THE WSDOT PAVEMENT MANAGEMENT SYSTEM: OPERATIONAL ENHANCEMENTS

WA-RD 315.2

Final Report
December 1995

Washington State
Department of Transportation

Washington State Transportation Commission
Planning and Programming Service Center
in cooperation with the U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 315.2	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE THE WSDOT PAVEMENT MANAGEMENT SYSTEM—OPERATIONAL ENHANCEMENTS		5. REPORT DATE December 1995 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Joe P. Mahoney and Marc Seferian		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, Box 354802 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement T9903, Task 6
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370		13. TYPE OF REPORT AND PERIOD COVERED Final report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. WSDOT technical contacts were Mr. Robyn Moore and Mr. Dennis Crimmins.

16. ABSTRACT

This report documents potential enhancements in three areas for the Washington State Pavement Management System (WSPMS): (1) a checking scheme for the annual pavement condition survey, (2) models for use in estimating vehicle operating costs due to pavement deterioration and their use in the optimal timing of rehabilitation, and (3) an alternate method for estimating pavement performance equations. The earlier report prepared for this study (WA-RD 315.1, "Statistical Methods for WSDOT Pavement and Material Applications") provides an overview of various statistical methods. A purpose of that report was to explain statistical methods (with special emphasis on regression analysis) in a straightforward manner to a broad group of users.

17. KEY WORDS Pavement management system, sampling, statistics, cost models, regression analysis, pavements, modules	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	90	

Final Report
Research Project T9903, Task 6
PMS Modification-II

THE WSDOT PAVEMENT MANAGEMENT SYSTEM—OPERATIONAL ENHANCEMENTS

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Prepared for

Washington State Transportation Commission
Department of Transportation
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SECTION 1

INTRODUCTION

1. SCOPE

The WSDOT Pavement Management System (WSPMS) has evolved over a period of 25 years, mostly through in-house effort. WSDOT, through this process, has become a leader among state highway agencies with respect to pavement management systems; however, a variety of needed enhancements have been identified. The potential enhancements reported herein include:

- pavement condition survey check procedure
- user cost model based on pavement roughness
- revised procedure for estimating pavement performance equations.

2. BACKGROUND

The WSPMS is continuously updated by WSDOT to enhance the use of its results. Annually, this includes adding a new visual distress survey for the route system as well as additional data on road roughness (IRI), rutting, and pavement structural information (mostly contract related work but also significant regional maintenance work such as chip seals). More recently, several updates were added to the WSPMS and documented in WSDOT Research Report WA-RD 274.1, "The WSDOT Pavement Management System—A 1993 Update." Some of these updates included

- surveys and documentation of WSDOT regions' personnel opinions about the WSPMS
- documentation of background information on pavement prediction models (including performance curves)
- documentation of national information on the basic requirements for a PMS

- documentation of national and state rule-making and legislation relating to PMS requirements
- documentation of the modifications and features added to the WSPMS, which included
    - a new pavement rehabilitation scoping technique
    - a completely revised scheme for a pavement condition rating index (specifically Pavement Structural Condition (PSC)).

The prior Phase I study accomplished several items. First, basic documentation relating to PMS in general and WSPMS specifically was prepared. This documentation was, in part, at the request of region personnel. Second, the pavement condition rating scheme needed updating to better reflect WSDOT pavement condition. Tied to this was a new system for "scoping" pavement rehabilitation, which was in the form of asphalt concrete (AC) overlays. The scoping technique was requested by the regions to better enable them to estimate the amount (hence cost) of rehabilitation needed at the earliest stages of the project programming cycle. Thus, a variety of rather basic issues were addressed that were deemed to be important in updating the WSPMS.

During the conduct of Phase I study, the next set of issues to address continued to evolve. During June 1993, the following issues requiring study were identified:

- **<u>Distress survey check procedure</u>**

    The annual pavement distress survey is conducted by up to six teams of two persons each. This work is conducted in the spring (starting about March 1) over a two-month period. WSDOT was concerned about the repeatability of these annual surveys and, hence, their accuracy. One way to address such variation was to develop a check system whereby a sample set of pavement surveys are obtained and compared to those obtained by all six teams (or however many teams are used in a given year).

- **Development procedure for performance equations**

  The importance of performance equations within the WSPMS cannot be overstated. These equations represent how individual pavement sections deteriorate with time. Currently, the PSC versus age relationship is the most significant; however, rutting and other such measures require predictive relationships as well. The general WSDOT regression model used to fit performance data (such as PSC) was validated during the Phase I study. Unfortunately, the situation is greatly complicated by the need for a "default" equation to predict performance for a pavement section that has been recently constructed or rehabilitated (i.e., has no substantial performance history). Additionally, other performance equations must be modified to recognize that some sections perform extremely well for several years and then deteriorate rapidly. Further, the default equations are currently developed annually. On the basis of recent results, WSDOT has some concern that the default equations may vary too much from year to year. This variation suggests that a careful evaluation of the pavement performance equation development process is in order.

- **"State-of-the-State" pavement summary**

  A document is needed to overview a condition of the pavement on the state route system. The primary audience for such a document includes personnel within WSDOT, the legislature, and the public. Some of the items currently anticipated for inclusion are

  - pavement condition
    - what it means
    - how it is measured
    - photos of various levels of PSC
    - a description of how pavement condition is related to preserving the investment in pavement infrastructure

- a description of the optimum least cost process (or lowest life cycle cost models)

- **Cost and optimization models**

  To better use the new priority programming law, that is, to incorporate the minimization of pavement life cycle costs in the selection of preservation projects (refer to Substitute Senate Bill 5963 (revisions to RCW 47.05.051)), various cost models are needed. These included but are not limited to the following:

  - pavement maintenance costs
  - user costs including those costs relating to pavement roughness and truck damage costs due to roughness.

  Additionally, an "optimal" rehabilitation scheme needs to be developed. The goal is to develop a procedure that is straightforward to understand, explain, and implement. Thus, the more "traditional" optimization schemes will most likely be unacceptable. The authors have long observed that most state DOTs that use complicated optimization procedures have some difficulty in implementing them.

3. REPORT CONTENTS AND ORGANIZATION

This report will be used to address a subset of the needed enhancements previously identified. As such, Section 2 will be used to describe the pavement condition survey check procedure. Section 3 will overview the summary of prior studies which have attempted to relate vehicle operating costs to pavement roughness (or condition). The use of such costs in determining the optimal timing of rehabilitation will be illustrated. Finally, Section 4 will illustrate a promising procedure for estimating pavement performance equations. Finally, Section 5 will be used to summarize the study findings.

SECTION 2

CHECKING PROCEDURE FOR THE ANNUAL PAVEMENT CONDITION SURVEY

1. INTRODUCTION

At least two basic issues must be addressed in order to "check" the annual visual pavement condition surveys. First, one must decide how to "sample" the route system to check the annual survey results. Second, once the sample is obtained, decide how to compare the data to make a decision. Each of these two basic issues will be addressed in the paragraphs which follow.

The current statewide visual condition survey was accomplished by five two-person teams for the 1993 survey year with one team rating the entire Interstate system. Each team leader is from the WSDOT Transportation Data Office in Olympia. The other team members are either permanent employees, temporary WSDOT employees or from the region being surveyed.

2. SAMPLE SIZE

The issue of how to sample the WSDOT route system is addressed in this paragraph. Naturally, there are numerous ways in which this can be done. The issue is how to select and obtain an efficient sample. Two approaches will be presented: a simple random sample and the precision method.

2.1 Simple Random Sample

For preliminary planning, a simple random sample will be assumed for each region. The sample is assumed to be a one mile long pavement segment located between two mileposts. Thus, if it is further assumed that only one side of a route is rated during the annual survey and there are about 1,000 centerline miles in each region, then a regional population is composed of 1,000 individual sample units.

A straightforward way to examine the issue of how many samples are needed to check the annual survey is to use estimates of the standard error. The standard error of a survey is analogous to the standard deviation for a set of data and, literally, is the standard deviation of means computed from samples taken from a population of data. The standard error decreases as the sample size increases (not exactly a surprise). The estimate of the standard error for a simple random sample is [1, 2]:

$$SE = \frac{S}{\sqrt{n}}\sqrt{1 - \frac{n}{N}} \qquad \text{(Eq. 2.1)}$$

where SE = standard error of a simple random sample,

S = standard deviation of the population,

n = number of one-mile highway segments sampled for a specific sample size,

N = total number of one-mile highway segments in a specific region, and

$\frac{n}{N}$ = sampling fraction.

If S is the standard deviation of <u>all</u> PSC values within a region, then assume, for now, various levels. A summary of possible SE estimates for various levels of S and sample sizes are shown in Table 2.1 (all based on calculations using Equation 2.1).

Based on data obtained from the Texas route system during the 1970s [2] and statistics developed for the WSDOT maintained route system [3], the standard deviation of regional and network route systems can be estimated. The analogous condition measure used by the Texas Highway Department during the 1970s was Pavement Rating Score (PRS) (similar to the Pavement Condition Rating (PCR) previously used by WSDOT). During the late 1970s only one district within Texas (roughly equivalent to a WSDOT region) had completed a complete survey (or "mass inventory") of all state maintained highways (District 21 — southern tip of the state). The means and associated standard deviations are (from Ref. 2):

Highway Type	PRS Mean	PRS Standard Deviation
• Interstate	83	8
• U.S. and State	82	13
• Farm-to-Market	78	16

Data summarized for WSDOT [3] for the complete statewide pavement network (not computed for specific regions):

Construction Type	PCR Mean	PCR Standard Deviation
• Asphalt Concrete—New or Reconstruction	58	21
• Asphalt Concrete-Overlays	62	25
• PCC—New Construction or Reconstruction	60	15

Table 2.1. Standard Error Estimates for a Simple Random Sample

Standard Deviation of Region PSC ("S")	Standard Error for Various Sample Sizes[1]					
	1%	2%	3%	4%	5%	10%
S = 10 (low)	3.1	2.2	1.8	1.5	1.4	0.9
S = 20 (low-medium)	6.3	4.4	3.6	3.1	2.8	1.9
S = 30 (medium)	9.4	6.6	5.4	4.6	4.1	2.8
S = 40 (high)	12.6	8.9	7.2	6.2	5.5	3.8
S = 50 (very high)	15.7	11.1	9.0	7.7	6.9	4.7

Note

1. If N = 1000, then a 1 percent sample = 10 sample units (each sample unit one-mile long). Similarly, a 10 percent sample = 100 sample units.

Based on the Texas and WSDOT "population" standard deviations, a reasonable condition rating standard deviation for a region is about 20. If this value is used in Table 2.1, then the associated sample size standard errors are:

Sample Size	Condition Rating Standard Error (SE)
1%	6.3
2%	4.4
3%	3.6
4%	3.1
5%	2.8
10%	1.9

An "optimum" sample size of two to three percent appears reasonable. If a two percent sample is used, then 20 individual sample units must be measured (again, assuming a regional population of 1,000 sample units). For the six WSDOT regions, this suggests a total of 120 sample units. Of course, other possibilities exist.

If specific road mileages are used for each of the regions, then the sample sizes need to be adjusted. Additionally, in a July 20, 1993, meeting at the WSDOT Materials Laboratory, it was decided that the Interstate system should be "separated" from the other WSDOT routes for sampling purposes. To this end, Table 2.2 was prepared which shows lane mileages by region and pavement type (pavement type is not considered in the sampling scheme but is provided for information). Additionally, the region centerline miles (often referred to as "route miles") and lane-miles are shown for the Interstate system.

For the Interstate system, visual condition surveys are conducted in both directions in the outside lane. A two percent sample results in the following number of one-mile samples (centerline miles x 2 x 0.02):

Region	Sample Size
Northwest	8
North Central	2
Olympic	2
Southwest	4
South Central	10
Eastern	4
	total = 30

For comparison purposes, the Interstate system should be compared as a whole, i.e., not by region.

Table 2.2. WSDOT Mileages

Region	All Route Systems (lane-miles)					
	BST	ACP	PCCP	Total w/o Ramps	Ramps	Grand Total
Northwest	193	2,536	939	3,668	277	3,945
North Central	1,558	1,037	6	2,601	24	2,625
Olympic	283	2,383	179	2,845	136	2,981
Southwest	76	1,660	195	1,931	83	2,014
South Central	983	1,193	721	2,897	145	3,042
Eastern	1,486	1,604	135	3,225	57	3,282
	4,579	10,413	2,175	17,167	722	17,889

Region	Interstate	
	Centerline Miles	Lane-Miles
Northwest	208	1,211
North Central	54	217
Olympic	55	331
Southwest	96	498
South Central	252	1,069
Eastern	107	445
	772	3,771

Similarly, the remainder of the WSDOT system (i.e., minus the Interstate mileage) can be sampled by dividing the lane-miles in each region by a factor of 2.13 then multiplying by 0.02. This factor is obtained by dividing 13,396 lane-miles by 6,276 centerline miles for the non-Interstate system. Thus, the factor of 2.13 represents the average number of lanes per mile of road. This suggests that most of the non-Interstate system is composed of two lane routes (i.e., one lane in each direction of travel). On such routes, visual condition surveys are generally performed only in one direction (the assumption being that the condition on one side of the pavement is about the same as the other side). The resulting number of one mile samples is ((lane-miles ÷ 2.13) x 0.02):

Region	Sample Size
Northwest	23
North Central	22
Olympic	24
Southwest	13
South Central	17
Eastern	26
	total = 125

Thus, a total of 155 one mile sections would be required for the two percent sample. This sample size may seem a bit large but the underlying premise is obtaining a sample large enough to enable the visual distress survey comparison and provide sample statistics which can be compared to population statistics. Thus, the sample results can be checked after the first round of comparison ratings and the sample reduced (potentially) for future comparisons (yearly visual surveys).

It must be noted that all sample units must be randomly selected to achieve a standard error of about 4 PSC points. If this is not done, then a basic assumption is violated and the estimate of the standard error invalid. The bottom line is that the sample may not fairly represent the annual survey.

2.2 Precision Method

A method which uses probability considerations can also provide an indication of the required number of samples for visual condition sampling plan. The method is based on the fact that the precision of the data estimates (PSC in this case) improves as the number of samples increases.

