOT's having both test sections for types of pavements of interest and sufficient histori-

cal data to support model input requirements for comparisons between predicted and actual distresses and performance measures.

4. Collection of construction, environmental, traffic, condition survey, nondestructive testing, and other historical data on selected test sections. Also material sampling and laboratory testing of samples for selected flexible pavement sections.

5. Development of a listing of models available to predict significant distresses and performance measures for the significant pavement types.

6. Evaluation of models to select the best for the specific studies planned.

7. Development of input values representative of test sections required by models for use in predictions of distresses and performance measures.

8. Comparisons of predicted and measured distresses and performance measures with time or traffic.

9. Improvements to existing models to increase their predictive accuracy, or development of models where no viable models exist. The improvements made to the models varied from new multiple regressions to increase statistical accuracy to simple multipliers for the predicted values to transform them to approximate measured values.

10. Multiple regression on 864 sets of flexible pavement predictions over a broad range of conditions to develop predictive damage models.

11. Develop a computer program to calculate load equivalence factors for the various distresses and for present serviceability index, and to combine the weighted results from the various damage models into a total damage function.

12. Furnish computer programs and comprehensive reports on the work effort and its results.

The twelve separate work items listed above have been combined into a lesser number of general categories for separate discussion below.

REVIEW OF WORK PLAN

A very detailed work plan had been prepared and included in the research proposal, but an important component of that work plan was an initial period of intensive planning and meetings early in the project to add detail to the work plan and to modify it as necessary to reflect the desires of the Federal Highway Administration and the additional ideas and recommendations of a Work Plan Review Panel of experts.

The review panel meeting was held in the offices of the Federal Highway Administration on November 5 and 6, 1980. It was attended by the panel of experts identified in the preface, interested parties from various divisions of the Federal Highway Administration, and the principal and co-principal investigators for this project. Officials of the Federal Highway Administration introduced their goals for this project and then the project management made their presentation. Very detailed and searching discussions continued throughout both days, with general approval of the work plan as proposed and a number of helpful suggestions.

SELECTION OF PAVEMENT MODELS

The project staff through work on other projects (Ref's. 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10) had previously identified and evaluated virtually all of the mathematical models that had been developed for prediction of distresses, loss of serviceability, and loss of skid resistance. To ensure that no model with application to this project had been overlooked or subsequently developed, a very detailed HRIS search was conducted for a number of key words. No additional models were identified, and those that were considered are discussed subsequently.

While there were a number of existing models to draw upon, there were not models for every significant distress nor were the great majority of the models available sufficiently accurate and/or practical for use in this project. This led to elimination of fatigue and reflection cracking of rigid and flexible pavements with flexible overlays from direct consideration in the project. Raveling and flushing of flexible pavements were also eliminated, and blow-ups for rigid pavements combined with D-cracking and joint spalling as "joint deterioration" because there were no satisfactory models available of general applicability. Raveling and flushing were not apparently of strong significance to the generation of repair or rehabilitation.

DATA COLLECTION

Data collection was a major activity on this project and included the activities indicated below:

1. Identification of States having both suitable test sections and sufficient data for the purposes of this project.

2. Selection of States to participate in the data collection effort.

3. Development of data requirement guidelines for use during data collection.

4. Visits to each participating State to locate the data, collect available data wherever it could be found, visit the test sections, and arrange for materials sampling for the flexible test sections.

5. Organize the data collected, analyze it, and transform it into input for the mathematical models.

The data gathering effort was a cooperative one between State DOT personnel and project staff, starting with telephone coordination and ending with a visit to the State. The individual making the State visits inspected all test sections, selected sampling locations for flexible pavements, and collected data both at the central headquarters and at district offices as required.

The data sought included inventory data as to construction of the pavement section and any maintenance or rehabilitation, historical traffic data, measured distress and performance from previous condition surveys, data on materials properties and material components, climatic data, and any other data pertinent to pavement condition or rate of deterioration.

MODEL TESTING AND IMPROVEMENT

Before predictive models could be selected, it was necessary to identify significant types of pavement and the significant distresses and performance measures for each of these types. The types of pavement that were considered in this project were flexible, flexible with flexible overlay, composite (rigid pavement with subsequent flexible overlay), jointed reinforced concrete pavement (JRCP), and jointed plain concrete pavements (JPCP). As the range of interest for this project was all federal aid highways, pavements such as continuously reinforced concrete pavements representing around 2% of the federal aid system were omitted as statistically insignificant.

The significant distresses and performance measures selected in coordination with the Federal Highway Administration and the panel of experts appear by type of pavement in Tables 2.1 and 2.2. It should be noted that significance in this case refers to potential for generation of costly repair or rehabilitation. The assessment of significance then included consideration of the probability of generating repair or rehabilitation, and the probable type and cost for the repair or rehabilitation. It should be noted that the list of significant distresses in the tables are quite comprehensive, and were consistent with the concept of not omitting distresses of low significance if suitable models could be found for their prediction. In fact, there were not models for all of the distresses and performance measures listed and compromises were made for some types of pavements.

The project staff was either intimately familiar with or had contributed directly to the development of the majority of mechanistic, mechanistic-empirical, or empirical models available, but a detailed HRIS search was conducted to seek other models not already identified. Once the entire pool of available models for the significant distresses identified was assembled, preliminary screening was conducted to assess their separate abilities to meet the project requirements in terms of nature of the output, mathematical and empirical basis for the model, applicability and importance of independent variables, and practicality in terms of producing the needed input variables with sufficient accuracy in a reasonable time period and with a reasonable amount of work effort.

Those models that appeared to have potential for fulfilling the needs of this project were then tested through comparisons of predicted versus measured distresses and performance

Table 2.1 Final List of Significant Distresses and Performance Measures for Flexible Pavements

FLEXIBLE PAVEMENTS	FLEXIBLE PAVEMENTS WITH FLEXIBLE OVERLAYS
Fatigue Cracking	Low-Temperature Cracking
Low-Temperature Cracking	Rutting
Rutting	Roughness Due to Differential Volume Change in Subgrade
Roughness Due to Differential Volume Change in Subgrade	Reduced Skid Resistance
Reduced Skid Resistance	Reduced Serviceability
Reduced Serviceability	

Note: Flexible pavements with flexible overlays were treated as flexible pavements because of modeling limitations

Table 2.2 Final List of Significant Distresses and Performance Measures for Rigid Pavements

PLAIN-JOINTED CONCRETE PAVEMENTS	JOINTED-REINFORCED CONCRETE PAVEMENTS	RIGID PAVEMENTS WITH FLEXIBLE OVERLAYS
Slab Cracking	Joint Deterioration	Reduced Skid Resistance
Joint Deterioration	Joint Faulting	
Joint Faulting	Depressions and Swells	
Depressions and Swells	Reduced Skid Resistance	
Reduced Skid Resistance	Reduced Serviceability	
Pumping*	Deterioration of Transverse Crack	
Reduced Serviceability	Pumping*	

*Not a distress but triggers Maintenance using the data collected for the test sections as described above.

