Pavement Performance Equations

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Washington State Department of Transportation
Planning, Research and Public Transportation Division

in cooperation with the
United States Department of Transportation
Federal Highway Administration

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16. ABSTRACT

The WSDOT PMS database was used to develop regression equations for three pavement surface types: bituminous surface treatments, asphalt concrete and portland cement concrete. The primary regression equations developed were to predict Pavement Condition Rating (PCR) which is a measure of the pavement surface distress (ranges from 100 (no distress) to below 0 (extensive distress)). Overall, the equations fit the data rather well given the expected variation of pavement performance information. The relative effects of age (time since construction or reconstruction) were illustrated for the three surface types.

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PAVEMENT PERFORMANCE EQUATIONS

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DISCLAIMER

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SUMMARY AND CONCLUSIONS

SUMMARY

The WSDOT PMS database was used to develop regression equations for three pavement surface types: bituminous surface treatments, asphalt concrete and portland cement concrete. The primary regression equations developed were to predict Pavement Condition Rating (PCR), which is a measure of the pavement surface distress and ranges from 100 (no distress) to below 0 (extensive distress). Overall, the equations fit the data rather well, given the expected variation of pavement performance information. The relative effects of age (time since construction or reconstruction) were illustrated for the three surface types.

RECOMMENDATIONS

This modeling effort produced simple but "strong" regression equations based on in-service WSDOT pavements. The effort should be continued to see what model improvements are possible with the use of independent variable transformations.

INTRODUCTION

THE PROBLEM

This study was conducted in response to Federal Highway Administration's Demonstration Project No. 302, "Pavement Performance Curves." The basic problem addressed was the lack of adequate pavement performance models (equations). Such models are needed to predict pavement performance for a variety of needs such as

(a) pavement life,

(b) relative measures of rehabilitation effectiveness, and

(c) life-cycle costs.

BACKGROUND

Nationwide, there is a dearth of models that can be used to predict pavement performance. In part, this lack of models is the justification for the Long Term Pavement Performance (LTPP) portion of the $150 million Strategic Highway Research Program [1]. Therefore, in anticipation of the full implementation of the LTPP project during 1988, the FHWA encouraged the state DOTs to use their own databases to see what kind and quality of performance models could be developed.

WSDOT's PMS

WSDOT has had in operation for several years a pavement management system (PMS). This system contains some of the kinds of pavement information needed to develop performance models. Further, the process used within the PMS program to identify the need for rehabilitation (where and when) for each unique pavement section within WSDOT's route system is based on the use of performance curves.

WSDOT has conducted a visual pavement condition survey every two years since 1969 on 100 percent of the state highway system. These surveys were used to develop a ranked list of projects for a priority array. This array was based only on the most recent survey, and was used as input in developing a six year budget every biennium. In the late 1970s and early 1980s

WSDOT developed an improved pavement management system that predicts the pavement condition for each project segment based on prior pavement condition data. The new system was partially implemented in the 1982 budget process and fully implemented in the 1984 highway construction program.

For flexible pavements the pavement condition survey is used to evaluate alligator cracking, longitudinal cracking, transverse cracking and patching. The following weighting values are applied to the deficiencies noted:

			Percent of Wheel Track per Station				
			1-24	25-49	50-74	75+	
Alligator Cracking		(1) Hairline	20	25	30	35	
		(2) Spalling	35	40	45	50	Negative Values
		(3) Spalling & Pumping	50	55	60	65	
			Average Width in Inches				
			1/8-1/4	1/4+	Spalled		
Longitudinal Cracking	Lineal Feet per Station	(1) 1-99	5	15	30		
		(2) 100-199	15	30	45		Negative Values
		(3) 200+	30	45	60		
			Average Width in Inches				
			1/8-1/4	1/4+	Spalled		
Transverse Cracking	Number per Station	(1) 1-4	5	10	15		
		(2) 5-9	10	15	20		Negative Values
		(3) 10+	15	20	25		
			Average Depth in Inches				
			0-1/2	1/2-1	1+		
Patching	Percent Area per Station	(1) 1-5	10	15	20		
		(2) 6-25	15	20	25		Negative Values
		(3) 26+	20	25	30		

The final Pavement Condition Rating (PCR) is a combination of the visual rating and ride rating:

$$PCR = [100 - \Sigma D] \left[1.0 - .3 \left(\frac{CPM}{5000} \right)^2 \right]$$

where ΣD is the sum of the detect values noted above, and

CPM is the counts per mile from a Cox Road Rater.