The population mean for a given data type lies within an interval defined by the following probability statement:

$$P(\bar{x} - z_{1-\alpha/2}\, SE \leq \mu \leq \bar{x} + z_{1-\alpha/2}\, SE) = 1 - \alpha \qquad \text{(Eq. 2.2)}$$

where: $\bar{x}$ = sample mean,

$z_{1-\alpha/2}$ = standard normal variable at a specified level of significance,

SE = $S/\sqrt{n}$ = sample error of a randomly obtained number of samples,

S = standard deviation of the population,

μ = population mean, and

α = level of significance.

By use of Equation 2.2 we can specify with a 100 $(1 - \alpha)$ percent confidence level that the population mean will fall within an interval length of $\pm$ d which is equal to $\pm z_{1-\alpha/2}\, S/\sqrt{n}$. The interval length also represents the precision of the estimate (or the amount of deviation from the true value in actual units or percent allowed). By rearranging terms the required number of samples for a given confidence level is:

$$n = \left| \frac{z_{1-\alpha/2}\, S}{d} \right|^2 \qquad \text{(Eq. 2.3)}$$

To calculate the required number of samples by use of Equation 2.3, the population standard deviation must be known or estimated and the data precision and confidence level selected.

By use of data in Paragraph 2.1 and Equation 2.3 for the following input values:

S = PSC region-level population standard deviation

= 20,

z = 1.960 for a 95 percent confidence level, and

d = 10 PSC points,

then, $n = \left|\frac{(1.960)(20)}{(10)}\right|^2 = 15.4 \simeq 16$ one mile sample segments

If we could only "tolerate" d = 5 PSC points, then (all other inputs the same)

$$n = \left|\frac{(1.960)(20)}{(5)}\right|^2 = 61.5 \simeq 62 \text{ one mile sample segments}$$

Clearly, the selected level of d (in terms of PSC units) is critical in selecting a sample size as is the standard deviation (S). This is further illustrated in Table 2.3 which shows the required 95 percent confidence level sample size for various levels of S and d.

Using the results in Table 2.3, it appears that the separate approaches for estimating the regional sample sizes (simple random sample and precision method) are, more or less, in agreement. Further, a two percent sample results in a precision level of about 7.5 to 10 PSC points (based on a region standard deviation of 20).

Table 2.3. Sample Size Estimates by the Precision Method for a 95% Confidence Level

Standard Deviation of Region PSC ("S")	Sample Size (N) for Various Levels of Precision (PSC)[1]			
	d = 2.5	d = 5.0	d = 7.5	d = 10.0
S = 10 (low)	62	16	7	4
S = 20 (low-medium)	246	62	28	16
S = 30 (medium)	554	139	62	35
S = 40 (high)	984	246	110	62
S = 50 (very high)	1,537	385	171	96

Note 1. Sample sizes rounded up to nearest whole number.

3. DATA COMPARISONS FOR CHECK SURVEY RESULTS

3.1 Introduction

Once the sample is obtained, then the results should be compared to the results from the annual survey for the same pavement segments (i.e., match visual condition results at the same mileposts). Several kinds of comparisons can be made, one of the more obvious is to compare PSC values.

3.2 Paired t-Test

A reasonable statistical test of "paired" observations" (rating results from the 20 or so sample units and the "matching" information from the annual survey) can be made. These paired observations along with hypothesis testing using the t-statistic can be used. The mean differences of PSC (as one possible measure) will be tested. The proposed hypothesis (null hypothesis) is that there are no statistically significant differences for identical sections. The specific equations needed for paired t-tests are shown in Table 2.4. An example using paired observations is shown in Table 2.5.

The two-tail t-statistics for α levels of 1, 5, and 10 percent for various sample unit sizes are:

No. of Sample Units	t-statistic		
	$\alpha = 1\%$	$\alpha = 5\%$	$\alpha = 10\%$
2	63.657	12.706	6.314
⋮	⋮	⋮	⋮
5	4.604	2.776	2.132
⋮	⋮	⋮	⋮
10	3.250	2.262	1.833
⋮	⋮	⋮	⋮
15	2.977	2.145	1.761
⋮	⋮	⋮	⋮
20	2.861	2.093	1.729
⋮	⋮	⋮	⋮
30	2.756	2.045	1.699
⋮	⋮	⋮	⋮
∞	2.576	1.960	1.645

Table 2.4. Formulas Required for Paired Section Analysis (after Blank [4])

1. Statistical tests reported are "mean tests for paired sections"
2. Null hypothesis is $H_o: \delta = \delta_o$ $H_1: \delta \neq \delta_o$ Where: δ = mean difference between paired measurements $\delta_o = 0$ (<u>assumes</u> there is <u>no</u> difference between pairs in a population)
3. t - statistic $t = \dfrac{(\delta-\delta_o)}{\frac{s_d}{\sqrt{n}}} = \dfrac{(\overline{d}-0)}{\frac{s_d}{\sqrt{n}}}$ Where: $\overline{d} = \dfrac{\Sigma d_i}{n}$ $\Sigma d_i = \Sigma(X_{i1} - X_{i2})$ X_{i1} = PSC on Section i for annual survey X_{i2} = PSC on Section i for sample survey $s_d = \left(\dfrac{\Sigma d_i^2}{n-1} - \dfrac{n}{n-1}\overline{d}^2\right)^{1/2}$

Table 2.5. Illustrative Example of Comparison of Two Different Survey Methods

Assume the measured variable is PSC measured by the annual survey and PSC by the regional sample

Segment No.	Survey Method		d_i	d_i^2
	Annual	Sample		
1	100	90	10	100
2	100	85	15	225
3	60	40	20	400
4	50	40	10	100
5	70	50	20	400
6	35	30	5	25
7	80	65	15	225
8	40	20	20	400
9	50	30	20	400
10	60	50	10	100
11	80	80	0	0
12	50	55	-5	25
13	60	70	-10	100
14	70	75	-5	25
15	80	65	15	225
16	90	95	-5	25
17	95	95	0	0
18	85	80	5	25
19	65	40	25	625
20	80	50	30	900

$\Sigma d_i = 195$, $\overline{d} = 9.75$, $\Sigma d^2 = 4325$

$$s_d = \left(\frac{\Sigma d_i^2}{n-1} - \frac{n}{n-1}\,\overline{d}^{\,2}\right)^{1/2}$$

$$= \left(\frac{4325}{19} - \frac{20}{19}(9.75)^2\right)^{1/2} = 11.3$$

$$t_{\text{calculated}} = \frac{\overline{d} - 0}{\frac{s_d}{\sqrt{n}}} = \frac{9.75}{\frac{11.3}{\sqrt{20}}} = +3.859$$

$t_{\text{critical}*} = +2.093$

*$\alpha = 5\%$, $n = 20$ (obtained from any t-table contained in most statistical texts)

Thus, the conclusion is that there is a significant difference between the annual and sample surveys run on the same 20 segments (since $t_{\text{calculated}} > t_{\text{critical}}$).

Additional analysis must be done in order to check the β (Type II error). The basic errors in hypothesis testing for this condition are:

- Type I error (α): risk of rejecting a true null hypothesis (H_0) and thus concluding the annual and sample surveys are different when in fact they are not.
- Type II error (β): risk of accepting a false null hypothesis (H_0) and thus concluding the annual and sample surveys are the same when in fact they are not.

To check the potential for a Type II error, an operating characteristic curve was used for a two-sided t-statistic and $\alpha = 0.05$ (from p. 368, Blank [4]). The Type II error decreases as the difference between the means of the annual survey and sample survey increases. Below are listed the sample size, β and 1 - β (defined as the "power" of a test and is the probability of rejecting the null hypothesis (no difference between means) when it is false). The ΔPSC is the difference between the mean of the annual survey and the sample survey.

	β			1 - β		
ΔPSC	n = 20	n = 25	n = 30	n = 20	n = 25	n = 30
2.5	0.82	0.79	0.75	0.18	0.21	0.25
5.0	0.52	0.42	0.35	0.48	0.58	0.65
7.5	0.17	0.10	0.05	0.83	0.90	0.95
10.0	0.02	0.01	~0	0.98	0.99	~1.00

The larger the power the better. Thus, sample sizes of 20 have reasonable power in detecting mean differences in PSC of about 7.5 points or more. A sample size of 30 is almost adequate to detect differences in PSC of 5.0 points. It would take a sample size of greater than 100 to detect mean differences as small as 2.5 points ($\beta = 0.25$, $1 - \beta = 0.75$, $n = 100$) and a sample size of 75 to detect mean differences of 5.0 points ($\beta = 0.05$, $1 - \beta = 0.95$, $n = 75$).

The bottom line is that the paired t-test with the range of sample sizes planned for most of the regions should provide reasonable probabilities against rejecting a true hypothesis (no mean differences between the two surveys) and accepting a false hypothesis (the two surveys are different) for differences in PSC of about 7.5 or more points.

3.3 Nonparametric Statistic

The paired t-test discussion in the previous paragraph assumed the samples are to be taken from a normal distribution of PSC differences. If this is not the case, nonparametric ("distribution free") statistics can be used. Nonparametric tests assume that the sampled data are simply from a continuous variable.

A "two-sample signed rank test for means" will be used (referred to as the Wilcoxon test—refer to Blank [4], p. 456). The Wilcoxon is the nonparametric equivalent of the paired t-test. Tables 2.6, 2.7, and 2.8 are used to describe the Wilcoxon procedure and show an example problem (example uses same data as used in Table 2.5).

To further check this procedure, the "handmapped" and "automated" data for WSDOT Routes SR28 and SR283 (from Lee [5]) were used. The results are shown in Tables 2.9 and 2.10. Interestingly, the conclusions drawn by Lee are upheld in that the null hypothesis is accepted (no mean differences between the two surveys).

3.4 Predictive Comparison

Statistical hypothesis testing is a logical, systematic way of comparing survey data; however, the basis for such tests must not be overlooked in that "means" are being tested, not individual section comparisons. This limitation can be overcome somewhat by pooling all the regional data to examine a statewide view. Individual comparisons within a region are particularly difficult due to the high probabilities of Type II errors (risk of accepting a false hypothesis) which are likely to occur for the small sample sizes associated with Wilcoxon nonparametric tests (occurs due to the elimination of all ΔPSC = 0 values from the sample).

Table 2.6. Wilcoxon Paired Section Analysis (after Blank [4])

1. Null hypothesis is $H_o: \delta = \delta_o$ $H_1: \delta \neq \delta_o$ Where: δ = mean difference between paired measurements $\delta_o = 0$
2. T statistic T = smaller sum of absolute value of signed ranks of differences = $\min[D_1, D_2]$ If $T \leq T_0$, reject H_0 If $T > T_0$, accept H_0 where T_0 = table value of T
3. Procedure (a) Subtract paired samples to obtain differences $d_i = X_{i1} - X_{i2}$ and discard <u>all</u> $d_i = 0$ values and reduce n accordingly. (b) Arrange absolute values, $\vert d_i \vert$, in increasing order. (c) Assign ranks (1, 2, ..., n) to the ordered differences. "Ties" are given the <u>average</u> of the assigned ranks. (d) Compute the sums $D_1 = \Sigma d_i$ for all $d_i > 0$ $D_2 = \Sigma d_1$ for all $d_i < 0$ (e) Compute T test statistic $T = \min\,[D_1, D_2]$ (f) Refer to Table 2.7 for table T values

Table 2.7. Typical Two-Tail T Distribution Values (from Blank [4])

Sample Size (n)	α level = 0.05
6	0
7	2
8	4
9	6
10	8
11	11
12	14
13	17
14	21
15	25
16	30
17	35
18	40
19	46
20	52
21	59
22	66
23	73
24	81
25	89

Note: T values shown can be used for sample sizes up to 25. For larger sample sizes, use a standard normal distribution and

$$z = \frac{T - \mu_T}{\sigma_T}$$

where:

$$\mu_T = \frac{n\,(n + 1)}{4}$$

$$\sigma_T = \left[\frac{n\,(n + 1)(2n + 1)}{24}\right]^{1/2}$$

Table 2.8. Illustrative Example of Wilcoxon Hypothesis Test

1. Use the example data in Table 2.5 (recall eliminate all $d_i = 0$)

		Ranks		
d_i	$\lvert d_i \rvert$ ordered	Plus	Minus	
10	5	3		recall, all repeated ranks
15	5		3	given the <u>avg</u> rank, i.e.,
20	5		3	ranks 1, 2, 3, 4, 5 equal
10	5		3	15 and avg = 3
20	5	3		
5	10	7.5		
15	10	7.5		
20	10	7.5		
20	10		7.5	
10	15	11		
0	15	11		
-5	15	11		
-10	20	14.5		
-5	20	14.5		
15	20	14.5		
-5	20	14.5		
0	25	17		
5	30	18		
25				
30		154.5	16.5	

2. $n = 18$, $T_0 = 40$ for $\alpha = 0.05$ (Table 2.7)

3. $T = \min [150.5, 16.5]$

4. Since $(T = 16.5) < (T_0 = 40)$, conclude that H_0 is <u>false</u>, i.e., there is a significant difference between sample means.

Table 2.9. PCR Comparison Between Hand-Mapped and Automated Procedures— Wilcoxon Test — SR28 (data from Lee [5])

1. Data		Ranks	
d_i	$\lvert d_i \rvert$	Plus	Minus
-5	5		4
-5	5		4
5	5	4	
5	5	4	
5	5	4	
-5	5		4
-5	5		4
+15	15	8.5	
+15	15	8.5	
+20	20	10.5	
+20	20	10.5	
and 15 "0's" which were deleted		50.0	16

2.	$n = 11$, $T_0 = 11$ for $\alpha = 0.05$ (Table 2.7)
3.	$T = \min [50, 16]$
4.	Since $(T = 16) > (T_0 = 11)$, accept H_0.