The primary model used for flexible pavements was the FHWA VESYS flexible pavement model. A number of improvements were made to provide a capability for tandem as well as single axles and other capabilities to be described in more detail in Volume 2 of the report. This improved version of VESYS was called VESYS III-B. Although this is believed to be the most comprehensive model of flexible pavements ever developed, even its sophisticated subsystems do not match the complexity of nature, and its predictions were not found to be as accurate as required. As initially planned, simple multipliers were applied to the predicted results to improve their accuracy. Sets of multipliers were obtained for each test section and distress type such that multiplication of predicted results by the multipliers would result in the correct measured value toward the end of the analysis period. These multipliers for individual test sections were then compared and compromises developed to provide the best overall predictions. As an alternative, empirical multiple regression models developed by Lytton, et. al. (Ref. 4) were studied in detail and compared to the modified VESYS model, but the inference space from which these were developed was considered to be too limited for application nationwide, so the mechanistic model was selected.

Several models were exercised and reviewed carefully for low-temperature or thermal cracking for flexible pavements and one selected for use on this project. There was only one model available for predicting loss of serviceability due to expansive clay subgrades, so this model was selected and used for the project. Although there were a number of models available from various State DOT's for predicting reduction in skid resistance, none was considered specifically appropriate for this project and new models were developed through multiple regression analysis of published measurements.

The models available for predicting the rigid pavement distresses were predominantly empirical multiple regression equations based on measured data. These models were exercised and the results compared to measured data from existing data banks combined with new data developed from the data collection effort. It was decided that none of the models were sufficiently accurate or comprehensive, so new empirical models were developed for all the types of significant distresses and performance measures for both JPCP and JRCP. These models were based on the expanded data banks, were developed very carefully, and are believed to be the best available (in many cases the only available) at present.

Specific models for rigid and flexible pavements with flexible overlays were not used directly on the project, primarily because of inability to model with any reasonable degree of accuracy the mechanisms of reflection cracking. The primary reason for this is that all of the structural models are based on the assumption of continuity in layer materials that are not satisfied in reality and fatigue cracking damage relationships are related to initial conditions.

The flexible pavement models selected for use in this project are listed in Table 2.3

DEVELOPMENT OF DAMAGE FUNCTIONS

It is important at this point to define what is meant by damage functions. Damage functions are mathematical equations that predict distress or reductions in performance measures (such as Present Serviceability Index or Skid Number) as a fraction of a reference level of distress or reduction in performance established as a failure condition. The failure condition represented by this project is not structural failure, but rather that level of distress or loss of performance that may be expected to generate major repair or rehabilitation. The

Table 2.3 Distress and Performance Prediction Models for Flexible Pavements Selected for This Project

Distress or Performance Measure	Model Selected
Fatigue Cracking	VESYS III-B
Low-Temperature Cracking	TTI Regression*
Rutting	VESYS III-B
Roughness Due to Differential Volume Change in Subgrade	Velasco-Lytton
Reduced Skid Resistance	Roberts-Jordahl*
Reduced Serviceability	VESYS III-B

*Developed During This Project

form of the damage function or equation used in this project is similar to that used for the AASHO Road Test, where damage function "g" is calculated as follows:

$$g = \left(\frac{W}{\rho}\right)^{\beta} \tag{2.1}$$

where g = the damage function, which ranges from 0 to 1 with increasing damage

W = the number of 18-kip equivalent single axle loads (ESAL) applied

ρ = ESAL required to produce a damage level defined as failure

β = a power which represents the rate of damage increase.

The value of W represents the number of 18-kip ESAL at some time of interest and the values of ρ and β differ by type of distress and environmental zone and are functions of a variety of independent variables consistent with the form of distress or loss of performance under consideration.

As a general example, a loss in Present Serviceability Index (PSI) to a level of 1.5 was used in the AASHO Road Test to represent total failure. Consequently, a value of g equal to unity represented a reduction of PSI to 1.5 that was caused by some number of axle loads of an established magnitude. A damage function of 0.5 implied that the PSI has been reduced by one-half of the difference between the initial PSI and the established terminal PSI of 1.5. For this project, a terminal serviceability of 2.5 was utilized, and this will of course result in different values of ρ and β.

It can be seen that this study is much broader than that at the AASHO Road Test when it is remembered that the only damage function produced from the AASHO Road Test was for serviceability, while damage functions have been produced in this project for all significant distresses and performance measures for which damage functions could be feasibly developed within the time and work effort constraints.

Two approaches were planned and implemented for the development of damage functions. Where mechanistic models were to be used, these models were to be exercised over sufficient ranges of significant independent variables (including axle loads) to generate data banks for multiple regression analyses to develop damage functions.

The other approach planned was the direct use of empirical distress and performance equations obtained from multiple regression techniques through normalizing by failure levels to produce damage functions without further development. In fact, it was found necessary to develop numerous empirical equations using expanded data banks of measured data in order to achieve damage functions of suitable accuracy. In these cases, the multiple regressions were conducted in damage format, and damage functions were developed directly.

The only damage functions produced by multiple regression analyses on data banks generated by distress or performance models were those for fatigue cracking, rutting, and serviceability loss for flexible pavements. Data banks consisting of 216 separate solutions in full factorial format were generated for each of the four environmental zones. Values for ρ and β were obtained through regressions on distresses and reduction in serviceability as functions of the number of axle load passes; these values of ρ and β were then regressed against the independent factorial variables used to predict the distresses and reductions in serviceability.

To summarize, the damage functions were obtained through multiple regression on data banks generated by mechanistic models or through measurements from real pavements. The end results are values for ρ and β for use in Equation 2.1.

The predictive equations developed for flexible pavements appear in Table 2.4. The same form of equation is used for calculating ρ and β for fatigue cracking, rutting, and loss of serviceability; but the regression coefficients vary with type of distress and environmental zone. The independent variables in the equation include Structural Number SN, axle load L_1, axle load code L_2 (1 for single axle, 2 for tandem), thickness of all bituminous layers T in inches, and subgrade stiffness E_s in psi.

The predictive equations for rigid pavements appear in Table 2.5 and the independent variables are identified in Table 2.6.

Damage functions for nonload associated distresses and performance measures were developed directly as regression equations in terms of time and other significant independent variables. These predicted damages in terms of time are correlated with traffic rates for the load-associated damage functions so that total damage can be considered in cost allocation studies.

DEVELOPMENT OF LOAD EQUIVALENCE FACTORS

Load equivalence factors as used in this project are defined in the same way as those resulting from the AASHO Road Test, but a more specific definition will be given, as the one published after the road test was somewhat confusing.