The ride input in the equation has little effect except for the worst conditions. As can be seen by the relative defect values, the PCR is largely a measure of fatigue cracking. The first stages of fatigue cracking is evident at a PCR of about 40. Service lives are generally measured to a PCR of 40 which is close to a Pavement Serviceability Index (PSI) of 3.0. There is no apparent roughness from distressed pavement at this stage.

A unique feature of the WSDOT's PMS is the systematic development of project specific pavement performance curves for the entire state system. These performance curves are based on pavement condition, measured every two years. A project specific system has the obvious advantage of identifying individual projects for each biennium's construction program (given that pavement performance is highly variable). Washington state's experience confirms the highly variable nature of pavement performance and verifies the concept of a project specific pavement management system.

Basic Model Requirements

Darter [2] noted four criteria to use in developing reliable pavement models. These criteria include

(a) an adequate database built from in-service pavements,

(b) the inclusion of all variables that significantly affect pavement performance,

(c) an adequate functional form of the model, and

(d) a model that meets the proper statistical criteria for precision and accuracy (error of prediction, coefficient of determination (R^2), etc.).

Essentially, all but one of the above criteria either partially exist in the WSDOT's PMS [3, 4] or can be performed by WSDOT personnel. The WSDOT's PMS does not contain all the variables that affect pavement performance, but it has provided an excellent start.

The reported study has been used to develop pavement performance equations with the help of regression analysis. Essentially, this process can be used to relate two or more quantitative variables so that one variable (the dependent variable) can be predicted from the others (independent variables).

OBJECTIVES

The objectives of this study were to develop pavement performance curves (equations) for new and rehabilitated pavements in order to more reliably predict pavement service life and remaining life so that these predictions could be incorporated into life-cycle cost analyses.

The following benefits result from meeting these basic objectives.

(a) The study contributes to the national effort supported by the FHWA by providing a fresh examination of pavement performance models derived from in-service pavements. Specifically, the results will contribute to the expected refinements to the LTPP experiment within SHRP and the FHWA's HPMS activity.

(b) The study better defines for the the WSDOT's PMS and life-cycle cost analyses the performance periods of "original" and "rehabilitated" pavements, as well as some of the controlling factors.

REPORT ORGANIZATION

The remainder of the report is organized as follows:

- Data and Analysis Approach
- Results

A companion report prepared during this study, entitled "Regression Analysis for WSDOT Material Applications" [5], provided the training framework that resulted in the reported regression equations.

DATA AND ANALYSIS APPROACH

INTRODUCTION

The primary variables used in the analysis are as follows.

(a) Pavement Condition Rating (PCR): This is a measure of the observed pavement surface distress and ranges from 100 (no distress) to 0 or below (extensive surface distress). PCR is primarily determined by measures of the extent and severity of pavement surface cracking.

(b) Age: Pavement age is determined from the time of construction, reconstruction or overlay to time of the last PCR.

(c) Accumulated 18,000 lb. equivalent single axle loads (ESAL): The number of ESALs estimated for the age of the pavement section.

(d) Pavement thickness (THICK): The thickness of the pavement surface course (for either BST, AC or PCC surfaces).

AVAILABLE DATA

The WSDOT's PMS data files contain 2,616 separate pavement sections (separate sections of pavement with relatively uniform construction and performance), which represent over 7,800 centerline miles of state maintained highways. The total number of pavement sections was initially separated into eight separate categories, as shown in Table 1. The number of pavement sections shown in the table is a subset of the total in the PMS and represent about 20 percent of the mileage on the route system. These subsets were created to include only pavement sections that exhibited a systematic (or classic) performance curve. Specific criteria used to develop these subsets include the following.

(a) The pavement section performance curve (Pavement Condition Rating (PCR) versus age) was based on actual performance data and exhibited an R^2 of no less than 0.75 (75 percent).

(b) The standard error of the performance curve was no larger than 10.

The last two columns of Table 1 (number of pavement sections) reflect the differences within the WSDOT's PMS on current traffic inputs. Column B reflects the number of pavement sections that have recent traffic and/or vehicle classification counts (or estimates). Clearly, for regression modeling an important variable is ESALs, and as such, this number should be estimated as accurately as possible. Regression models will be shown for both Columns A and B.