Table 2.10. PCR Comparison Between Hand-Mapped and Automated Procedures—
Wilcoxon Test — SR283 (data from Lee [5])

1. Data		Ranks	
d_i	$\lvert d_i \rvert$	Plus	Minus
-10	10		2.5
+10	10	2.5	
+10	10	2.5	
+10	10	2.5	
+25	25	5.5	
+25	25	5.5	
-30	30		7.5
-30	30		7.5
-40	40		9
-45	45		10
and no "0's"		18.5	36.5

2. $n = 11$, $T_0 = 11$ for $\alpha = 0.05$ (Table 2.7)

3. T = min [50, 16]

4. Since $(T = 16) > (T_0 = 11)$, accept H_0.

Due to such difficulties, a third approach should be considered. The comparisons (annual survey PSC versus sample survey PSC) should include some estimate of the upper limit of ΔPSC based on regression equation prediction error.

To initiate this examination, the 1993 asphalt concrete Interstate performance model for North Central Region will be used (refer to Table 4.3, from Kay et al. [6]). This model is:

$$PSC = 100 - 0.166\,(AGE)^{2.25}$$

and at a PSC $\simeq$ 50, the AGE = 12.6 years. Using the model at five year intervals including the PSC $\cong$ 50 age:

Data Point	AGE	Predicted PSC
1	0	100.0
2	5	93.8
3	10	70.5
4	12.6	50.3
5	15	26.5

The basic performance equation has been modified for various levels of systematic error (PSC: +10, +20, -10, -20) with the exception that the PSC at Age = 0 remains at 100.

AGE	PSC	PSC +10	PSC -10	PSC +20	PSC -20
0	100.0	100.0	100.0	100.0	100.0
5	93.8	100.0	83.8	100.0	73.8
10	70.5	80.5	60.5	90.5	50.5
12.6	50.3	60.3	40.3	70.3	30.3
15	26.5	36.5	16.5	46.5	6.5

The resulting data were plotted as shown in Figure 2.1. From this plot, the Ages at which the performance curve intercepted a PSC =50 (current programming level) were obtained. These are:

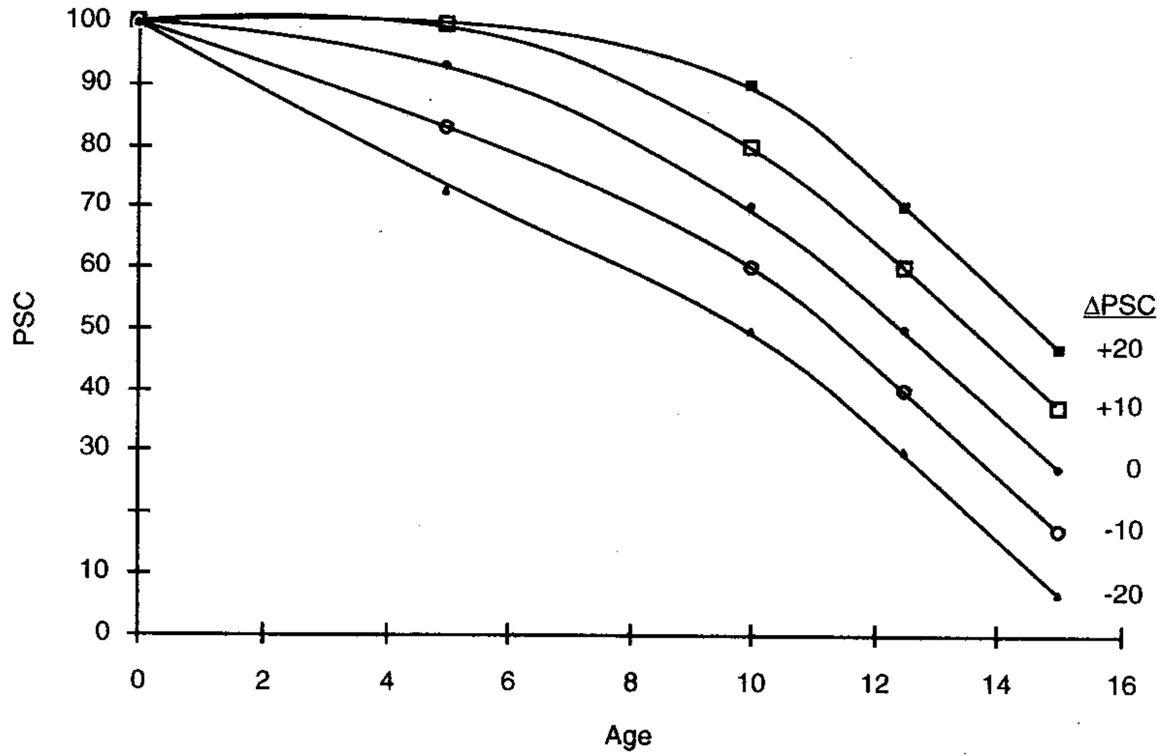

Figure 2.1. PSC vs. Age for Various Levels of Systematic Error

Performance Curve	Age @ PSC =50	Age Differences
PSC	12.6	0
PSC +10	13.7	1.1
PSC -10	11.4	1.2
PSC +20	14.7	2.1
PSC -20	10.0	2.6

Thus, a systematic error of ±10 PSC points would result in a project being programmed about one year earlier or later (possibly remaining in the same biennium). A systematic error of ±20 PSC points would change project programming by more than two years (the impact on the performance curve is greater for the negative PSC systematic error).

Based on the above, it appears that systematic rating errors which result in PSC differences greater than 10 points have an excessive impact on performance prediction. Naturally, other performance curves could result in different conclusions; however, the curve chosen is typical for a wide range of WSDOT performance conditions.

Random PSC rating errors can have various impacts on performance curves, none of which would be as severe as systematic errors of the same size.

4. FIELD VERIFICATION

During August 1993, a sampling scheme was used in North Central Region to obtain an "early look" at the annual survey. Twelve one-mile-long pavement segments were surveyed. These segments were not picked in a strict random manner but selected randomly along routes of travel being used to examine existing pavement construction projects (only segments with observable distress were selected). Therefore, routes such as SR17 and SR28 were sampled much more frequently than a strictly random selection process would provide; however, the goal was to do an early field check of the comparison process. The distress survey was conducted in accordance with the "Pavement Surface Condition Rating Manual" [7].

Table 2.11 is used to show the results from the 12 pavement segments: the specific distress types observed and associated PSC scores for both the annual and sample surveys. The distress survey categories were converted to extent via the "nomial" values published in Appendix E of WSDOT Research Report WA-RD 274.1 for both the annual and sample surveys. From Table 2.10, it is clear that the identification of similar distress types consistently matches (i.e., if longitudinal cracking was identified during the annual survey it was also identified during the sample survey). Naturally, there are a few exceptions. The major differences are between the distress severity levels and, to a lesser degree, distress extents. Overall, the calculated PSCs (annual and sample surveys) match well with an average difference of 4 PSC points (with the annual survey PSCs being the lower).

Tables 2.12 (paired t-test) and 2.13 (Wilcoxon hypothesis test) show the statistical tests of the North Central Region data. The calculations reveal no significant difference between segment means based on PSC scores.

Subsequent check sampling by WSDOT Materials Laboratory personnel done in 1994 and 1995 are summarized in Tables 2.14 through 2.17.

The results of the check survey for the 1994 annual condition survey included 27 samples. The route number, location (mileposts), and calculated PSCs are shown in Table 2.14 for each sample. The statistical hypothesis test for these data is shown in Table 2.15 (t-test for differences). The calculations are in accordance with the formulas shown originally in Table 2.4. The conclusion drawn is that the annual and sample surveys are significantly different; however, the mean PSC difference is about six points with the sample survey being lower (on average). The survey size was less than desirable (about 1/6 of that recommended) if the sample was intended to examine statewide trends.

As was noted in Paragraph 3.2, there are two hypotheses of interest (H_0 and H_1). Even though the limited size of the 1994 survey shows a significant difference between annual and sample survey PSCs, a mean PSC difference of six points is difficult to detect with a sample size of 27. This is illustrated by examining the β error (risk of accepting a false null hypothesis). At this sample size, there is a 42 percent chance that H_0 (the null hypothesis) is false. If one was willing to detect a larger Δ PSC (say 7.5 points as illustrated in Paragraph 3.2), then a sample size of 27 would result in a $\beta \approx 8$ percent - a much more acceptable number.

A fundamental question, casting most of the statistics aside for a moment, what Δ PSC can WSDOT live with? A way to view such a question was proposed in Paragraph 3.4. The conclusion drawn was that a systematic error of 10 PSC points or less seemed reasonable. Given this value, the 1994 survey data (mean Δ PSC = 6.1) is not unreasonable. However, the sample survey can point to inconsistencies for specific annual survey rating teams. Thus, the overall quality of the annual survey can continue to be improved. It should be kept in mind that hypothesis tests of comparisons only declare a yes or no answer — "OK or not OK". What WSDOT seeks is consistent, reliable annual surveys. If typically each year such comparisons are done and significant differences are found (i.e. accept H_1), either on a statewide basis or for a specific region, this suggests a much more fundamental problem with the rating teams (composition, training, etc.).

The check survey performed for the 1995 annual survey was twice as large as the 1994 check (n = 52 versus 27). The sample data is shown in Table 2.16 and statistical hypothesis calculations in Table 2.17. The conclusion drawn is that there were no significant differences in the annual and sample survey PSCs for the 1995 data. In fact, the mean difference was only about one PSC point.

5. ASSESSMENT

The ability of the paired t-test to detect differences (or lack of) between the annual and sample surveys with reasonable probabilities (Paragraph 3.2) is similar to the tolerance in prediction error (about 10 PSC points) described in Paragraph 3.4 ("Predicted Comparison"). The 1993, 1994, and 1995 field verifications further suggest the sample size and associated comparison methodologies are reasonable for evaluating the annual distress survey.

The research report WA-RD 315.1 provides further insight to the statistical procedures used in this section.

Table 2.11. North Central Region Distress Survey Sample

Route No.	Annual Survey MP	Sample Survey MP	Allig. Cr.		Long Cr.		Trans. Cr		Patch		Annual PSC	Sample PSC
			Annual	Sample	Annual	Sample	Annual	Sample	Annual	Sample		
SR17	54.00-59.10	55.0-55.5			30% M	30% L	2 M	7 L			76	78
SR17	60.00-61.00	60.0-61.0			30% M	30% L	2 M	2 L			76	86
SR17	64.00-66.00	65.0-66.0			30% L	30% L	2 M	7 L			82	78
SR17	67.00-69.00	68.0-69.0			30% L	30% L	2 L	2 L			86	86
SR282	4.00-4.92	4.0-5.0	5% L	30% L	30% M	30% L	7 M	2 L			61	42
SR28	34.00-35.00	34.0-35.0			30% L		2 M	2 M			82	86
SR28	41.00-42.00	41.0-42.0	5% L	15% L	30% M	30% L	2 M	2 L	15% M		48	62
SR28	18.00-19.10	18.0-19.0	5% L	5% L	30% M	30% L	2 M	2 L			71	78
SR28	14.00-15.00	14.0-15.0	15% L	5% L	30% M	30% L	2 L	2 L			59	78
SR2	179.0-182.0	181.0-182.0			30% L		2 M	2 M			82	86
SR2	185.0-186.0	185.0-186.0	5% L	5% L	30% L	30% L	2 M	7 M	15% L	5% M	62	58
SR17	137.0-138.0	137.0-138.0	5% L		30% M	30% M	7 M	2 M			61	76

Table 2.12. North Central Region Distress Survey Sample — Paired Section Analysis

Segment No.	Survey Method		d_i	d_i^2
	Annual PSC	Sample PSC		
1	76	78	-2	4
2	76	86	-10	100
3	82	78	+4	16
4	86	86	0	0
5	61	42	+19	361
6	82	86	-4	16
7	48	62	-14	196
8	71	78	-7	49
9	59	78	-19	361
10	82	86	-4	16
11	62	58	+4	16
12	61	76	-15	225

$\Sigma d_i = -48$ $\quad \Sigma d^2 = 1{,}360$

$\overline{d} = -4.0$

$$s_d = \left(\frac{1{,}360}{11} - \frac{12}{11}(-4.0)^2\right)^{1/2} = 10.3$$

$$t_{\text{calculated}} = \frac{-4.0 - 0}{\dfrac{10.3}{\sqrt{12}}} = -1.3$$

$$t_{\text{critical}} \simeq -2.2$$

Thus, conclude there is no significant difference between the annual and sample surveys.

Table 2.13. Distress 2 Distress Survey Sample—Wilcoxon Hypothesis Test

1. Use the data from North Central Region shown in Table 2.11.

d_i	$\lvert d_i \rvert$ ordered	Ranks Plus	Ranks Minus	
-2	2		1	
-10	4	3.5		
+4	4		3.5	2, 3, 4, 5 = 14,
0	4		3.5	and avg = $\frac{14}{4}$ = 3.5
19	4	3.5		
-4	7		6	
-14	10		7	
-7				
-19	14		8	
-4	15		9	
+4	19	10		
-15	19		11	
		17	49	

2. $n = 11$, $T_0 = 11$ for $\alpha = 0.05$ (Table 2.7)

3. $T = \min [17,49]$

4. Since $(T = 17) > (T_0 = 11)$, conclude that H_0 is true, i.e., there is <u>no</u> significant difference between sample means.