A load equivalence factor for an arbitrary axle load is the ratio of the number of standard axle loads (18-kip single axles in this project as in the AASHO Road Test) to produce a predefined level of distress or reduction in performance, to the number of the arbitrary axle loads necessary to produce the same level of distress or reduction in performance. As for the AASHO Road Test, these ratios were calculated at the predefined failure level when damage is 1.0. It can be seen then that the

Table 2.4 Regression Coefficients for Flexible Pavement Damage Functions for Fatigue Cracking (DI), Rutting (RD), and Loss of Serviceability (PSI)

$$y = c + a(L_1+L_2)^{b_1+b_2T+b_3T^2+e_2E_s+e_3E_s^2}(L_2)^{c_1+c_2T+c_3T^2+g_2E_s+g_3E_s^2}(E_s)^d(SN)^e(T)^f$$

y	c	a	b_1	b_2	b_3	e_2	e_3	c_1	c_2	c_3	g_2	g_3	d	e	f	R^2
Wet Freeze zone																
DI ρ	.00	1.04E+4	-0.44	-.555	.032	1.50E-5	-1.66E-10	-0.70	.686	-.038	-2.01E-5	2.24E-10	0.19	-0.05	5.59	.993
RD β	.00	1.45E-1	0.10	-.019	.001	1.10E-7	-4.24E-12	-0.08	.013	.000	-9.55E-7	1.61E-11	-0.00	0.18	-0.22	.929
RD ρ	.00	1.08E-5	-4.19	-.732	.031	6.78E-6	-4.39E-10	1.95	.577	-.037	1.18E-4	-2.15E-09	3.33	-1.76	14.87	.953
PSI β	.09	6.39E+2	-0.10	-.162	.014	6.54E-5	-1.32E-09	-1.49	.455	-.042	5.65E-6	-2.21E-10	-0.68	-2.0[illegible]	0.55	.604
PSI ρ	.00	6.78E-8	-3.08	-.374	.008	-4.22E-5	4.27E-10	2.56	-.061	.023	1.47E-4	-2.64E-09	3.54	3.56	8.37	.864
Dry Freeze zone																
DI ρ	.00	1.83E+4	-0.26	-.581	.033	1.22E-5	-7.11E-11	-0.86	.697	-.038	-1.88E-5	1.41E-10	0.21	-0.08	5.49	.991
RD β	.00	1.12E-1	0.12	-.017	.001	-1.69E-6	2.76E-11	-0.69	.009	.000	-9.42E-7	3.92E-11	0.02	0.23	-0.24	.913
RD ρ	.00	8.32E-1	-4.75	-.683	.032	6.07E-6	-1.78E-10	2.2[illegible]	.585	-.042	1.31E-4	-2.86E-09	2.08	-4.23	17.39	.947
PSI β	.08	1.55E+2	0.24	-.219	.018	4.61E-5	-8.51E-10	-1.50	.502	-.045	1.27E-5	-8.16E-10	-0.62	-2.07	0.61	.450
PSI ρ	.00	8.38E-9	-3.91	-.101	-.015	-9.03E-5	1.52E-09	3.99	-.673	.078	1.16E-4	-1.76E-09	3.73	3.94	8.25	.788
Wet No-Freeze zone																
DI ρ	.00	1.11E+4	-0.33	-.611	.035	1.66E-5	-1.80E-10	-0.97	.794	-.044	-1.93E-5	1.67E-10	0.17	-0.13	6.09	.994
RD β	.00	1.51E-1	-0.01	.001	-.000	2.74E-7	-2.03E-12	0.02	-.003	.000	-1.30E-7	1.58E-12	-0.02	-0.08	0.07	.964
RD ρ	.00	1.76E+1	-5.11	-.705	.041	7.00E-5	-1.31E-09	1.87	.744	-.057	9.80E-5	-2.20E-09	3.34	1.42	4.84	.989
PSI β	.07	6.57E+1	0.07	-.216	.016	5.87E-5	-1.12E-09	-1.48	.407	-.032	1.15E-5	-5.20E-10	-0.60	-2.88	1.62	.799
PSI ρ	.00	1.00E-5	-5.53	-.172	.011	-3.43E-5	5.46E-10	3.17	-.022	-.001	1.84E-4	-3.37E-09	4.18	5.04	1.18	.915
Dry No-Freeze zone																
DI ρ	.00	1.14E+4	-0.15	-.630	.036	1.48E-5	-1.19E-10	-1.09	.785	-.043	-1.98E-5	1.60E-10	0.19	-0.11	5.90	.992
RD β	.00	1.59E-1	-0.09	.018	-.001	6.7[illegible]E-7	-1.32E-11	0.09	-.020	.001	-2.03E-7	6.67E-12	-0.02	-0.06	0.00	.974
RD ρ	.00	3.16E+7	-3.10	-1.069	.060	8.34E-5	-1.30E-09	-0.10	1.198	-.081	5.89E-5	-1.62E-09	2.37	1.03	4.93	.977
PSI β	.08	1.14E+3	0.00	-.194	.014	7.59E-5	-1.45E-09	-1.19	.337	-.026	-1.06E-5	-1.32E-10	-0.94	-2.92	1.66	.742
PSI ρ	.00	5.15E-6	-5.45	-.038	.004	-9.77E-5	1.95E-09	3.15	-.004	-.004	1.97E-4	-3.27E-09	4.59	5.91	-0.08	.876

Table 2.5 Summary of Newly Developed Predictive Models for JPCP and JRCP

Distress	Pavement Type	Equation
Pumping	JPCP	ln ρ = 1.39 DRAINTY + 4.13 β = 0.772 $(THICK - 2.3)^{1.61}$ /SUMPREC + 0.0157 JLTS* THICK + 0.104 BASETYP + 0.17 DRAINTY + 0.137 SOILTYP - 0.247
Pumping	JRCP	ln ρ = 1.028 BASETYP + 4.966* 10^{-4} THICK 3.47 - 0.01248 FRINDEX + 1.667 CBR + 5.476 β = -0.01363 IMOIST + 0.02527 THICK + 0.423
Joint deterioration	JPCP	ln ρ = -3.738 DCRACK - 0.094416 SPACING + 0.7161 THICK + 1.1734 β = 0.736
Joint deterioration	JRCP	ln ρ = -1.877 DCRACK - 2.135 REACT - 0.32946 TRANGE - 2.597 AVGMAXT -2.395 CSTE - 0.1061 SUMPREC - 1.877* 10^{-4} FRINDEX*IMOIST + 209.24 β = 1.15
Faulting	JPCP	ln ρ = JLTS (-0.1444 $THICK^2$ + 3.48 THICK - 14.68) + 3.2 BASETYP -0.009 IMOIST - 0.005332 FRINDEX + 1.8534 β = 0.0021 CBR + 0.0052 SOILTYP - 0.001196 CSTE + 0.63 JLTS + 0.292
Faulting	JRCP	ln ρ = 1.5754 THICK - 0.09256 IMOIST - 8.173 β = -0.0972/CBR + 0.0061 THICK*DOWDIA - 3.175* 10^{-6} FRINDEX * SUMPREC + 0.2935
Reduced PSI	JPCP	ln ρ = 1.333 SOILTYP - 0.009024 FRINDEX + BASETYP (1.156 THICK - 6.966) + JLTS (0.6556 THICK + 1.763) + 0.803 β = 0.0006076 FRINDEX + BASETYP (-0.0683-0.01435 THICK) + JLTS (0.7107-0.0997 THICK) + 0.544
Reduced PSI	JRCP	ln ρ = 0.4593 THICK - 0.01167 IMOIST + 0.6758 BASETYP - 1.709 β = 7.656/SPACING + 0.04152 BASETHI + 0.43516