ANALYSIS APPROACH

In order to develop regression equations, the data sets described in the preceding section were further resorted into two new data files as follows.

(a) **General project data**

This file contains only the last PCR point for each pavement section. Individual types of data include

(i) most recent PCR,

(ii) current pavement age (years),

(iii) accumulative 18,000 lb. equivalent single axle loads (ESALs) at time of last PCR rating, and

(iv) pavement surface course thickness (inches).

(b) **Project regression file**

This file is similar to the "general project data" file but also contains the PCR, age and ESALs at the time of construction. PCR was assumed to equal 100, Age to equal 0 and ESAL to equal 0 at construction (or reconstruction).

All regression analyses and summary statistics were obtained with the MINITAB microcomputer based statistics package (refer to MINITAB Handbook [6]).

Table 1. Basic Pavement Categories Used for Developing General Statistics and Regression Models

Surfacing Type	Construction Type	Column A Number of Pavement Sections (Standard Traffic)	Column B Number of Pavement Sections (Revised Traffic)
Bituminous Surface Treatment	New or Reconstruction	6	2
	Age ≥ 5 years	5	1
Asphalt Concrete	New or Reconstruction	58	15
	New or Reconstruction Age ≥ 10 years	40	9
	Overlays	383	100
	Overlays Age ≥ 5 years	341	86
Portland Cement Concrete	New or Reconstruction	31	3
	New or Reconstruction Age ≥ 15 years	29	3

RESULTS

GENERAL STATISTICS

Tables 2 through 5 contain general statistical measures for the various pavement section subsets. These tables contain the number of pavement sections in a specific subset, the mean, median, standard deviation, and minimum and maximum values.

Bituminous Surface Treatment

The general statistical measures for the four bituminous surface treatment data subsets are shown in Table 2. In general, few pavement sections were available for analysis (a maximum of six). The ESALs accumulated until the last PCR rating averaged about 258,000 at an age of about eight years. Thus, these sections met the AASHTO's definition of a "low volume road" [7].

The difference between the "standard traffic" and "revised traffic" designations was simply that the revised traffic is a more recent and accurate estimate for calculating ESALs. This is because it uses more recent ADT estimates and truck classifications.

All bituminous surface treatment categories were for new or reconstructed pavement structures.[1] The research team also examined how a minimum survival time of five years would influence the results. As one can see in Table 2, the average age increased slightly, but otherwise the two categories showed little difference.

Asphalt Concrete

The general statistical measures for the eight asphalt concrete data subsets are shown in Tables 3 and 4. Table 3 is for new or reconstructed pavement structures and Table 4 for asphalt concrete overlays.

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[1]This means that the project was either to completely rebuild the existing roadway with 1.0 to 2.0 feet of gravels and crushed bases surfaced with a BST, or an existing roadway was covered with 4 to 6 inches of crushed base and resurfaced with a BST.

Table 2. General Statistics for Bituminous Surface Treatments

Construction Type	Variable	Number of Pavement Sections	Mean ($\bar{x}$)	Median	Standard Deviation (s)	Minimum	Maximum
New or Reconstruction (Standard Traffic)	PCR	6	69	75	31	32	98
	AGE	6	8.2	6.5	4.8	3.0	15.0
	ESAL	6	258,000	185,000	236,000	45,000	603,000
	THICK	6	1.1	0.7	0.9	0.5	3.0
New or Reconstruction (Revised Traffic)	PCR	2	65	65	46	32	98
	AGE	2	8.0	8.0	7.1	3.0	13.0
	ESAL	2	348,000	348,000	444,000	34,000	662,000
	THICK	2	1.0	1.0	0.3	0.7	1.2
New or Reconstruction Age ≥ 5 years (Standard Traffic)	PCR	5	63	55	31	32	96
	AGE	5	9.2	7.0	4.5	5.0	15.0
	ESAL	5	291,000	277,000	248,000	45,000	603,000
	THICK	5	1.1	0.7	1.1	0.5	3.0
New or Reconstruction Age ≥ 5 years (Revised Traffic)	PCR	1	32	32	---	32	32
	AGE	1	13.0	13.0	---	13.0	13.0
	ESAL	1	662,000	662,000	---	662,000	662,000
	THICK	1	0.7	0.7	---	0.7	0.7

PCR = Pavement Condition Rating
AGE = Age (years)
ESAL = Accumulated 18,000 lb. equivalent single axle loads
THICK = Surface course thickness (inches)

Table 3 shows that the average new asphalt concrete surfacing layer was 5.3 inches thick (standard traffic data subset) and the average PCR was 58 at an age of about 12.7 years. The ACP depths were not evenly distributed but fell into two distinct groups, at about 4 inches and 8 to 9 inches. The accumulated ESALs at these average conditions was a bit less than 1,500,000.