Table 2.14 Comparison of Annual and Sample Survey PSCs - 1994 Data

Route No.	Mileposts	Annual PSC	Sample Survey PSC	d_i	d_i^2
20	16.98-17.98	67	79	-12	144
20	72.95-73.95	86	88	-2	4
20	66.95-67.95	88	88	0	0
20	57.94-58.94	71	28	43	1,849
20	48.81-49.81	100	56	44	1,936
20	79.95-80.95	100	100	0	0
20	28.96-29.96	71	79	-8	64
20	95.82-96.82	80	88	-8	64
11	1.00-2.00	88	88	0	0
9	90.91-91.91	88	78	10	100
9	76.92-77.92	63	63	0	0
9	69.92-70.92	63	63	0	0
9	60.96-61.96	68	41	27	729
9	49.97-50.97	50	64	-14	196
9	40.00-41.00	53	53	0	0
20	33.94-34.94	82	88	-6	36
530	21.82-22.82	32	22	10	100
546	3.00-4.00	100	100	0	0
544	7.67-8.63	69	51	18	324
542	11.00-12.00	100	100	0	0
539	13.00-14.00	100	100	0	0
539	9.25-10.25	100	100	0	0
539	3.00-4.00	100	88	12	144
530	39.82-40.82	53	27	26	676
530	11.82-12.82	61	53	8	64
525	24.24-25.24	63	69	-6	36
525	11.22-12.22	87	63	24	576

		$\bar{x}$ = 77.1	71.0	Σd_i = 166	Σd_i^2 = 7,042
		s = 19.0	23.8		

n = 27

$$\bar{d} = \frac{166}{27} = 6.1$$

Table 2.15 Comparison of Annual and Sample Survey PSCs — 1994 Data

1. Two -sided t-test for differences (Blank, p. 385)

   H_0: $\bar{d} = 0$
   H_1: $\bar{d} \neq 0$

2. d_i = individual differences between annual and sample PSCs.

3. Calculations (formulas from Blank, p. 384 and input from Table 2.14)

$$s_d = \left(\frac{\Sigma d_i^2}{n-1} - \frac{n}{n-1}\,\bar{d}^{\,2}\right)^{1/2}$$

$$= \left(\frac{7042}{26} - \frac{27}{26}\,(6.1)^2\right)^{1/2} = 15.2$$

$$t_{calculated} = \frac{\bar{d} - 0}{s_d/\sqrt{n}} = \frac{6.1}{15.2/\sqrt{27}} = +2.085$$

4. t critical

   t critical = +2.056
   (two-tail t, $\alpha = 5\%$, $\nu = n-1 = 26$)

5. Conclusion

   Conclude annual and sample survey PSCs are different at $\alpha = 5\%$ (risk of rejecting a true H_0).

6. Risk of accepting a false H_0 with a sample size (n) = 27, i.e., estimate the β error. From Blank, p. 384, use an operating characteristic curve for a two-sided t-test with $\alpha = 0.05$. The input into the OCC is:

$$d = \frac{|\bar{d} - 0|}{s_d} = \frac{6.1}{15.2} = 0.4.$$

The corresponding β errors are:

Sample size (n)	β
27 (actual)	0.42
30	0.36
40	0.25
50	0.17
75	0.07
100	0.02

Table 2.15 Comparison of Annual and Sample Survey PSCs — 1994 Data (Continued)

Thus, the ability to protect against a false hypothesis is marginal with n = 27 and $\bar{d}$ = 6.1 (from sample). Sample sizes substantially larger are required to balance the α and β risks. Smaller n's are acceptable if larger $\bar{d}$'s are tolerable. For example, if $\bar{d}$ = 10 is tolerable (using s_d = 15.2 from original sample), then

Sample size (n)	β
27 (actual)	0.12
30	0.08
40	0.04
50	0.01

Thus, a sample size between 30 and 40 results in a β which matches the selected α. It must be noted that matching the α and β errors is not a necessary requirement.

Table 2.16 Comparison of Annual and Sample Survey PSCs — 1995 Data

Route No.	Mileposts	Annual PSC	Sample Survey PSC	d_i	d_i^2
261	53.00-54.00	76	82	-6	36
17	8.51-9.51	100	100	0	0
17	124.38-125.38	88	88	0	0
12	154.54-155.64	50	69	-19	361
12	133.71-134.71	100	100	0	0
12	110.71-111.71	100	100	0	0
12	89.71-90.71	100	100	0	0
12	69.70-70.70	86	88	-2	4
241	23.00-24.00	55	55	0	0
243	11.00-12.00	49	62	-13	169
97	17.17-18.17	100	82	18	324
261	38.00-39.00	76	78	-2	4
17	40.51-41.51	49	8	41	1,681
395	49.76-50.27	86	86	0	0
971	1.00-2.00	33	52	-19	361
5	84.07-85.07	88	88	0	0
5	74.07-75.07	88	64	24	576
2	131.02-132.03	82	88	-6	36
2	124.03-125.03	100	88	12	144
2	79.95-80.95	100	88	12	144
2	50.95-51.95	36	88	-52	2,704
2	32.95-33.95	32	88	-56	3,136
2	20.95-21.95	100	100	0	0
2	7.00-8.00	52	37	15	225
2	5.00-6.00	53	37	16	256
243	19.97-20.97	49	49	0	0
971	11.00-12.00	52	69	-17	289
97	236.16-237.16	70	70	0	0
97	209.16-210.16	100	100	0	0
97	199.16-200.16	100	100	0	0
90	128.19-129.16	49	37	12	144
90	116.29-117.29	54	54	0	0
26	69.00-70.00	76	78	-2	4
26	59.00-60.00	65	86	-21	441
26	45.00-46.00	58	62	-4	16
24	31.95-32.95	73	70	3	9
12	178.62-179.62	86	74	12	144
21	20.00-21.00	67	68	-1	1
17	51.49-52.49	76	78	-2	4

Table 2.16 Comparison of Annual and Sample Survey PSCs — 1995 Data (Continued)

Route No.	Mileposts	Annual PSC	Sample Survey PSC	d_i	d_i^2
395	73.56-74.56	78	78	0	0
2	3.00-4.00	62	58	4	16
395	84.56-85.56	78	75	3	9
395	90.56-91.56	82	82	0	0
97	30.17-31.17	86	88	-2	4
97	36.31-37.31	74	78	-4	16
150	9.70-10.70	74	88	-14	196
395	50.27-50.76	92	100	-8	64
173	7.00-8.00	100	88	12	144
21	10.00-11.00	92	100	-8	64
17	97.38-98.38	100	88	12	144
17	78.49-79.49	73	72	1	1
22	10.32-11.32	65	62	3	9
		$\bar{x} = 75.2$	76.3	$\Sigma d_i = -58$	$\Sigma d_i^2 = 11,880$
		$s = 20.2$	19.8		

$n = 52$

$\bar{d} = \frac{-58}{52} = -1.1$

Table 2.17 Comparison of Annual Sample Survey PSCs - 1995 Data

1. Two-sided t-test for differences (Blank, p. 385)

   H_0: $\bar{d} = 0$

   H_1: $\bar{d} \neq 0$

2. Calculations (formulas from Blank, p. 384) and input from Table 2.16

$$s_d = \left(\frac{\Sigma d_i^2}{n-1} - \frac{n}{n-1}\,\bar{d}^2\right)^{1/2}$$

$$= \left(\frac{11{,}880}{51} - \frac{52}{51}(-1.1)^2\right)^{1/2} = 15.2$$

$$t_{calculated} = \frac{\bar{d} - 0}{s_d/\sqrt{n}} = \frac{-1.1}{15.2/\sqrt{52}} = -0.52$$

3. t critical

   t critical $\cong -2.01$
   (two-tail, $\alpha = 5\%$, $\nu = n-1 = 51$)

4. Conclusion

   Conclude annual and survey PSCs are not significantly different at $\alpha = 5\%$ (risk of rejecting a true H_0).

SECTION 3

VEHICLE OPERATING COSTS RELATED TO PAVEMENT CONDITION AND IMPLICATIONS FOR LIFE CYCLE COSTING

1. INTRODUCTION

There is a need to relate various levels of pavement deterioration to vehicle operating costs to assist in the development of pavement investment policies. To do this, the following items/activities are required:

- develop relationship between total vehicle operating costs (VOC) and pavement deterioration
    - develop VOC as a function of IRI
    - relate IRI to PSI and Pavement Structural Condition (PCS)
- apply VOC increases to state highway system vehicle miles of travel
- illustrate the impact of VOC on optimization of project life cycle costs.

The items/activities will be developed in the subsequent paragraphs.

2. RELATIONSHIPS BETWEEN VOC AND PAVEMENT CONDITION

A primary source of information which can be used to relate VOC and pavement condition was the major study performed in Brazil approximately 20 years ago. Data collected in Brazil and reported by the World Bank were used in developing approximate factors to relate VOC and IRI (refer to Table 3.1). The factors shown are percentage increase in total vehicle operating costs as a function of IRI. These costs include

- fuel and lubricants
- maintenance (parts and labor)]
- crew (time)
- depreciation and interest.

Being as the two sets of values shown in Table 3.1 are similar but different, the following are a reasonable combination:

- auto: 6%/IRI
- light trucks: 6%/IRI
- bus: 3%/IRI
- heavy trucks: 6%/IRI

Table 3.1. Vehicle Operating Costs as a Function of Road Roughness (IRI)

Reference	Percentage Increase in Vehicle Operating Costs as a Function of IRI[1]	
Watanatada, Dhareshwar, Lima [8]	Utility:	5.5%/IRI
	Bus:	2.9%/IRI
	Heavy Truck:	5.9%/IRI
	(Source data p. 395)	
Chesher and Harrison [9]	Car:	7.2%/IRI
	Bus:	3.9%/IRI
	Medium Truck:	8.0%/IRI
	Artic Truck:	7.2%/IRI
	(Source data, p. 329)	

Note:

1. Percentage increases of VOC as a function of IRI calculated from source data contained in References 8 and 9.

Table 3.2. Tire Expense Adjustment Factors vs. Present Serviceability Index (from Zaniewski et al. [10])

PSI	Passenger Cars and Pickup Trucks[2]	Single Unit Trucks and Single Trailer Trucks (2-S2, 3-S2)[2]
4.5	0.76	0.92
4.0	0.86	0.95
3.5[1]	1.00	1.00
3.0	1.16	1.07
2.5	1.37	1.16
2.0	1.64	1.27
1.5	1.97	1.44
1.0	2.40	1.67

[1] PSI = 3.5 assumed as a baseline condition; therefore Adjustment Factor = 1.0

[2] Data from Brazil used to determine proportional changes to various PSI levels.

Naturally, numerous other studies preceded the Brazil/World Bank effort. One of the more recent studies (1982) was performed by Zaniewski et al. [10] for the FHWA. Some of the results from this study follow. Extensive use of the Brazil study data was made.

Zaniewski et al. [10], for example, produced various cost factors for various VOC components. Their adjustment factors as a function of PSI for tire costs are shown in Table 3.2 and maintenance and repair costs in Table 3.3. These adjustment factors illustrate the magnitude of VOC change with pavement condition.

To convert PSI (as used by Zaniewski) to IRI, two relationships were examined with both being shown in Table 3.4. Based on WSDOT experience, the Paterson relationship appears more applicable. It should be noted that the PSI versus IRI relationship primarily supported by the FHWA [17] was developed by Al-Omari and Darter [12] and is:

$$PSR = (5)\left(e^{-0.26(IRI)}\right)$$

where IRI is in units of mm/m.

Table 3.5 shows the <u>total</u> vehicle operating costs for various vehicle classes as a function of PSI as developed by Zaniewski [10]. If the percent differences are calculated for a modest range in PSI (4.0 to 3.0), the following percent increases result:

- Passenger car(medium size) = 7.8%
- Pickup = 8.4%
- Single unit truck—2 axles = 4.9%
- Single unit truck—3 axles = 6.3%
- Single trailer truck (2-S2) = 8.2%
- Single trailer truck (3-S2) = 8.2%

If the above values are made a function of IRI (PSI = 4.0, IRI = 1.2; PSI = 3.0, IRI = 2.8), the following percentages result:

Table 3.3. Maintenance and Repair Expense Adjustment Factors vs. Present Serviceability Index (from Zaniewski et al. [10][2, 3]

Present Serviceability Index	Passenger Cars and Pickup Trucks	Single Unit Trucks	Single Trailer Trucks (2-S2, 3-S2)
4.5	0.83	0.90	0.86
4.0	0.90	0.94	0.92
3.5[1]	1.00	1.00	1.00
3.0	1.15	1.07	1.11
2.5	1.37	1.17	1.27
2.0	1.71	1.30	1.50
1.5	1.98	1.48	1.82
1.0	2.30	1.73	2.35

[1] PSI = 3.5 assumed as a baseline condition; therefore Adjustment Factor = 1.0

[2] Data from Brazil used to determine proportional changes to various PSI levels.

[3] Includes cost components for

- power train
- engine
- body
- chassis
- electrical
- brakes

Table 3.4. Conversion of PSI to IRI

PSI	IRI[1]	IRI[2]
4.5	0.6	0.4
4.0	1.2	0.9
3.5[1]	2.0	1.4
3.0	2.8	2.0
2.5	3.9	2.7
2.0	5.1	3.5
1.5	6.7	4.6
1.0	8.9	6.2

[1] Paterson [11] correlation: $IRI = \ln\left(\frac{PSI}{5}\right) / -0.18$

[2] Al-Omari et al. [12] correlation: $IRI = \ln\left(\frac{PSI}{5}\right) / -0.26$

Table 3.5. Total Vehicle Operating Costs for Various Vehicle Classes vs. Present Serviceability Index (after Zaniewski et al. [10])

PSI	Total Costs per 1000 mi ($/1000 mi)					
	Passenger Car (medium size)	Pickup	Single Unit Truck— 2 Axles	Single Unit Truck— 3 Axles	Single Trailer Truck (2-S2)	Single Trailer Truck (3-S2)
4.5	126	127	261	372	308	357
4.0	129	131	264	379	316	366
3.5	133	135	270	390	327	379
3.0	139	142	277	403	342	396
2.5	147	152	288	422	364	420
2.0	160	167	301	445	393	452
1.5	171	180	319	477	435	499
1.0	184	195	344	520	501	573

Assumptions

- Percent grade = 0%
- Constant speed = 55 mph (89 kph)
- Total costs include
  - Fuel consumption
  - Oil consumption
  - Tire wear
  - Vehicle maintenance and repair
  - Use-related depreciation

- Passenger car (medium size) = 4.9%
- Pickup = 5.2%
- Single unit truck—2 axles = 3.1%
- Single unit truck—3 axles = 3.9%
- Single trailer truck (2-S2) = 5.1%
- Single trailer truck (3-S2) = 5.1%

Finally, a relationship developed in Sweden for the Swedish National Road Administration was made available by Lenngren [14]. The model and a range of results are shown in Table 3.6. The results are in terms of Swedish krona (SEK) per kilometer of road. Apparently, the results cannot directly be compared to the prior studies summarized. However, the cost increases appear to be substantial. Lenngren reports that this relationship was developed at the Swedish Traffic and Road Safety Institute by Strandberg et al.