Table 2.5 Summary of Newly Developed Predictive Models for JPCP and JRCP (continued)

Distress	Pavement Type	Equation
Depressions and Swells	JPCP	$g = AGE\,(1.59 * 10^{-4}\ IMOIST - 4.515 * 10^{-5}\ CBR - 0.0155\ BASETYP + 7.06 * 10^{-3}\ F2 + 1.713 * 10^{-3}\ F3 + 0.023746)$
Depressions and Swells	JRCP	$g = AGE\,(3.5 * 10^{-4}\ SUMPREC - 7.427 * 10^{-3}\ BASETYP - 0.01785)$
Reduced Skid No.	JPCP & JRCP	(a) $g = (Trucks/27.7\ (million))^{0.299}$ (b) $g = (ESAL/28.2\ (million))^{0.323}$ (c) $g = (Total\ Traffic/128.6\ (million))^{0.290}$
Slab Cracking	JPCP	$\ln \rho = JLTS\,(5.722 + 0.0435\,(THICK - 7)^3 - 1.7\ PUMPING) + BASETYP\,(0.0535\ THICK^2 - 0.2745\ THICK) + 1.698\ SOILTYP - 0.105\ TDIF + 2.386$ $\beta = 0.16\ BASETYP + 1.51$
Deteriorated Cracks	JRCP	$\ln \rho = 79.51/SUMPREC - 0.5949\ THICK + 0.053188\ THICK^2 + 0.7\ DRAINTY - 0.0011546\ FRINDEX + 0.550745\ BASETYP + 2.805$ $\beta = -0.003513\ IMOIST + 1.324$

*All models except for depressions and swells and skid number are in the form

$$g = \left(\frac{ESAL}{\rho}\right)^{\beta}$$

where ESAL = Accumulated equivalent 18-Kip single axle loads, millions. Thus, equations are given for ln ρ and β, which are substituted into this equation to obtain g(The ln is to the base e(2.718)).

Table 2.6 Definitions of Variables Used in Predictive Models for JPCP and JRCP

Variable	Description
THICK	Slab thickness, in
JLTS	0 Undowelled pavements, 1 Dowelled pavements
SPACING	Transverse joint spacing, ft
BASETYP	Subbase type - 0 Nonstabilized, 1 Stabilized
DRAINTY	0 No underdrains exist, 1 Underdrains exist
SOILTYP	Type of foundation soil - 0 granular, 1 coarse
CBR	California Bearing Ratio of foundation soil
PUMPING	Severity of pumping - 0 None, 1 Low, 2 Medium, 3 High
DCRACK	Existence of "D" cracking - 0 No, 1 Yes
TDIF	Average monthly temperature range - °C
SUMPREC	Average annual precipitation, cm.
FRINDEX	Freezing index (32°F - CE Method)
IMOIST	Thornthwaite Moisture Index
CSTE	Concentration of summer thermal efficiency
AGE	Age of pavement, years
ESAL	Accumulated equivalent 18-Kip single axle loads, millions
DOWDIA	Diameter of dowel bar, in
BASETHI	Subbase thickness, in
REACT	Presence of reactive aggregate distress 0 No, 1 Yes
TRANGE	Average yearly temperature range, °C
AVGMAXT	Average maximum monthly temperature, °C

ratio represents the relative number of standard versus any other axle load necessary to produce an equivalent damage. As found at the AASHO Road Test, these load equivalence factors are dependent on the definition of failure or level of damage on which they are based.

During the course of the project, it was interesting to note through discussions with the panel of experts and others, that the new load equivalence factors were expected for any distress to approximate those resulting for serviceability loss from the AASHO Road Test. In actuality, the physical mechanisms involved in say fatigue cracking or faulting of rigid pavements are quite different from those that combine to produce serviceabilty loss, so there is no physical reason to expect similar load equivalence factors. There also appeared to be an expectation that the load equivalence factors would be invariant with environmental zone. While the mechanisms for a specific distress remain essentially the same between environmental zones, the interactions between independent variables including the environment may differ such that again some variation in load equivalence factors would be expected.

The calculation of load equivalence factors for the flexible pavements, where the values of ρ and β were developed directly from a data bank that included four levels of single axle loads and four levels of tandem axle loads, was rather direct. The load equivalence factors in these cases were simply the ratio of the ρ for the standard axle to the ρ for the axle of interest. Unfortunately, characterizations of the axle load data for rigid pavement damage functions were totally in terms of 18-kip ESAL. The development of load equivalence factors from these damage functions was therefore mathematically complex, and innovative techniques involving assumptions with limited physical support were required.

While the tables of load equivalence factors (LEF's) developed in this project are too long to include in this executive summary, Figures 2.1 through 2.5 provide graphical representations. Figures 2.1 through 2.3 are for flexible pavements, and also include plots of the LEF's based on PSI from the AASHO Road Test. Figure 2.3 also includes plots of LEF's calculated from the AASHO fatigue cracking regression equation. Figures 2.4 and 2.5 are examples of LEF's for a typical pavement and set of conditions for jointed plane concrete pavements and jointed reinforced concrete pavements, respectively, in a wet-freeze climate.