For asphalt concrete overlays, Table 4 illustrates notable differences between the typical overlays used by WSDOT and new asphalt concrete surface courses. The overlays were thinner (1.7 versus 5.3 inches), newer (8.2 versus 12.7 years), had fewer accumulated ESALs (712,000 versus 1,439,000) but were in about the same overall condition (average PCR of 62 for overlays versus 58 for new asphalt concrete surface courses). Further, there were more overlays in the WSDOT's PMS database. The overlays included thin "maintenance" type seals (0.75 to 1.0 inch) as well as structural overlays (1.75 to 3.0 inches).

Minimum survival times of ten years for new or reconstructed asphalt concrete surface courses and five years for asphalt concrete overlays were also examined. The summary statistics are shown in Tables 3 and 4, respectively.

Portland Cement Concrete

The general statistical measures for the four portland cement concrete data subsets are shown in Table 5. This information shows that, when compared to new asphalt concrete surface courses, portland cement concrete surfaces were older (26.4 versus 12.7 years) and thicker (8.4 versus 5.3 inches), had experienced substantially more ESALs (9,933,000 versus 1,439,000), but were in about the same overall condition, as measured by PCR.

The revised traffic estimates resulted in few PCC pavement sections and thus were not valid statistical estimates for the population of PCC pavements. A minimum survival time of 15 years was also examined.

Table 3. General Statistics for Asphalt Concrete - New or Reconstruction

Construction Type	Variable	Number of Pavement Sections	Mean ($\bar{x}$)	Median	Standard Deviation (s)	Minimum	Maximum
New or Reconstruction (Standard Traffic)	PCR	58	58	62	21	5	96
	AGE	58	12.7	13.0	4.5	4.0	24.0
	ESAL	58	1,439,000	802,000	1,679,000	20,000	6,925,000
	THICK	58	5.3	4.2	2.3	1.8	10.2
New or Reconstruction (Revised Traffic)	PCR	15	63	66	23	8	96
	AGE	15	11.9	12.0	5.5	4.0	22.0
	ESAL	15	1,279,000	1,394,000	965,000	31,000	3,548,000
	THICK	15	4.8	4.2	2.0	2.4	10.2
New or Reconstruction Age ≥ 10 Years (Standard Traffic)	PCR	40	50	57	21	5	74
	AGE	40	15.0	14.0	3.5	10.0	24.0
	ESAL	40	1,856,000	1,091,000	1,864,000	90,000	6,925,000
	THICK	40	5.4	4.2	2.4	2.4	10.2
New or Reconstruction Age ≥ 10 Years (Revised Traffic)	PCR	9	52	58	22	8	72
	AGE	9	15.3	13.0	4.2	10.0	22.0
	ESAL	9	1,831,000	1,692,000	777,000	926,000	3,548,000
	THICK	9	5.2	4.2	2.5	2.4	10.2

PCR = Pavement Condition Rating
AGE = Age (years)
ESAL = Accumulated 18,000 lb. equivalent single axle loads
THICK = Surface course thickness (inches)

Table 4. General Statistics for Asphalt Concrete - Overlays

Construction Type	Variable	Number of Pavement Sections	Mean ($\bar{x}$)	Median	Standard Deviation (s)	Minimum	Maximum
Overlay (Standard Traffic)	PCR	383	62	65	25	-45	98
	AGE	383	8.2	8.0	3.0	3.0	21.0
	ESAL	383	712,000	429,000	903,000	13,000	5,662,000
	THICK	383	1.7	1.8	0.9	0.2	5.4
Overlay (Revised Traffic)	PCR	100	61	64	27	-45	98
	AGE	100	7.8	7.0	2.9	3.0	17.0
	ESAL	100	813,000	603,000	742,000	45,000	4,393,000
	THICK	100	1.7	1.8	0.7	0.6	4.2
Overlay Age ≥ 5 years (Standard Traffic)	PCR	341	61	63	25	-45	97
	AGE	341	8.8	8.0	2.7	5.0	21.0
	ESAL	341	748,000	458,000	940,000	13,000	5,662,000
	THICK	341	1.8	1.8	0.8	0.2	5.0
Overlay Age ≥ 5 years (Revised Traffic)	PCR	86	58	60	27	-45	95
	AGE	86	8.5	8.0	2.6	5.0	17.0
	ESAL	86	874,000	691,000	776,000	45,000	4,393,000
	THICK	86	1.8	1.8	0.7	0.6	4.2