A reasonable composite model based on the studies summarized is:

Vehicle Types	Percent Increase in VOC per IRI
• Passenger car/ pickup	5.5%/IRI
• Single unit trucks/buses	3.0%/IRI
• Single trailer trucks	5.5%/IRI

Table 3.6. Swedish Vehicle Cost Model Results for a Range of ADT and Percent Trucks (after Lenngren [14]

Average Daily Traffic[1]	Percent Trucks	SEK/km	
		IRI = 1.0	IRI = 2.8
1000	5%	0.19	106
	20%	0.16	138
10,000	5%	1.9	1059
	20%	1.6	1383
100,000	5%	19	16
	20%	10,588	13,833

Notes:

1. Model

$$\text{Vehicle cost (SEK/km)} = \text{ADT}\,[(\text{IRI}^2)\,(0.001)\,(1 - \text{T}) + (\text{IRI})\,(0.0489) + 0.1241\,(\text{T})) - (0.0497 + 0.1233\,(\text{T}))]$$

where ADT = average daily traffic

T = proportion of trucks

IRI = International Roughness Index (mm/m)

2. Vehicle cost = 0 for IRI ≤ 1.0

3. Example assumes all lanes equally rough

3. RELATIONSHIP BETWEEN IRI AND PSC

If WSDOT chooses to estimate the change in VOC as a function of PSC, a correlation between IRI and PSC was required. To do this, a review of PSC and IRI data in the WSPMS was used to develop the approximate relationships shown in Table 3.7. It is recognized that for many pavement sections, a strong association between pavement distress (as used to calculate PSC) and IRI does not exist.

As a further check of the IRI-PSC relationship, the Paterson [11] PSI-IRI correlation was used to calculate PSI values from IRIs. The following results:

IRI	PSI*	PSC**
1.0	4.2	100
2.0	3.5	75
3.0	2.9	50
4.0	2.4	25
5.0	2.0	0

*Calculated from $PSI = 5e^{(-0.18(IRI))}$

**Calculated from $PSC = 100 - 25\ (IRI - 1.0)$

At this point, WSDOT likely has a better "feel" how pavement condition (PSC) is related to PSI (as opposed to IRI). The above results appear reasonable.

The data in Table 3.8 tend to suggest that the WSDOT route system has maximum IRI values of about 4.0 (Interstate) and 5.0 on other highway functional classes. Thus, the IRI values at very low PSC levels (PSC range of 0 to 25) are in the "ball park." It must be noted that three of the four routes shown in Table 3.8 represent somewhat atypical conditions. In examining various WSDOT routes, it became apparent rather quickly that the highest IRI values occur at bridge approaches/decks.

Table 3.7. Approximate Relationship Between PSC and IRI

Pavement Surface Type[1]	PSC vs. IRI[2]	
	PSC	IRI
ACP/PCCP[3]	100 75 50 25 0	1.0 2.0 3.0 4.0 5.0
BST[4]	100 75 50 25 0	1.5 2.5 3.5 4.5 5.5

Notes:

1. Pavement surface type is used to recognize that there is a modest difference in pavement roughness (as measured by IRI) depending on whether the surface is ACP/PCCP or BST.

2. Source for data: 1993 WSPMS

3. Equation for ACP/PCCP $PSC = 100 - 25\ (IRI - 1.0)$

   or $IRI = \frac{125 - PSC}{25}$

4. Equation for BST $PSC = 100 - 25\ (IRI - 1.5)$

   or $IRI = (137.5 - PSC)/25$

Table 3.8. Maximum IRI Values on a Selection of WSDOT Routes

Route	Mileposts	Pavement Surface Type	IRI and Associated PSC
I5[1]	253.52 - 253.63	PCC	4.27/54
I90[1]	55.16 - 55.49	PCC	3.99/69
SR20	288.62 - 288.73	BST	4.92/27
SR21[2]	166.90 - 166.99	BST	4.48/100

Notes:

1. Mileposts shown for I5 and I90 located between bridges, which is an extreme condition.
2. SR21 location is in the vicinity of Danville, Washington, and the Canadian border—again, likely atypical for the WSDOT route system.

Table 3.9. Percentage of Vehicle Miles Traveled by Functional Class

System	Functional Class			
	Principal Arterial	Minor Arterial	Collector	Interstate
Rural	13%	10%	3%	15%
Urban	22%	4%	1%	32%

Ref. WSDOT, "1989 Washington State Highway Accident Report," Transportation Data Office; Planning, Research, and Public Transportation Division, Washington State Department of Transportation, Olympia, Washington, 1989.

4. CHANGES IN VOC

In order to estimate how VOC could change with changed IRI or PSC on a statewide basis, an estimate of vehicle-miles by vehicle class is required. To do this, the following information was obtained:

- Total statewide vehicle-miles in 1995
  (from WSDOT [15]) ≅ 52,000,000,000 vehicle-miles

- Vehicle-miles which can be attributed to

  - Passenger cars/pickups: 71.6%
  - Single unit trucks/buses: 24.0%
  - Single trailer trucks: 4.4%

  based on percentages of vehicle-miles developed from USDOT national data [16]

Further, cost data from each of the three basic vehicle types were obtained from Table 3.5 and updated for inflation since 1982. Using a PSI of 4.0 as a datum, the following costs per mile were estimated (multiplier of 1.7 based on CPI data from USDOT [16]):

- Passenger cars and pickups
  $0.13/mile x 1.7 = $0.22/mi

- Single unit trucks and buses
  $0.32/mi x 1.7 = $0.55/mi

- Single trailer trucks
  $0.34/mi x 1.7 = $0.58/mi

Given the preceding, various examples can be developed to show how VOC can change based on pavement condition changes.

4.1 VOC and IRI Example

For example, if the current average IRI for the WSDOT Interstate System is 1.2 (PSI = 4.0) and this is allowed to deteriorate to 2.0 (PSI = 3.5), what total VOC increases might be expected? Using data from Table 3.9, the total vehicle miles of travel on the Interstate is 47 percent of the state total. Thus, the following calculations result:

- Interstate vehicle-miles (annual)

  52,000,000,000 (0.47) ≅ 24,000,000,000 vehicle-miles

- VOC increases

  - passenger cars and pickups

    (veh-mi) (% of veh-mi) (ΔIRI) (VOC % incr.) ($/mi)
    (24,000,000,000) (0.716) (2.0 - 1.2) (0.055) ($0.22/mi)
    ≅ $166,000,000 (about 1 cent/veh-mi)

  - single unit trucks and buses

    (24,000,000,000) (0.24) (2.0 - 1.2) (0.03) ($0.55/mi)
    ≅ $76,000,000 (about 1.3 cents/veh-mi)

  - single trailer trucks

    (24,000,000,000) (0.044) (2.0 - 1.2) (0.055) ($0.58/mi)
    ≅ $27,000,000 (about 2.6 cents/veh-mi)

  - total increase in VOC

    $269,000,000
    (annual costs as long as assumed conditions exist)

4.2 VOC and PSC Example

If the overall PSC of the WSDOT rural collector route system is allowed to deteriorate from 70 to 65, what increase in VOC can be expected?

- IRI (before) $= \frac{137.5 - PSC}{25}$ (assume BST surfaces—formula from Table 3.7)

  $= \frac{137.5 - 70}{25} = 2.7$

- IRI (after) $= \frac{137.5 - 65}{25} = 2.9$

- VOC increases

  - passenger cars and pickups

    (52,000,000,000) (0.03) (0.716) (2.9 - 2.7) (0.055) ($0.22/mi)
    ≅ $2,700,000 (about 0.2 cent/veh-mi)

- single unit trucks and buses

  (52,000,000,000) (0.03) 0.24) (2.9 - 2.7) (0.03) ($0.55/mi)
  $\cong$ $1,200,000 (about 0.3 cent/veh-mi)

- single trailer trucks

  (52,000,000,000) (0.03) (0.044) (2.9 - 2.7) (0.055) ($0.58/mi)
  $\cong$ $440,000 (about 0.6 cent/veh-mi)

- total increase in VOC

  $4,340,000
  (annual costs as long as assumed conditions exist)

How long would such a decrease take (that is, PSC decreasing from 70 to 65)? If we use a statewide BST default curve of PSC = 100 - 0.809 $(\text{Age})^{2.00}$ (1993 WSPMS) and rewrite as a function of Age,

$$\text{Age} = \left(\frac{100 - \text{PSC}}{0.809}\right)^{0.5}, \text{ then if PSC} = 70$$

$$\text{Age} = \left(\frac{100 - 70}{0.809}\right)^{0.5} = 6.1 \text{ years}$$

$$\text{PSC} = 65, \text{ Age} = \left(\frac{100 - 65}{0.809}\right)^{0.5} = 6.6 \text{ years}$$

The decrease of ΔPSC = 5 points could occur in about six months systemwide if <u>no</u> preservation funds were available (undoubtedly a worst case condition).

Clearly, any number of such examples with various funding levels could be developed.

5. VOC IMPLICATIONS FOR PROJECT LIFE CYCLE COSTS

Given the relationship developed for VOC as a function of pavement condition, it is appropriate to see how life cycle costs vary with frequency of rehabilitation. The need for such an examination was suggested in Volume IV of the Cambridge Systematics January 1992 report to the Legislative Transportation Committee.

The details of the analysis to estimate the optimum timing of rehabilitation are contained in Appendix B. For the assumed conditions (Interstate ACP in the Olympic Region), and using project specific costs (construction and user delay costs) as well as annual VOCs, the minimum life cycle costs occurred 10 to 14 years after rehabilitation. This corresponds to a PSC ranging between 70 to 40. This analysis supports the currently used WSDOT required priority array criterion which uses a project due date at a PSC of 50. Presumably, other assumed conditions could lead to slightly different conclusions.

6. SUMMARY

Clearly, VOC and changes to them constitute a major transportation expense. Using the three vehicle groupings developed earlier in this section, about $16.4 billion is spent annually on passenger car, bus, and truck transport. Further, this estimate excludes expenses such as insurance. If insurance and related costs are included, this number would be about twice as large.

Based on the methodology contained in this section and the different estimated level of vehicle-miles, the following VOC increases can be expected:

- For every 0.1 increase in IRI statewide, the VOC increases about $73,000,000. This amounts to an increase of about 0.1¢ per mile for every vehicle-mile traveled.
- For every 1 point decrease in PSC statewide (ACP/PCCP model), the VOC increases about $29,000,000.

The increases in VOC costs as a function of pavement condition are largely based on data from a major study conducted in Brazil 20 years ago. Do results from Brazil apply to Washington State? The range of conditions measured in Brazil were large and data were collected within a designed experiment. Because of such controls, such results, at least in part, are reasonable for Washington State.

A further condition is noted. The percentage increases used herein were developed for nominal ranges of IRI (hence PSC) — not extremes. If more severe pavement conditions are to be examined, then the percentages need reexamination. Such an examination can be done with the information contained in this section.

The nation's highway system is supported by taxes and fees which amount to about 5.0 cents per vehicle-mile of travel (based on USDOT [16] source data—current as of 1992). This amounts to about 10 percent of the vehicle operating costs. A change in IRI of 1.0 (e.g., IRI (initial) = 1.5 to IRI (final) = 2.5) based on Washington State conditions, would increase VOC by about 1 cent per vehicle-mile traveled. This is equivalent to 20 percent of taxes and fees which support the route system.

Use of the VOCs along with project specific assumptions support WSDOT's criterion of using a PSC of 50 to program projects.

The VOCs which can be calculated using the information contained in this section are approximate. The basis of the VOCs shown are not based on cost data obtained within the state of Washington. Current efforts under way internationally and by the National Cooperative Highway Research Program will add to our understanding of these important costs in the near future.

SECTION 4

PAVEMENT PERFORMANCE MODELS

1. INTRODUCTION

This section will be used to describe options for modeling the performance of pavements in the WSPMS. The focus will be on a general model for PSC versus age, PRC (rutting) versus age, and development of default equations.

2. GENERAL PSC PERFORMANCE MODEL

The current general model used by WSDOT for PSC versus age relationships is (Kay et al. [6]):

$$PSC = C - mA^P \qquad \text{(Eq. 4.1)}$$

where PSC = Pavement Structural Condition rating,

A = Age which represents the time since construction or the last resurfacing (years),

C = model constant for maximum rating (~ 100),

m = regression slope coefficient, and

P = "selected" exponent that controls the degree of curvature of the performance curve.

This model ("power model") has worked reasonably well in the WSPMS for about 15 years; however, not without some difficulty.

As noted by Kay et al. [6], use of this model to produce acceptable performance equations can be difficult. Reasons for such difficulties can include

- limited number of PSC versus Age points to regress against for a relatively new surface course, and
- random fluctuation of condition ratings which results in a poor fit of the data.

Further, for pavements allowed to be in poor condition (low PSCs), the power model always predicts a PSC = 0 at some age. This is a bit unrealistic in that the actual PSC is rarely allowed to reach zero.

There is no question concerning the desirability of retaining individual project level performance models. This fundamental approach has proven itself over many years. By definition, this leads to some type of regression model.

Of the various regression models examined (power, polynomial, nontransformed, etc.), a promising approach evolved. The model is called a "logistic response function" or "logit" model. Generally, this type of model is used with a binary dependent variable (0 or 1 data) with repeat observations at each level of the independent variable. Appendix A documents the model including simplifying assumptions and examples.

Basically, the logit model when applied to PSC versus Age data takes the following form:

$$PSC = 100\left[\frac{e^{(b_o - b_1 (Age))}}{1 + e^{(b_o - b_1 (Age))}}\right]$$

This results in an "S-shaped" curve.

To use the above model, the dependent variable (PSC) must be transformed by the following:

$$y' = \log_e\left(\frac{PSC}{100 - PSC}\right)$$

where y' = transformed dependent variable, and

PSC = Pavement Structural Condition with the restriction that it be ≤ 99 (a PSC = 100 in the transformation will result in division by zero).