Structural Number = 4.5
Subgrade Modulus = 15,000 psi
A.C. Thickness = 6 inches

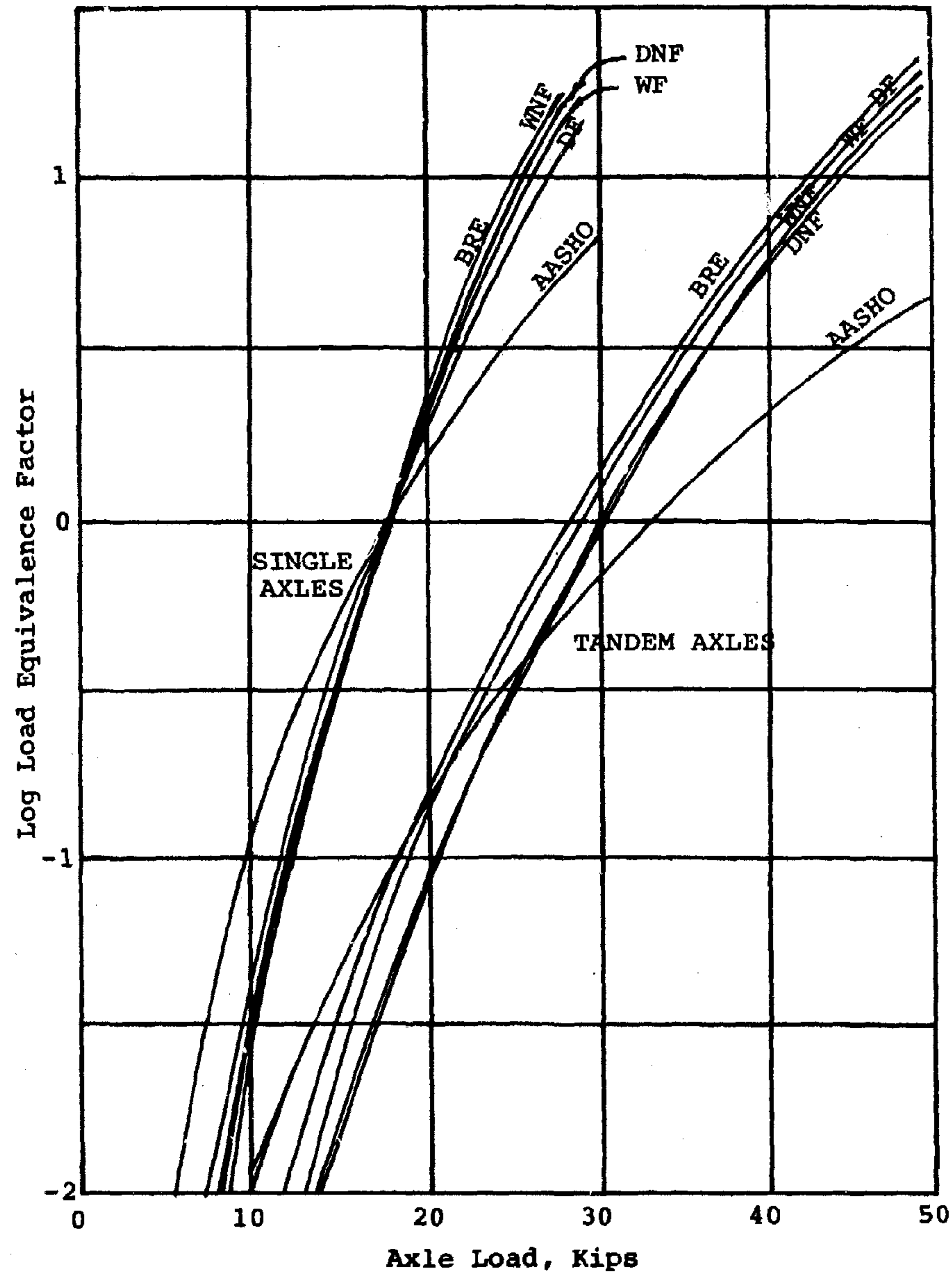

Figure 2.1 Load Equivalence Factors for PSI

Structural Number = 4.5
Subgrade Modulus = 15,000 psi
A.C. Thickness = 6 inches

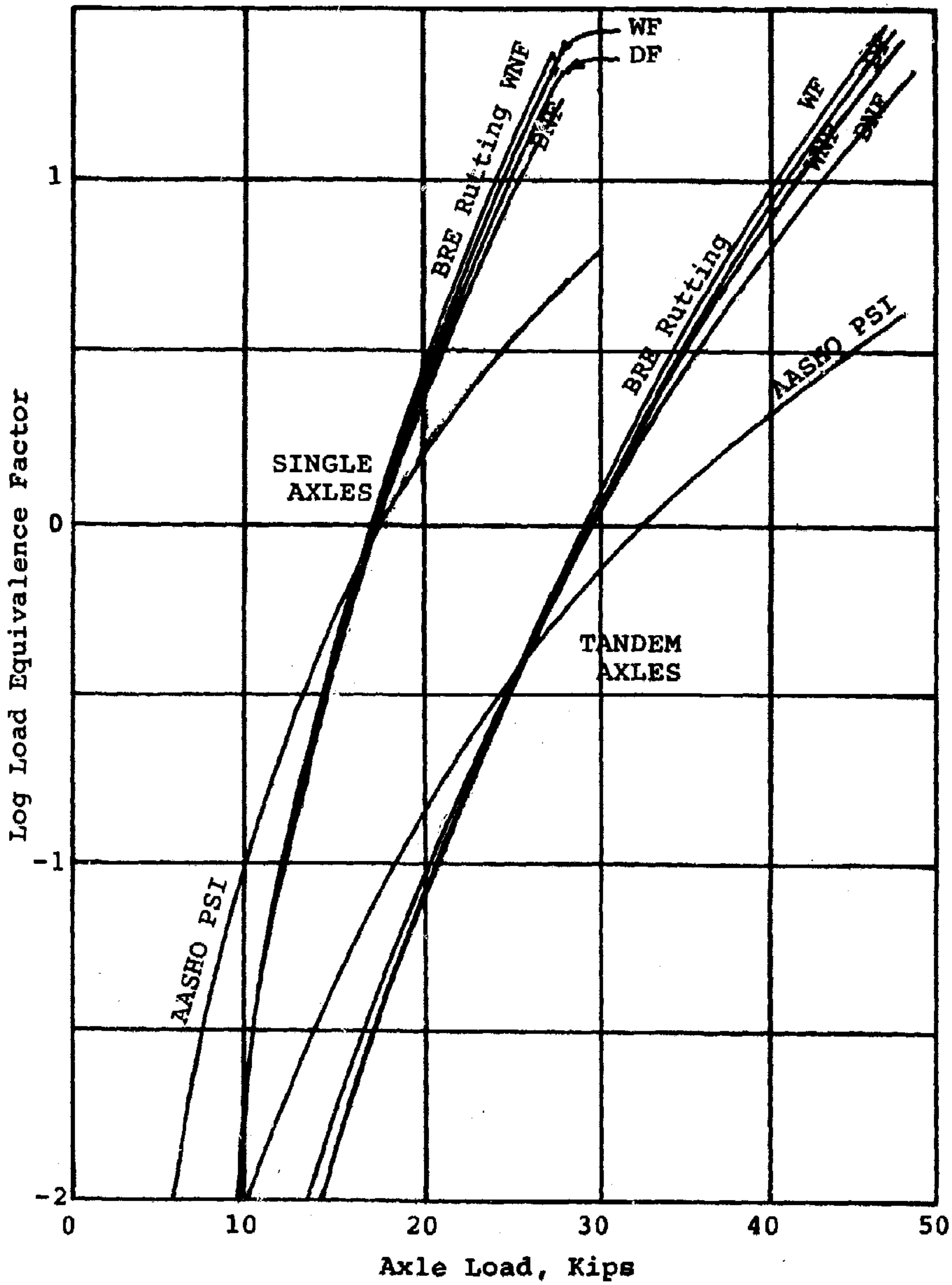

Figure 2.2 Load Equivalence Factors for Rutting

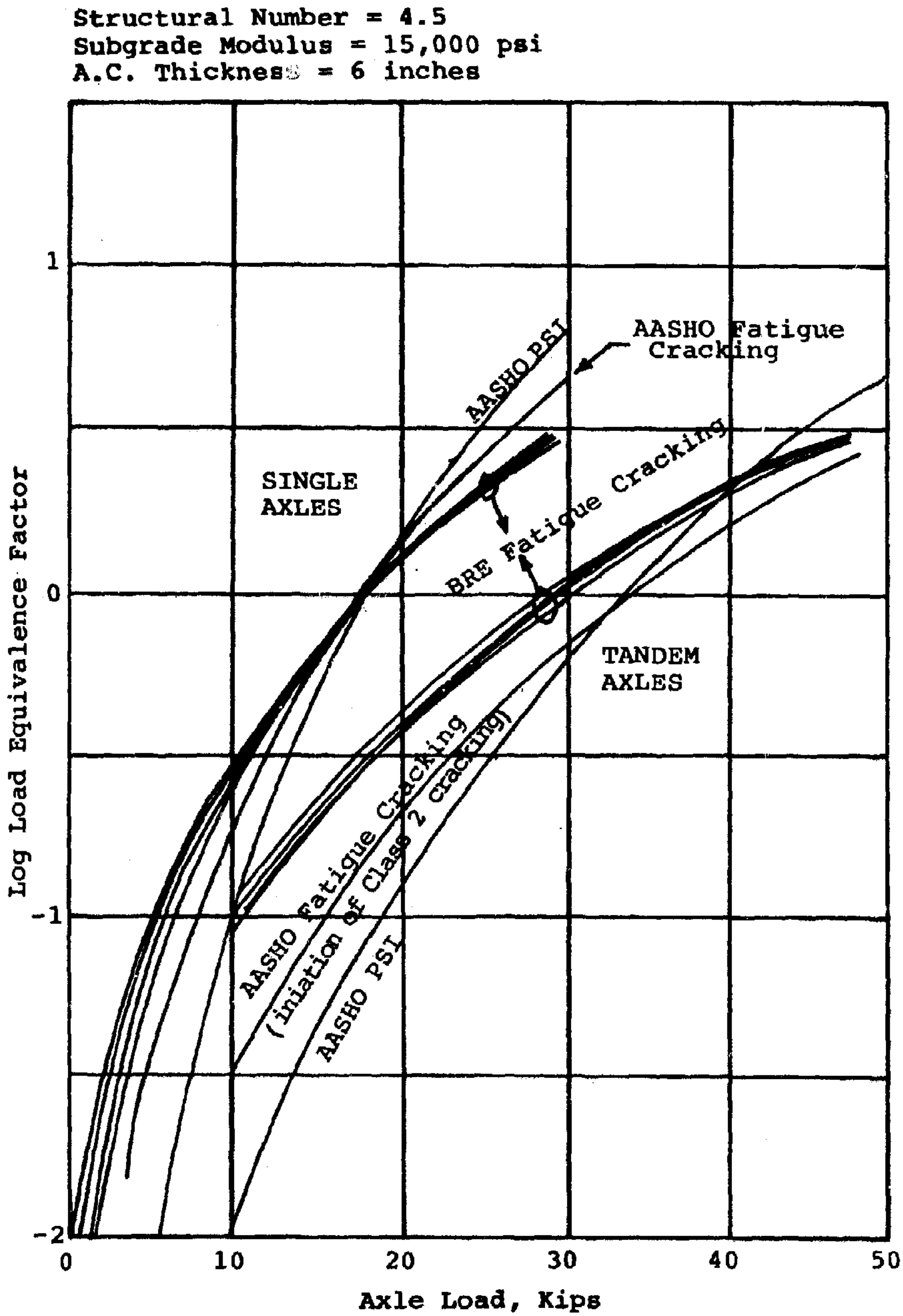

Figure 2.3 Load Equivalence Factors for Fatigue Cracking

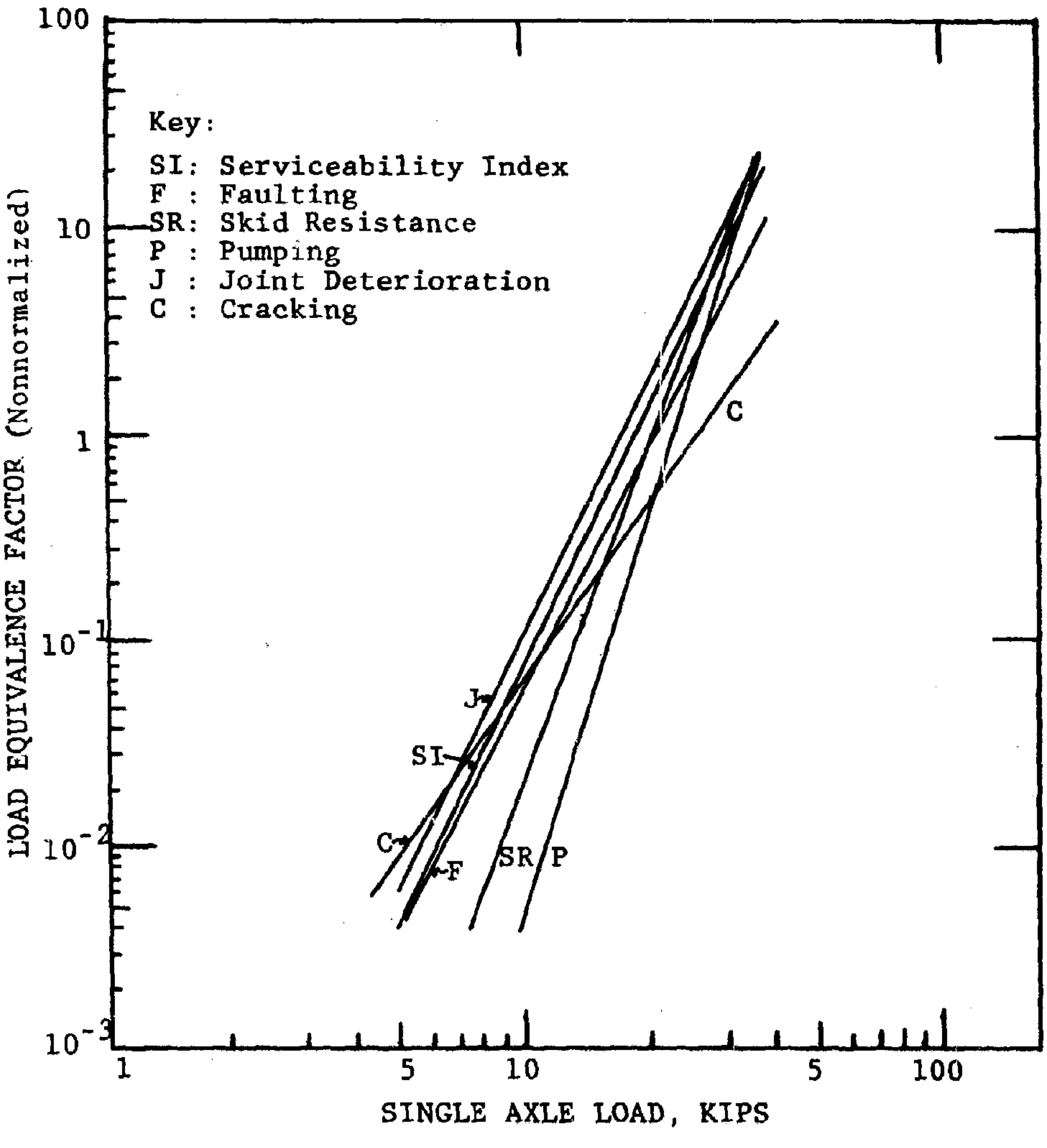

Figure 2.4 Example load equivalence factors for JPCP, 9 in slab in wet-freeze climate.

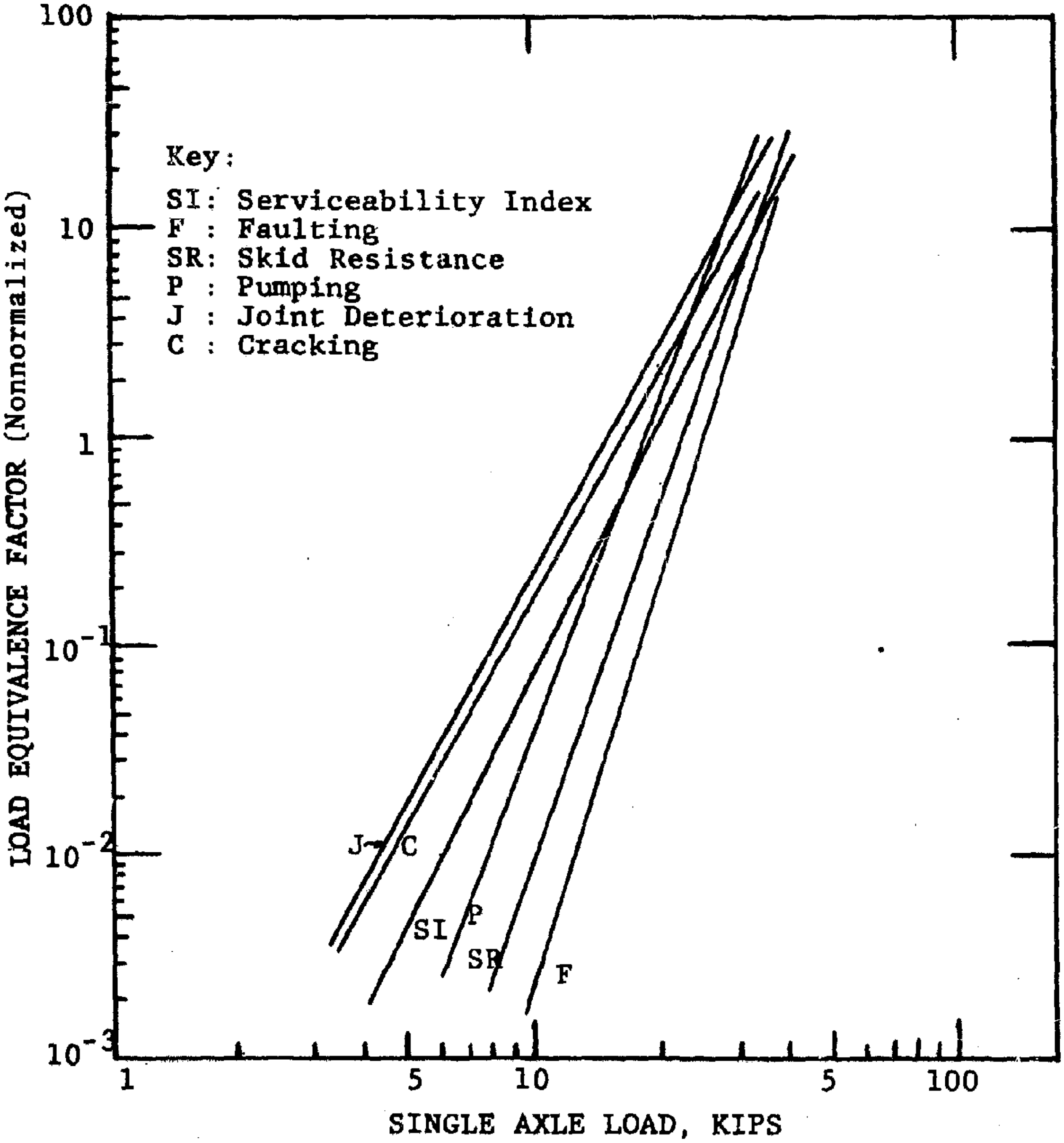

Figure 2.5 Example load equivalence factors for JRCP, 9 inch slab in wet-freeze climate.

CHAPTER 3

CONCLUSIONS AND RECOMMENDATIONS