PCR = Pavement Condition Rating
AGE = Age (years)
ESAL = Accumulated 18,000 lb. equivalent single axle loads
THICK = Surface course thickness (inches)

Table 5. General Statistics for Portland Cement Concrete

Construction Type	Variable	Number of Pavement Sections	Mean ($\bar{x}$)	Median	Standard Deviation (s)	Minimum	Maximum
New or Reconstruction (Standard Traffic	PCR	31	60	59	15	29	95
	AGE	31	26.4	21.0	14.4	5.0	69.0
	ESAL	31	9,933,000	9,448,000	5,342,000	1,722,000	22,191,000
	THICK	31	8.4	9.0	1.0	5.0	9.0
New or Reconstruction (Revised Traffic)	PCR	3	54	55	8	45	60
	AGE	3	21.0	21.0	---	21.0	21.0
	ESAL	3	15,346,000	9,572,000	10,002,000	9,572,000	26,896,000
	THICK	3	8.4	8.0	0.6	8.0	9.0
New or Reconstruction Age ≥ 15 years (Standard Traffic)	PCR	29	58	58	12	29	79
	AGE	29	27.6	21.0	14.0	15.0	69.0
	ESAL	29	10,386,000	9,701,000	5,221,000	1,722,000	22,191,000
	THICK	29	8.4	9.0	1.0	5.0	9.0
New or Reconstruction Age ≥ 15 years (Revised Traffic)	PCR	3	54	55	8	45	60
	AGE	3	21.0	21.0	---	21.0	21.0
	ESAL	3	15,346,000	9,572,000	10,002,000	9,572,000	26,896,000
	THICK	3	8.4	8.0	0.6	8.0	9.0

PCR = Pavement Condition Rating
AGE = Age (years)
ESAL = Accumulated 18,000 lb. equivalent single axle loads
THICK = Surface course thickness (inches)

REGRESSION EQUATIONS

Interpretation of Regression Equations

The basic measures used to examine the "validity" of the regression equations are described in detail by Mahoney in a companion report to this one [5]. Basically, these measures were as follows.

(a) Number of data points (n): Generally, a larger number of data points results in a more valid regression equation, all other measures being equal.

(b) Coefficient of determination (R^2): The R^2 is used to show how much of the variation in the dependent variable is explained by the regression equation. An R^2 of 100 percent results when the regression equation explains all of the variation in the dependent variable.

(c) Standard error of the estimate (SEE): This is used to estimate the standard deviation of the dependent variable about the regression line and is in units of the dependent variable. The smaller the SEE for a regression equation, the better.

(d) t-ratios for independent variable(s): These t-ratios should generally be greater than 2.0 for each independent variable to be a relatively "strong" predictor for the dependent variable. Refer to Reference 5 for additional details.

"Best" Regression Equations

The "best" regression equations were selected from the various data subsets for each of the three major pavement surface types. These equations and their associated measures of "validity" follow.

(a) **Bituminous Surface Treatment — New or Reconstruction (standard traffic)**

$$PCR = 109 - 4.43\,(AGE) - 0.000026\,(ESAL) \qquad \text{Eq. 1}$$

n = 12 data points (6 pavement sections)

R^2 = 90%

SEE = 9

|t-ratios| > 2.0 for independent variables

(b) **Bituminous Surface Treatment — New or Reconstruction with AGE ≥ 5 years (standard traffic)**

PCR = 103 - 4.59 (AGE) Eq. 2

n = 10 data points (5 pavement sections)

R^2 = 86%

SEE = 11

|t-ratio| > 7.0 for independent variable

(c) **Asphalt Concrete — New or Reconstruction (standard traffic)**

PCR = 100 - 3.08 (AGE) - 0.0000014 (ESAL) Eq. 3

n = 116 data points (58 pavement sections)

R^2 = 74%

SEE = 13

|t-ratio| > 1.8 for independent variables

(d) **Asphalt Concrete — New or Reconstruction (revised traffic)**

PCR = 97.2 - 2.68 (AGE) Eq. 4

n = 30 data points (15 pavement sections)