The logit model takes the form shown in Figure 4.1. To develop the equation, data from Example 2, Paragraph 2.2, Appendix A, was used. The following equation was used to generate the fit shown (refer to Appendix A for details):

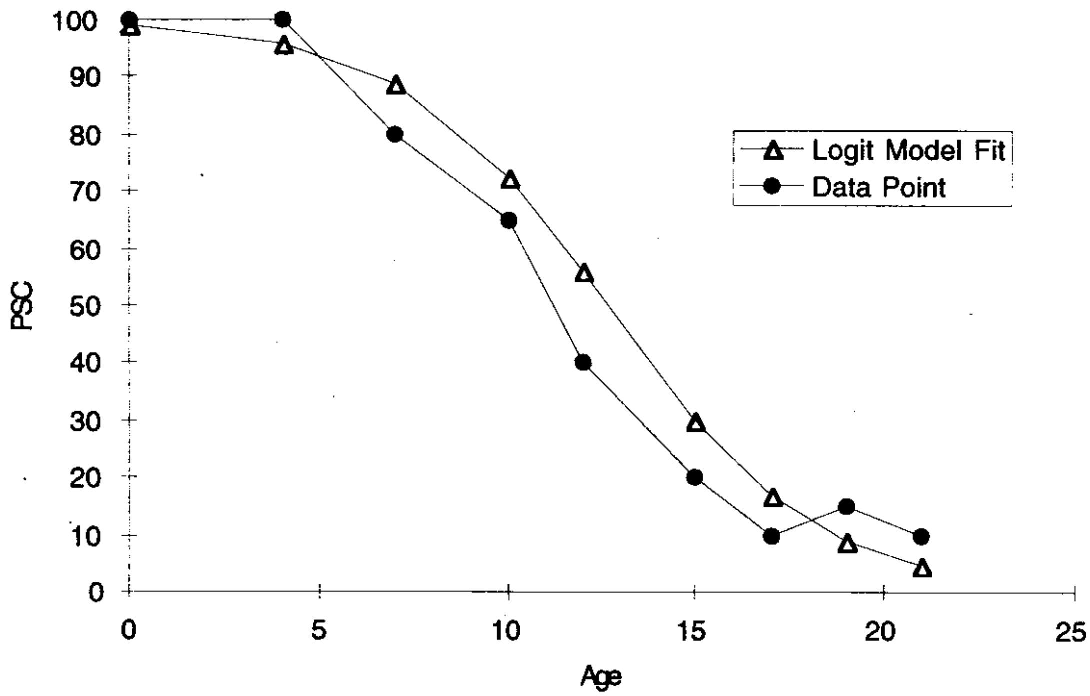

Figure 4.1. Illustration of Logit Model — PSC vs. Age Data

$$PSC = 100\left[\frac{e^{(4.623 - 0.365\,(Age))}}{1 + e^{(4.623 - 0.365\,(Age))}}\right]$$

The equation essentially becomes asymptotic with the x-axis (Age).

The apparent advantages of the logit model for use with WSPMS performance data include:

- improved modeling of highly deteriorated pavement units
- improved modeling of long-lived PCCP
- improved modeling of early pavement performance (i.e., the first few years after new construction or overlay)
- a slightly improved approach for developing default equations.

The logit model was examined for both ACP and PCCP. There is a strong possibility that the logit model may supplant, to some extent, the need for Type III regressions in the WSPMS. Again, these examinations are contained in Appendix A.

3. GENERAL PRC PERFORMANCE MODEL

WSDOT currently uses a power model with the exponent fixed at one (PSC = 1.0—refer to Eq. 4.1) to model rutting data (PRC) for individual pavement units. A question arises which requires an answer: does the PRC actually trend in a linear manner with increasing pavement age?

Results shown for five WSDOT routes in Table 4.1 suggest that rutting, in general, conforms to a linear trend. The results shown are based on 1995 rut measurements contained in the WSPMS—1995. It is of interest that the rutting rate (mm per million ESALs) do not vary all that much for a specific route (as illustrated by the associated standard deviations). It is of special interest that the rutting rates vary so much among the five routes. For the four east-west routes, analysis units were sampled both east and west of the Cascade crest with little apparent difference in results.

Table 4.1. Rutting Statistics for Five WSDOT Routes

	Rutting Rate (mm/million ESALs)		1995 Measured Rutting (mm)		ESALs (millions)		Surface Course Age (years)	
Route	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
SR20	4.0	2.2	4.1	1.5	1.17	0.52	12.1	3.4
US195	5.7	1.1	4.2	0.5	0.72	0.17	9.5	1.0
US12	5.0	2.0	6.2	1.7	1.40	0.56	10.0	5.4
I90	2.0	0.6	6.7	3.7	3.44	2.01	7.8	4.0
I5	0.5	0.2	5.4	2.0	11.22	4.60	13.2	6.8

Notes: 1. Only analysis units with accumulated ESALs > 500,000 and surface course ages > 2 years were used.

2. Rut depths measured with the South Dakota Profilometer.

The sampling of analysis units was done only for the existing surface courses with accumulated ESALs more than 500,000 and ages more than two years old. This was done to exclude construction related problems and provide a more reasonable measure of performance. The ranges of the 1995 measured ruts were:

	Range of Ruts (mm)	
Route	Low	High
I5	3	7
I90	1	13
US12	4	9
US195	4	5
SR20	2	6

The mean measured ruts were actually quite similar for the five routes in spite of quite different accumulated ESALs. These ruts ranged from 4.1 to 6.7 mm (or about 1/6 to 1/4 inch). This rather modest amount of rutting is further supported by statistics produced from 1994 measured rut data in the WSPMS—1994. Statewide, the following statistics were generated for ACP:

Rutting Severity	Percentage of Total Lane-Miles
1/8" to 1/2" (3.2 mm to 12.7 mm)	9.1
1/2" to 3/4" (12.7 mm to 19.0 mm)	1.4
> 3/4" (19.0 mm)	0.00

This suggests that rutting for ACP is currently relatively minor on the WSDOT route system.

Given that the applied ESALs per year vary by more than a factor of ten, the information shown in Table 4.1 suggests that environmental factors along with studded tires may be significant in causing the observed rutting.

Even though there is evidence that the observed rutting trend for WSPMS analysis units is, in general, linear, a logit model was evaluated for predicting PRC versus Age trends. The specifics of the evaluation are contained in Appendix A. In general, the logit model appears suitable for making such predictions. Any improvements over the currently used constrainted power model were modest at best.

4. GENERATION OF DEFAULT EQUATIONS

The generation of annual default equations for the WSPMS was documented by Kay et al. [6]. Unfortunately, the variation in these equations, on an annual basis, is significant. An illustration of the problem can be seen by comparing the default equations contained in Tables 4.2 and 4.3. These two tables contain the Interstate System 1995 (Table 4.2) and 1993 (Table 4.3) default equations. A straightforward way to make this comparison is to look at the differences in the predicted time to a PSC = 50. These

Table 4.2. Pavement Performance Default Equations for the Interstate Functional Classification — WSPMS — 1995

Region	Pavement Surface	Performance Equation	Age to PSC = 50	Model
Northwest (1)	AC	$PSC = 100 - 0.00113 (Age)^{3.75}$	17.3	1
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.290 (Age)^{1.50}$	31.0	1
North Central (2)	AC	$PSC = 100 - 0.141 (Age)^{2.25}$	13.6	1
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.0744 (Age)^{1.75}$	41.3	2
Olympic (3)	AC	$PSC = 100 - 0.293 (Age)^{2.00}$	13.1	2
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.0744 (Age)^{1.75}$	41.3	2
Southwest (4)	AC	$PSC = 100 - 0.00733 (Age)^{3.25}$	15.1	1
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.161 (Age)^{1.75}$	26.6	1
South Central (5)	AC	$PSC = 100 - 0.0319 (Age)^{2.75}$	14.5	1
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.245 (Age)^{1.50}$	34.7	1
Eastern (6)	AC	$PSC = 100 - 5.77 (Age)^{1.00}$	8.7	1
	BST	$PSC = 100 - 3.16 (Age)^{1.50}$	6.3	2
	PCC	$PSC = 100 - 0.530 (Age)^{1.25}$	38.0	1

Model Code

1 = Model based on actual projects for listed conditions
2 = Default model based on statewide projects

Table 4.3. Pavement Performance Default Equations for the Interstate Functional Classification — WSPMS — 1993

Region	Pavement Surface	Performance Equation	Age to PSC = 50	Model
Northwest (1)	AC	$PSC = 100 - 0.196 (Age)^{2.00}$	16.0	2
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.018 (Age)^{2.25}$	33.5	1
North Central (2)	AC	$PSC = 100 - 0.166 (Age)^{2.25}$	12.6	1
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.034 (Age)^{2.00}$	38.1	2
Olympic (3)	AC	$PSC = 100 - 0.009 (Age)^{3.00}$	17.5	1
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.109 (Age)^{1.75}$	33.2	1
Southwest (4)	AC	$PSC = 100 - 0.0018 (Age)^{3.50}$	18.6	1
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.0055 (Age)^{2.75}$	27.5	1
South Central (5)	AC	$PSC = 100 - 0.029 (Age)^{2.75}$	15.1	1
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.112 (Age)^{1.75}$	32.7	1
Eastern (6)	AC	$PSC = 100 - 0.574 (Age)^{1.75}$	12.8	1
	BST	$PSC = 100 - 0.809 (Age)^{2.00}$	7.9	2
	PCC	$PSC = 100 - 0.034 (Age)^{2.00}$	38.1	2

Model Code

1 = Model based on actual projects for listed conditions
2 = Default model based on statewide projects

differences are shown in Table 4.4. It is of special interest to note the differences in these predictions for AC surfaces for the Olympic (4.4 years), Southwest (3.5 years), and Eastern Regions (4.1 years).

The way to resolve this difficulty is not entirely clear since the annual condition surveys may contribute to the observed variation. However, it is the opinion of those which work with the WSPMS that the annual variation in the default equations is excessive and should be reduced.

The way this variation will likely be reduced will require multiple equation generation runs on multiple year data contained within the WSPMS. Some of the recommended changes as compared to past modeling include:

Modeling Characteristic	Current	Future
• Most recent condition survey	PSC ≤ 75	PSC ≤ 75
• Intercept "C"	≥ 80	≥ 90
• Length of analysis unit	≥ 0.1 mile	≥ 0.1 mile
• Production equations used	Can include Type IIIs	Exclude Type IIIs
• Model type	Power model only	Include use of logit and power models
• Annual PSC data	Use only data for one annual survey to generate annual equations	Consider use of two or three annual surveys to generate annual equations
• Excluded PSC data	Eliminate upper and lower 10 percent of equations	Use no exclusion criterion

Table 4.4. Differences in Predicted Time to PSC = 50 (Interstate)

Region	Pavement Surface	Time to PSC = 50 (years)	
		1993	1995
Northwest (1)	AC	16.0	17.3
	BST	7.9	6.3
	PCC	33.5	31.0
North Central (2)	AC	12.6	13.6
	BST	7.9	6.3
	PCC	38.1	41.3
Olympic (3)	AC	17.5	13.1
	BST	7.9	6.3
	PCC	33.2	41.3
Southwest (4)	AC	18.6	15.1
	BST	7.9	6.3
	PCC	27.5	26.6
South Central (5)	AC	15.1	14.5
	BST	7.9	6.3
	PCC	32.7	34.7
Eastern (6)	AC	12.8	8.7
	BST	7.9	6.3
	PCC	38.1	38.0

The primary differences being proposed is to

- try use of the logit model (in addition to the power model)
- "pool" PSC data over a two or three year period to generate the default equations
- do not use Type III equations
- consider doing a traditional regression analysis without the use of analysis unit equations

The efficacy of the above will only be determined following actual model development.

SECTION 5

SUMMARY

This report has been used to address three primary topics:

- distress survey check procedure
- vehicle operating costs as a function of pavement condition and their use in optimal rehabilitation timing
- WSPMS performance equations.

A sampling scheme was developed and tested which can be used to check the annual distress survey. A two percent sample was designed for this purpose. To make statistically based comparisons of the sampled data both paired t-test and Wilcoxon hypothesis tests were applied and evaluated (both appear to work well). All documentation is shown in Section 2.

A potentially significant vehicle operating cost (VOC) was identified for use in pavement management decisions. A VOC model was developed as a function of both International Roughness Index (IRI) and Pavement Structural Condition (PSC). Illustrations of how changes in IRI or PSC could influence such costs are contained in Section 3. Calculations on how total project costs including VOCs influence the optimum timing of rehabilitation were made. The optimum timing occurred within the range that WSDOT currently uses.

Finally, in Section 4, the performance models used by WSDOT were examined. The conclusion drawn is that the logit model should be tried in the WSPMS—to model not only performance of individual pavement units but also in the development of default equations. It may exhibit superior modeling characteristics to the currently used power model. Only application to actual data in the WSPMS will allow a proper assessment.

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APPENDIX A

LOGISTIC MODEL FOR PAVEMENT PERFORMANCE

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LOGISTIC MODEL FOR PAVEMENT PERFORMANCE

1. INTRODUCTION

If it is desirable to fit an "S" shape curve to pavement condition-age performance data, one approximate way this can be done is to use a "logistic response function" or "logit" (refer to Neter and Wasserman [A.1], p. 329-330). Generally, this type of model is used with a binary dependent variable (0 or 1) with repeat observations at each x (AGE in this case). To apply the logit model to PMS data requires approximations as will be subsequently described.