Pavement damage functions have been developed for those flexible and rigid pavement distresses considered to be significant in terms of generating major repair or rehabilitation. The damage functions fall into two categories, those that are load-induced and those that are caused by the environment and are generally independent of axle loads. These damage functions for load-induced distress were then used to develop load equivalence factors for each of these significant distresses and for loss of serviceability. A computer program called Program DAMAGE was developed and may be used to generate load equivalence factors for specific pavement structures and specific environmental zones. Detailed descriptions are provided in the report for all steps in the work effort leading to the damage functions, the load equivalence factors, and program DAMAGE.

The two most troublesome aspects of this work effort were the expedited schedule necessary to service FHWA needs for cost allocation studies, and the absence of suitable distress models for many of the significant distresses. The expedited schedule limited opportunity for iterative improvements in the models and applications, while the need for new models diverted effort to their production that could have been used profitably on other portions of the work effort. Another problem was that development of load equivalence factors for rigid pavements could not be made independent of the 18-Kip ESAL based on PSI damage at the AASHO Road Test. However, the innovative procedure described in Chapter 7, Volume 1 of the report allowed the development of LEF's for rigid pavements that appear to be reasonable. While lack of mathematical independence required some assumption in order to develop LEF's, the assumption used was carefully studied and is believed to be the best available.