R^2 = 60%

SEE = 16

|t-ratios| > 6.4 for independent variable

(e) **Asphalt Concrete — New or Reconstruction with AGE ≥ 10 years (standard traffic)**

PCR = 98.5 - 3.10 (AGE) Eq. 5

n = 80 data points (40 pavement sections)

R^2 = 73%

SEE = 15

|t-ratio| > 14.4 for independent variable

(f) **Asphalt Concrete — New or Reconstruction with AGE ≥ 10 years (revised traffic)**

PCR = 95.9 - 2.62 (AGE) Eq. 6

n = 18 data points (9 pavement sections)

R^2 = 57%

SEE = 20

|t-ratio| > 4.6 for independent variable

(g) **Asphalt Concrete — Overlay (standard traffic)**

PCR = 95.1 - 4.51 (AGE) + 2.69 (THICK) Eq. 7

n = 766 data points (383 pavement sections)

R^2 = 65%

SEE = 15

|t-ratios| > 4.1 for independent variables

(h) **Asphalt Concrete — Overlay (revised traffic)**

PCR = 102.7 - 5.02 (AGE) - 0.000003 (ESAL) Eq. 8

n = 200 data points (100 pavement sections)

R^2 = 68%

SEE = 16

|t-ratios| > 2.0 for independent variables

(i) **Asphalt Concrete — Overlay with AGE ≥ 5 years (standard traffic)**

PCR = 95.4 - 4.51 (AGE) + 2.73 (THICK) Eq. 9

n = 682 data points (341 pavement sections)

R^2 = 67%

SEE = 15

|t-ratios| > 3.8 for independent variables

(j) **Asphalt Concrete — Overlay with AGE ≥ 5 years (revised traffic)**

PCR = 103.3 - 5.03 (AGE) - 0.0000032 (ESAL) Eq. 10

n = 172 data points (86 pavement sections)

R^2 = 69%

SEE = 16

|t-ratios| > 2.0 for independent variables

(k) **Portland Cement Concrete — New or Reconstruction (standard traffic)**

PCR = 93.8 - 1.05 (AGE) Eq. 11

n = 62 data points (31 pavement sections)

R^2 = 60%

SEE = 14

|t-ratio| > 9.5 for independent variable

(l) **Portland Cement Concrete — New or Reconstruction (revised traffic)**

PCR = 100 - 2.21 (AGE) Eq. 12

n = 6 data points (3 pavement sections)

R^2 = 96%

SEE = 6

|t-ratio| > 10.2 for independent variable

All of the above equations were developed from the project regression file's data subsets, described earlier. Thus, the number of data points were doubled with the assumption that AGE = 0, the PCR = 100 and accumulated ESALs = 0.

Overall, the one independent variable that was a strong predictor for all regression equations was age. This is fortunate, since that the regression coefficient (b_1) for age shows the relative rate of PCR loss per year for the various pavement types considered. For example, the following trends can be stated based on these equations:

(a) bituminous surface treatments and asphalt concrete overlays decrease in PCR about 50 percent faster than new or reconstructed asphalt concrete surface courses;

(b) bituminous surface treatments and asphalt concrete overlays decrease in PCR at about the same rate; and

(c) new or reconstructed asphalt concrete surface courses decrease in PCR about 150 to 200 percent faster than new or reconstructed portland cement concrete.

The validity of these trends are dependent on how representative the pavement sections used in developing the regression equations are of the overall WSDOT route system (i.e., the "population" of pavement sections).

The reported regression equations had R^2 values ranging from a low of 57 percent to a high of 96 percent, which was better than originally expected. These R^2 values were achieved without transforming the independent variables.* Such transformations would probably have improved the predictive capability of ESALs, since this variable, for some data sets, was not normally distributed.

Figure 1 is used to illustrate how PCR changes with age for the four pavement surface types examined. The regression models used were Equation 1 for new bituminous surface treatments, Equation 3 for new asphalt concrete surface courses, Equation 7 for asphalt concrete overlays, and Equation 11 for new portland cement concrete. These models contained the largest number of pavement sections for each of the four pavement surface types. For equations that contained an independent variable other than age, the mean value for that variable was used in developing the straight line plots. This figure shows that new bituminous surface treatments and asphalt concrete overlays perform about the same; however the differences in ESALs and thicknesses should not be overlooked. New asphalt concrete surface courses perform better than asphalt concrete overlays, as they should, and portland cement concrete performs significantly better than <u>all</u> others.