2. LOGIT MODEL

To start the logit modeling process, the dependent variable (PSC in this case) is transformed by

$$y' = \log_e\left(\frac{PSC}{100 - PSC}\right)$$

where $PSC \leq 99$ (note: a $PSC = 100$ will result in division by zero)

2.1 Example 1—ACP

Using the PSC-AGE data from a prior example contained in Research Report WA-RD 315.1 ("Statistical Methods for WSDOT Pavement and Material Applications" [A2]), the necessary calculations follow:

Data Point	PSC	(x) AGE	(y') $\log_e\left(\frac{PSC}{100 - PSC}\right)$	(x) (y')
1	100*	0	4.59512	0
2	100*	4	4.59512	18.38048
3	80	7	1.38629	9.70403
4	65	10	0.61904	6.19040
5	40	12	-0.40547	-4.86564
6	20	15	-1.38629	-20.79435
*Use max PSC = 99		48	9.40381	8.61492

$\Sigma y' = 9.40381$

$\Sigma x = 48$

$\Sigma x^2 = 534$

$\Sigma xy' = 8.61492$

$$b_1 = \frac{\Sigma xy' - \frac{\Sigma x \Sigma y'}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}} = \frac{8.61492 - \frac{(48)\,(9.40381)}{6}}{534 - \frac{(48)^2}{6}}$$

$$= -0.44410$$

$$b_0 = \frac{1}{n}(\Sigma y' - b_1\,\Sigma x) = \frac{1}{6}(9.40381 - (-0.44410)\,(48))$$

$$= 5.12010$$

The following equation results:

$$y' = \frac{e^{b_0 + b_1\,(AGE)}}{1 + e^{b_0 + b_1\,(AGE)}}$$

and predicted PSC = 100 (y'), therefore

$$\text{predicted PSC} = 100\left[\frac{e^{(5.12010 - (0.44410)\,(AGE))}}{1 + e^{(5.12010 - (0.44410)\,(AGE))}}\right]$$

This results in the following (also refer to Figure A.1):

Data Point	AGE	Actual PSC	Predicted PSC	$\hat{y}'$ (see Note 1)
1	0	100	99.4	5.10998
2	4	100	96.6	3.34680
3	7	80	88.2	2.01151
4	10	65	66.4	0.68117
5	12	40	44.8	-0.20875
6	15	20	17.6	-1.54389

Note 1: $\hat{y}' = \log_e\left(\frac{\hat{PSC}}{100 - \hat{PSC}}\right)$

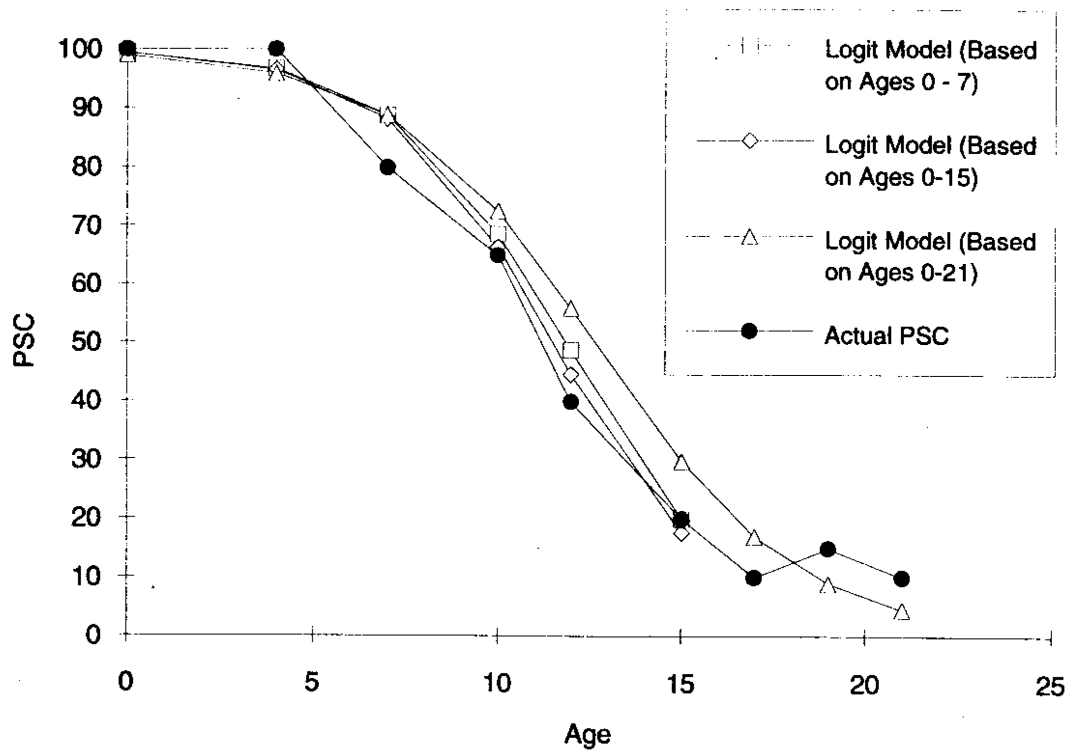

Figure A.1. Illustrations of Logit Fit of PSC vs. Age Data

To calculate the coefficient of determination (R^2), calculate the total sum of squares (SSTO) and regression sum of squares (SSR).

Total sum of squares (SSTO)	SSTO	=	$\sum_{i=1}^{6} (y'_i - \bar{y}')^2$ and $\bar{y} = \frac{9.40381}{6} = 1.56730$
		=	$(4.59512 - 1.56730)^2 + \ldots + (-1.38629 - 1.56730)^2$
		=	31.88286
Regression sum of squares (SSR)	SSR	=	$\sum_{i=1}^{6} (\hat{y}_i' - \bar{y}')^2$
		=	$(5.10998 - 1.56730)^2 + \ldots + (-1.54369 - 1.56730)^2$
		=	29.53236
Coefficient of deterioration (R^2)	R^2	=	$\frac{29.53236}{31.88286} = 0.926$ (or 92.6%). Reasonable agreement.

2.2 Example 2—ACP with Maintenance

A second example better illustrates the capability of the logit model. Use a slightly modified set of data which illustrates the condition of a pavement which is badly deteriorated but, due to maintenance, does not reach a PSC = 0.

Data Point	AGE	PSC	
1	0	100*	From prior example
2	4	100*	
3	7	80	
4	10	65	
5	12	40	
6	15	20	
7	17	10	Erratic PSC values due to maintenance
8	19	15	
9	21	10	

*Use max PSC = 99 as before

Data Point	PSC	(x) AGE	$y' = \log_e\left(\frac{PSC}{100 - PSC}\right)$	(x) (y')
1	99	0	4.59512	0
2	99	4	4.59512	18.38048
3	80	7	1.38629	9.70403
4	65	10	0.61904	6.19040
5	40	12	-0.40547	-4.86564
6	20	15	-1.38629	-20.79435
7	10	17	-2.19722	-37.35274
8	15	19	-1.73460	-32.95740
9	10	21	-2.19722	-46.14162
		$\Sigma = 105$	$\Sigma = 3.27477$	-107.83684

and $\Sigma x^2 = 1{,}625$

$$b_1 = \frac{\Sigma xy' - \frac{\Sigma x \Sigma y'}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}} = \frac{-107.83684 - \frac{(105)\,(3.27477)}{9}}{1{,}625 - \frac{(105)^2}{9}}$$

$$= -0.36511$$

$$b_0 = \frac{1}{n}(\Sigma y' - b_1\, \Sigma x) = \frac{1}{9}(3.27477 - (-0.36511)\,(105))$$

$$= 4.62348$$

Therefore, the predicted PSC is

$$\hat{PSC} = 100\left[\frac{e^{(4.62348\, -\, 0.36511\, (AGE))}}{1 + e^{(4.62348\, -\, 0.36511\, (AGE))}}\right]$$

This results in the following:

Data Point	AGE	Actual PSC	Predicted PSC
1	0	100	99.0
2	4	100	95.9
3	7	80	88.8
4	10	65	72.6
5	12	40	56.0
6	15	20	29.9
7	17	10	17.0
8	19	15	9.0
9	21	10	4.5

Both curves (AGES 0 to 15 years and AGES 0 to 21 years) are shown in Figure A.1.

2.3 Example 3—ACP in Early Life

A third condition should be evaluated for the logit model. For example, if only three PSC vs. AGE data points are available (which might represent a pavement early in its current performance period), use the AGES 0 to 7 data from the example to illustrate the kind of fit the model would achieve.

Data Point	PSC	(x) AGE	$y' = \log_e\left(\frac{PSC}{100 - PSC}\right)$	(x) (y')
1	100*	0	4.59512	0
2	100*	4	4.59512	18.38048
3	80	7	1.38629	9.70403
			10.57653	28.08451

*Use max PSC = 99

$\Sigma x = 11$

$\Sigma x^2 = 65$

$\Sigma y' = 10.57653$

$\Sigma xy'$ 28.08451

$$b_1 = \frac{28.08451 - \frac{(11)\,(10.57653)}{3}}{65 - \frac{(11)^2}{3}} = -0.43363$$

$$b_0 = \frac{1}{3}\,(10.57653 - (-0.43363)\,(11)) = 5.11549$$

Therefore, the predicted PSC is

$$\hat{PSC} = 100\left[\frac{e^{(5.11549\ -\ 0.43363(AGE))}}{1 + e^{(5.11549\ -\ 0.43363\ (AGE))}}\right]$$

This results in the following:

Data Point	AGE	Actual PSC	Predicted PSC	
1	0	100	99.4	Equation based only on these data points
2	4	100	96.7	
3	7	80	88.9	
4	10	—	68.6	Equation used to predict into future
5	12	—	47.8	
6	15	—	20.0	

Data points 4, 5, and 6 compare favorably with the original example data. This suggests that the logit model may hold some promise for eliminating the use of the Type III curve in the WSPMS (refer to WSDOT Research Report WA-RD 274.1, "The WSDOT Pavement Management System—A 1993 Update," p. 20 [A3]). The developed curve is shown in Figure A.1.

3. DEFAULT EQUATIONS

3.1 ACP Default Equations

To explore the potential for use of the logit model to create the WSPMS default equations, the 1993 conventional default equations were examined (Kay et al. [A3]). The 1993 equations were used to estimate the PSC at pavement ages of 5, 10, 15, and 20 years, with the results being shown in Table A.1. Next, the PSC means were

Table A.1. Results from 1993 Asphalt Concrete Default Equations

Region	Functional Class	1993 Default Equation	Calculated PSC @ Age Shown			
			5 years	10 years	15 years	20 years
Northwest	Interstate	$100 - 0.196(Age)^{2.0}$	95.1	80.4	55.9	21.6
	Prin. Art.	$100 - 0.196(Age)^{2.0}$	95.1	80.4	55.9	21.6
	Minor Art.	$100 - 0.109(Age)^{2.25}$	95.9	80.6	51.7	7.8
	Major Coll.	$100 - 0.234(Age)^{2.0}$	94.2	76.6	47.4	6.4
		mean =	95.1	79.5	52.7	14.4
North Central	Interstate	$100 - 0.166(Age)^{2.25}$	93.8	70.5	26.5	0
	Prin. Art.	$100 - 0.239(Age)^{2.25}$	91.1	57.5	0	0
	Minor Art.	$100 - 0.419(Age)^{2.0}$	89.5	58.1	5.7	0
	Major Coll.	$100 - 0.129(Age)^{2.25}$	95.2	77.1	42.9	0
		mean =	92.4	65.8	18.8	0
Olympic	Interstate	$100 - 0.009(Age)^{3.0}$	98.9	91.0	69.6	28
	Prin. Art.	$100 - 0.063(Age)^{2.5}$	96.4	80.1	45.1	0
	Minor Art.	$100 - 0.172(Age)^{2.25}$	93.6	69.4	23.8	0
	Major Coll.	$100 - 0.136(Age)^{2.25}$	94.9	75.8	39.8	0
		mean =	96.0	79.1	44.6	7.0
Southwest	Interstate	$100 - 0.0018(Age)^{3.5}$	99.5	94.3	76.5	35.6
	Prin. Art.	$100 - 0.023(Age)^{2.75}$	98.1	87.1	60.6	13.0
	Minor Art.	$100 - 0.036(Age)^{2.5}$	98.0	88.6	68.6	35.6
	Major Coll.	$100 - 0.0096(Age)^{3.0}$	98.8	90.4	67.6	23.2
		mean =	98.6	90.1	68.3	26.8
South Central	Interstate	$100 - 0.029(Age)^{2.75}$	97.6	83.7	50.3	0
	Prin. Art.	$100 - 0.202(Age)^{2.5}$	Not Used	Not Used	Not Used	Not Used
	Minor Art.	$100 - 0.099(Age)^{2.5}$	94.5	68.7	13.7	0
	Major Coll.	$100 - 0.074(Age)^{2.5}$	95.9	76.6	35.5	0
		mean =	96.0	76.3	33.2	0
Eastern	Interstate	$100 - 0.574(Age)^{1.75}$	90.4	67.7	34.0	0
	Prin. Art.	$100 - 1.74(Age)^{1.50}$	80.5	45.0	0	0
	Minor Art.	$100 - 0.916(Age)^{1.75}$	84.7	48.5	0	0
	Major Coll.	$100 - 1.82(Age)^{1.50}$	79.7	42.4	0	0
		mean =	83.8	50.9	8.6	0

calculated for each of the pavement ages (averaged for all four functional classifications). By inspection, the Northwest and Olympic Regions were combined. The resulting PSC means were used to develop logit models. The resulting model by region follows:

Northwest Region:

$$PSC = 100\left[\frac{e^{(4.69 - 0.33\,(Age))}}{1 + e^{(4.69 - 0.33\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean*	Logit PSC
0	100.0	99.1
5	95.6	95.4
10	79.3	80.1
15	48.6	43.5
20	10.7	12.9

*Means for both Northwest and Olympic Regions

North Central Region:

$$PSC = 100\left[\frac{e^{(4.57 - 0.40\,(Age))}}{1 + e^{(4.57 - 0.40\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean	Logit PSC
0	100.0	99.0
5	92.4	92.9
10	65.8	63.9
15	18.8	19.3
20	0.0	3.1

Olympic Region:

$$PSC = 100\left[\frac{e^{(4.69 - 0.33\,(Age))}}{1 + e^{(4.69 - 0.33\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean*	Logit PSC
0	100.0	99.1
5	95.6	95.4
10	79.3	80.1
15	48.6	43.5
20	10.7	12.9

*Means for both Northwest and Olympic Regions

Southwest Region:

$$PSC = 100\left[\frac{e^{(5.10 - 0.29\,(Age))}}{1 + e^{(5.10 - 0.29\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean	Logit PSC
0	100.0	99.4
5	98.6	97.5
10	90.1	90.0
15	68.3	67.9
20	26.8	33.2