The prediction of fatigue cracking damage (or indeed any tensile cracking damage) is problematical due to the many highly variable parameters that control crack initiation and propagation. Even in nature, the variability in cracking damage is great for apparently identical pavement structures and conditions. However, it is believed that the damage function for Class 2 and 3 fatigue cracking adopted is quite good for the typical pavement materials and conditions it represents. It should be remembered, however, that the equation for transforming distress index or damage into area cracked is applicable only to the typical fatigue relationship used in this study.

The load equivalence factors developed for fatigue cracking reflect the trends anticipated and have no known important limitations affecting their credibility. The use of these load equivalence factors ascribes less damage to the heavier axles than would be ascribed by the PSI-based LEF's from the AASHO Road Test. Use of LEF's from the cracking equation developed from Road Test data also indicates this trend.

The load equivalence factors for loss of serviceability (see Figure 2.1) differ considerably from the AASHO Road Test LEF's in that they ascribe much more responsibility for damage to the heavier axles and much less for the lighter axles. The reasons for these differences between the two sets of LEF's has been explored and discussed in Chapter 8, Volume 1 of the report. While the relative accuracy of the two sets of LEF is not known, the authors believe that the magnitudes of the BRE LEF's may be somewhat high for the heavier axles and low for the light axles. That is, the "truth" lies somewhere between the two. There were fairly serious problems in the multiple regression analysis of data from the AASHO Road Test due to its variability and the different forms of damage relationships encountered, and there were limitations imposed by the mechanistic model and its materials characterizations.

As might be expected, the LEF's for rutting follow the same trends as those for PSI. There are no other LEF's for rutting known to exist, so no comparisons can be made.

The LEF's for serviceability loss in rigid pavements are identical to those derived from the AASHO Road Test. This is a consequence of the dependence of these equations upon the AASHO LEF's for PSI. The LEF's for other distresses vary considerably from those for loss of serviceability. These LEF's are believed to reasonably represent the relative effects of the axle loads, although there are no other LEF's or known data that may be used to check them.

The computer program called DAMAGE has been structured such that the damage functions can be replaced with new or improved equations as they are developed. This is a very flexible tool that may be used to generate load equivalence factors for various types of damage, ascribe the percents of the total damage to the different axle load classes for each damage type individually, apply deduct values or weights to the percents of distress ascribed, and process all of this data to arrive at overall distributions of total damage responsibility for the various vehicle classes. A range of decision rules may be applied to control the termination of the process. These include termination when the pavement score reaches a certain minimum level, when the first distress reaches its critical value, when PSI falls below its terminal level, when a selected distress reaches its critical value, or when the pavement reaches a selected age.

One of the primary objectives of this work effort was the development of a more comprehensive methodology for distributing responsibility for damage to the various axle load classes. The methodology reflected in program DAMAGE allows the consideration of all significant distresses instead of only loss of serviceability (which does not appear to be the primary generator of major repair and rehabilitation). With the development of damage functions where none previously existed and the improvement of a number of others, the use of program DAMAGE is now feasible. However, limited studies continue to improve these damage functions.

A number of problems and limitations have been discussed for both the AASHO Road Test and this computer-based road test. Each had advantages and disadvantages. The one thing shared by both is the difficulties in transforming the data through multiple regressions into truly representative relationships.

It is the belief of the authors that the results of this work effort, like those from the AASHO Road Test, will not prove to be final answers. However, our capabilities for assigning responsibility for damage have been greatly broadened. As the establishment of the responsibilities for damage will involve assignment of responsibilities for billions of dollars, there seems to be little doubt that additional studies will be forthcoming. Fortunately, the nature of these studies is such that they will overlap with other established needs for predicting damage and consequent needs for repair and rehabilitation. It is believed that input to future improvements may come from the long-term monitoring studies that are now being implemented on a limited basis, other accelerated studies (perhaps such as those done in South Africa with their heavy vehicle simulators), and from other theoretical studies using mechanistic or empirical models. All of these approaches have important limitations, so that it will be necessary to draw from each of these sources to progress toward a clear understanding of load equivalence factors.

These studies have indicated that the magnitudes of the LEF's may be considerably dependent on the forms of the damage equations from which they are derived. Theoretical studies and empirical comparisons could prove very profitable in clarifying this. The possibility of using a three-parameter damage function instead of the two-parameter (ρ and β) now considered basic, should not be disregarded. Also, the laborious but more accurate nonlinear regressions required to include the obvious inter-dependence of these two parameters should probably be used for studies with more relaxed schedules.

It is believed that this study has not only satisfied the majority of reasonable expectations, but has produced a wealth of improved damage functions for future use in pavement management systems and other evaluation needs. Because of its very broad scope, it has dealt with the great majority of accumulated knowledge on pavements. It is certainly one of the most challenging projects undertaken by the authors collectively or individually, and we are both proud and appreciative for the opportunity to participate and contribute in this work effort.

REFERENCES

1. Rauhut, J. B., F. L. Roberts, and T. W. Kennedy, "Models and Significant Material Properties for Predicting Distresses in Zero-Maintenance Pavements," Draft Report No. FHWA-RD-78-84, June 1979 (not published).

2. Rauhut, J. B., F. L. Roberts, and T. W. Kennedy, "Response and Distress Models for Pavement Studies," Transportation Research Record 715, 1979.

3. Shahin, M. Y., M. I. Darter, and S. R. Kohn, "Development of a Pavement Maintenance Management System, Vol. IV: Appendices A through I, Maintenance and Repair Guidelines for Airfield Pavements," Technical Report No. CEEDO-TR-77-4, U. S. Air Force Civil Engineering Development Office, September 1977.

4. Lytton, R. L., T. Scullion, B. D. Garrett, and C. M. Michalak, "Effects of Truck Weights on Pavement Deterioration," Texas Transportation Report RF 4087-2 to the American Trucking Association, June 1981.

5. Lytton, R. L. and Shanmugham, U., "Analysis and Design of Pavements to Resist Thermal Cracking Using Fracture Mechanics," Proceedings, 5th International Conference on the Structural Design of Asphalt Pavements, Amsterdam, 1982.

6. Velasco, M. O. and R. L. Lytton, "Pavement Roughness and Expansive Clays,"Interim Report No. FHWA/TX-80/-+284-2, prepared by the Texas Transportation Institute, October 1980.

7. Velasco, M. O. and R. L. Lytton, "Pavement Roughness on Expansive Clays," Transportation Research Record 790, 1981.

8. Darter, M. I., M. B. Snyder and R. E. Smith, "Development of a System for Nationwide Evaluation of Portland Cement Concrete Pavements," Final Report, NCHRP Project 1-19, 1980.

9. Darter, M. I., "Design of Zero-Maintenance Plain Jointed Concrete Pavement, Vol. I - Development of Design Procedures," Report FHWA-RD-77-111, Federal Highway Administration, 1977.

10. Darter, M. I. and S. L. Brandau, "Predictive Distress and Serviceability Models for Illinois JRCP," Report prepared for Texas Transportation Institute, March 1981.