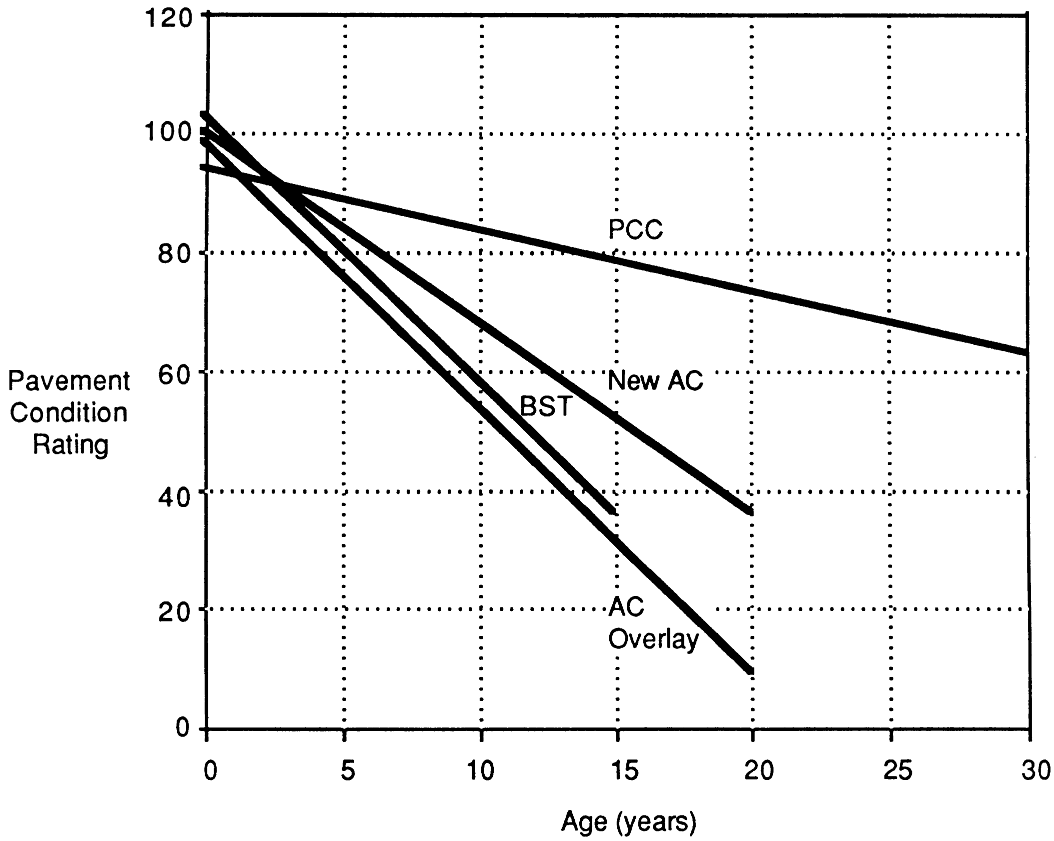

Figure 1. Pavement Condition Rating versus Age
for Various Pavement Types

REFERENCES

1. "Strategic Highway Research Program — Research Plans," National Cooperative Highway Research Program, Washington, D.C., May 1986.

2. Darter, M.I., "Requirements for Reliable Predictive Pavement Models," Presentation Paper, Annual Meeting, Transportation Research Board, National Research Council, Washington, D.C., January 1980.

3. Nelson, T.L. and LeClerc, R.V., "Development and Implementation of Washington State's Pavement Management System," Research Report WA-RD 50.1, Washington State Department of Transportation, Olympia, Washington, September 1982.

4. Jackson, N.C., "Operation of the Washington State Pavement Management System," Transportation Research Record 1048, Transportation Research Board, National Research Council, Washington, D.C., 1985.

5. Mahoney, J.P., "Regression Analysis for WSDOT Material Applications," Research Report WA-RD 143.2, Washington State Department of Transportation, Olympia, Washington, November 1987.

6. Ryan, B.F., Joiner, B.L., and Ryan, T.A., Minitab Handbook — Second Edition, PWS Publishers, Boston, Massachusetts, 1985.

7. American Association of State Highway and Transportation Officials, "AASHTO Guide for Design of Pavement Structures — 1986," American Association of State Highway and Transportation Officials, Washington, D.C., 1986.