South Central Region:

$$PSC = 100\left[\frac{e^{(4.74 - 0.36\,(Age))}}{1 + e^{(4.74 - 0.36\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean	Logit PSC
0	100.0	99.1
5	96.0	95.0
10	76.3	75.8
15	33.2	34.1
20	0.0	7.9

Eastern Region:

$$PSC = 100\left[\frac{e^{(4.35 - 0.45\,(Age))}}{1 + e^{(4.35 - 0.45\,(Age))}}\right]$$

Pavement Age	1993 Default Equation PSC Mean	Logit PSC
0	100.0	98.7
5	83.8	89.1
10	50.9	46.2
15	8.6	8.3
20	0.0	0.9

3.2 PSC PCCP Performance and Default Equations

A common problem with PCCP is sensible default equations to use in WSPMS. The WSDOT PCCP typically has long lives to a PSC = 50. This, unfortunately, makes it difficult to determine when an unacceptable pavement condition will occur. To examine this issue, the 1993 PCCP default equation for the Northwest Region principal arterials was used (from Table 3.5, Kay et al. [A3]).

$$PSC = 100 - 0.025\,(Age)^{2.00} \qquad \text{(Eq. A1)}$$

PSCs generated from Equation A1 will be used to examine the various aspects of the logit model. PSCs were calculated for 10 year intervals:

Data Point	Age	Calculated PSC from Eq. A1
1	0	100
2	10	97.5
3	20	90.0
4	30	77.5
5	40	60.0
6	50	37.5

(Note: PSC = 50 @ Age = 44.7 years)

The logit model was then used to calculate PSC values (based on data from Eq. A1). The resulting logit model equation is:

$$PSC = 100\left[\frac{e^{(4.53 - 0.104\,(Age))}}{1 + e^{(4.53 - 0.104\,(Age))}}\right]$$

A comparison of results from both the WSDOT power model and the logit model follows:

Data Point	Age	PSC (WSDOT Power Model)	PSC (Logit Model)
1	0	100	98.9
2	10	97.5	97.0
3	20	90.0	92.1
4	30	77.5	80.4
5	40	60.0	59.1
6	50	37.5	33.8

Thus, the logit model matches the power model results reasonably well. If ages beyond 50 years are used, which is a bit unrealistic, then:

Age = 55	PSC (power) = 24	PSC (logit) = 23
Age = 60	PSC (power) = 10	PSC (logit) = 15

If only the first three ages are used to develop the logit model (0, 10, and 20 years), the following results (compared to logit model developed with six data points):

$$PSC = 100\left[\frac{e^{(4.69 - (0.12)\,(Age))}}{1 + e^{(4.69 - (0.12)\,(Age))}}\right]$$

Age	PSC (Logit Model— 6 Data Points	PSC (Logit Model— 3 Data Points
0	98.9	99.1
10	97.0	97.0
20	92.1	90.8
30	80.4	74.8
40	59.1	47.3
50	33.8	21.2

The comparison is favorable. In fact, the time to a PSC = 50 is 39 years with the three-point logit model, 44 years with the six-point logit model, and the WSDOT power model 45 years.

A more extreme test of the logit model is to examine its predictive power following development based on, say, 10 years of data—all of which have high PSC values. Using the prior WSDOT power model to generate PSCs ranging from Age 0 to 10 years, a logit model was then fitted. The following results:

Data Point	Age	PSC (from WSDOT Power Model)	PSC (from Logit Model Fit)
1	0	100	99.2
2	2	100	99.0
3	4	99.6	98.8
4	6	99.1	98.6
5	8	98.4	98.4
6	10	97.5	98.0
	20		95.2
	30		89.2
	40		76.5
	50		56.7

Logit model based on Age = 0 to 10 years

$$\text{PSC} = 100\left[\frac{e^{(4.82 - 0.091(\text{Age}))}}{1 + e^{(4.82 - 0.091\,(\text{Age}))}}\right]$$

Even though the logit model PSCs overpredict performance, it should provide more realistic assessments of future pavement performance "early" in the life of a PCC pavement (as compared to the WSDOT power model).

A specific example from the 1995 WSPMS is used to further compare the power and logit models. Data from I82, MP 15.02 - 19.07 (analysis unit) shows a PCCP construction date of 1971. A power model in the WSPMS currently starts in 1984 (i.e., Age = 0) and is:

$$\text{PSC} = 90.81 - 0.0000383\,(\text{Age})^{3.0}$$

(Note: the measured PSC was 90 in 1984)

Using only three data points, a logit model was fitted to the following:

Year	Age	Measured PSC
1971	0	100
1984	13	90
1995	24	91

The following model was developed:

$$PSC = 100\left[\frac{e^{(4.24 - 0.0975(Age))}}{1 + e^{(4.24 - 0.0975\,(Age))}}\right]$$

A comparison can be made of the two models:

Year	Age	Actual PSC	PSC (Logit Model)	PSC (WSPMS Power Model)
1971	0	100	98.6	90.8
1984	13	90	95.1	90.0
1995	24	91	87.0	85.5
2001	30	—	78.8	80.5
2011	40	—	58.4	66.3
2021	50	—	34.6	42.9

The WSPMS power model predicts a PSC = 50 at Age = 47 years (Year 2018) and the logit model at Age = 43 years (Year 2014). Further, the power model is a Type III fit (the appropriate standard default curve is "added" to the existing PSC data and regressed) and the logit model is not.

4. PRC PERFORMANCE AND DEFAULT EQUATIONS

4.1 Introduction

The Pavement Rutting Condition (PRC) currently used in WSPMS is calculated as follows:

$$PRC = 100 - 3.3\,(Rut)^{1.18}$$

where PRC = Pavement Rutting Condition

Rut = Depth of wheelpath ruts (mm).

Thus, a 10 mm rut results in a PRC = 50 and a 18 mm rut in a PRC = 0. To develop predictive PRC equations as a function of Age, the WSDOT power model is currently used. The exponent is fixed at 1.0, thus all fits of actual data result in a straight line.

An examination was made of several conditions to examine the question of whether the logit model would be appropriate for this type of data as was PSC. To do this, two WSPMS analysis units were used as examples. A third condition was examined for a generated straight line fit. All three examples follow in the subsequent paragraphs.

4.2 I5, MP 79.09 - 79.21 NB

This analysis unit showed substantial rutting within a short time and thus makes for a good example. The actual PRC from 1991 to 1994 will be used along with the assumption that the PRC = 100 following an ACP overlay in 1990.

Year	Age	Actual PRC
1990	0	100
1991	1	73
1992	2	78
1993	3	26
1994	4	32

The actual PRC values are a bit erratic but with a major decreasing trend apparent.

The following comparisons were made:

- predicted PRC based on a three data-point straight line fit
- predicted PRC based on a three data-point logit model fit
- predicted PRC based on a five data-point straight line fit
- predicted PRC based on a five data-point logit model fit

The following equations were generated:

- Straight line—three points (Ages = 0, 1, 2)

$$PRC = 94.7 - 11.0\,(Age)$$

- Logit model—three points (Ages = 0, 1, 2)

$$PRC = 100\left[\frac{e^{(3.108 - 0.845(Age))}}{1 + e^{(3.108 - 0.845\,(Age))}}\right]$$

- Straight line—five points (Ages = 0, 1, 2, 3, 4)

$$PRC = 98.4 - 18.3\,(Age)$$

- Logit model—five points (Ages = 0, 1, 2, 3, 4)

$$PRC = 100\left[\frac{e^{(3.2 - 1.103(Age))}}{1 + e^{(3.2 - 1.103\,(Age))}}\right]$$

A comparison of the results from these four equations as compared to actual PRC are:

			Predicted PRC			
			3 Points		5 Points	
Year	Age	Actual PRC	Straight Line	Logit	Straight Line	Logit
1990	0	100	94.7	95.7	98.4	96.1
1991	1	73	83.7	90.6	80.1	89.0
1992	2	78	72.7	80.5	61.8	73.0
1993	3	26	61.7	63.9	43.5	47.4
1994	4	32	50.7	43.2	25.2	22.9

If only three data points are available to regress (an early pavement life condition), the logit model does a bit better in predicting the Age at PRC = 50; however, the differences between the two models (straight line and logit) are small. If five data points are used in developing the models, the differences in time to PRC = 50 also are minimal.

4.3 I5, MP 83.23 - 83.28 NB

This analysis showed a modest rutting trend with what appears to be an erratic data point in 1994. The PSC - Age data from the WSPMS are:

Year	Age	Actual PRC
1990	0	100
1991	1	88
1992	2	83
1993	3	78
1994	4	93
1995	5	67

The following equations were developed—a straight line fit and the logit model (both using all six data points to achieve a fit):

- Straight line fit

$$PRC = 95.9 - 4.43\ (Age)$$

- Logit model

$$PRC = 100\left[\frac{e^{(3.46 - 0.529\ (Age))}}{1 + e^{(3.46 - 0.529(Age))}}\right]$$

A comparison of the results reveals:

Year	Age	Actual PRC	Straight Line Fit—PRC	Logit Model—PRC
1990	0	100	95.9	96.9
1991	1	88	91.5	94.9
1992	2	83	87.0	91.7
1993	3	78	82.6	86.6
1994	4	93	78.2	79.3
1995	5	67	73.8	69.2

Overall, both models appear adequate predictors given the variability of the actual PRC data. Of greater interest to WSDOT is the time to a predicted PRC = 50. For the straight line fit, time to 50 is 10.4 years (or Year 2000). For the logit model, time to 50 is 6.5 years (or Year 1997). The three year difference is significant.

4.3 Logit Model Fit of Straight Line Data

PRC data points were "manufactured" according to a straight line to achieve a PRC = 67 at Age = 5 (from Paragraph 4.2). The required straight line fit equation to achieve this is:

$$PRC = 100 - 6.6\ (Age)$$

Using PRC values from the equation, a logit model was fit to same. The purpose of this exercise is to see how well a logit model can conform to data it is not well-configured to fit. The logit model developed from the generated data is:

$$PSC = 100\left[\frac{e^{(3.83 - 0.71\,(Age))}}{1 + e^{(3.83 - 0.71\,(Age))}}\right]$$

A comparison of the generated data and the logit model predicted data is:

Age	PRC— Generated from Straight Line Equation	PRC— Logit Model
0	100.0	97.9
1	93.4	95.8
2	86.8	91.7
3	80.2	84.5
4	73.6	72.8
5	67.0	56.7

Clearly, the logit model underpredicts the PRC at Age = 5 years. If, for example, a sixth data point is used (PRC = 60.4 at Age = 6; straight line) and the logit model rerun, the following equation results:

$$PRC = 100\left[\frac{e^{(3.68 - 0.62\,(Age))}}{1 + e^{(3.68 - 0.62\,(Age))}}\right]$$

The PRC predicted from the above model is 49.0 at Age = 6 versus a PRC = 39.1 from the prior logit model. Thus, the logit model, based on this example, quickly adjusts to additional annual survey data.

4. SUMMARY

Based on the preliminary analyses presented in this appendix, the logit model appears to have potential for use in the WSPMS. At least two possibilities exist:

- standard model for project and analysis road segments
- default equation model.

APPENDIX A

REFERENCES

A1. Neter, J., and Wasserman, W., "Applied Linear Statistical Models," R. D. Irwin, Inc., Homewood, Illinois, 1974.

A2. Mahoney, J.P., "Statistical Methods for WSDOT Pavement and Material Applications," Research Report WA-RD 315.1, Washington State Department of Transportation, Olympia, Washington, February 1994.

A3. Kay, R.K., Mahoney, J.P., and Jackson, N.C., "The WSDOT Pavement Management System—A 1993 Update," Research Report WA-RD 274.1, Washington State Department of Transportation, Olympia, Washington, September 1993.

APPENDIX B

AN EXAMPLE OF OPTIMUM REHABILITATION TIMING

APPENDIX B

AN EXAMPLE OF OPTIMUM REHABILITATION TIMING

1. INTRODUCTION

This appendix will be used to illustrate how vehicle operating costs (VOC) can influence the optimum timing of rehabilitation. The optimization technique will be a minimization of the total life cycle costs.

2. ASSUMPTIONS

To conduct this examination, a number of assumptions are required:

- Overall Assumptions
  - The principal rehabilitation technique will be asphalt concrete overlays, the extent (cost) of which will vary with increasing time between rehabilitation.
  - The pavement type to be overlaid is a flexible pavement. A typical AC performance equation was selected from the Olympic Region Interstate System (WSPMS—1995) as illustrated in Table 4.2 (Section 4 of the main report):

$$PSC = 100 - 0.293\,(Age)^{2.0}$$

- Project Specific Costs
  - Use a \$25.00/ton cost for AC mix.
  - Assume that the AC represents 40 percent of the total project costs.
  - Use a 12 ft wide lane 1 mile long (1 lane-mile).
  - Delay costs cue to construction will be included.
- VOC
  - The VOCs were estimated via the technique described in Section 3 of this report.

- Total Costs
    - All costs were annualized to determine the optimum age for rehabilitation.

3. CALCULATIONS

3.1 Calculation of PSCs and IRIs

Using the performance equation for ACP noted in Paragraph 2, the following were calculated:

n (years)	PSC[1]	IRI[2]	n (years)	PSC[1]	IRI[2]
0	100.0	1.000	11	64.5	2.420
1	99.7	1.012	12	57.8	2.688
2	98.8	1.048	13	50.5	2.980
3	97.4	1.104	14	42.6	3.296
4	95.3	1.188	15	34.1	3.636
5	92.7	1.292	16	25.0	4.000
6	89.5	1.420	17	15.3	4.387
7	85.6	1.576	18	5.1	4.796
8	81.2	1.752			
9	76.3	1.948			
10	70.7	2.172			

Notes: 1. $PSC = 100 - 0.293\,(Age)^{2.0}$

2. $IRI = \dfrac{125 - PSC}{25}$

3.2 Calculation of Project Specific Costs

For Ages 1 to 10 years: 0.15 ft AC overlay @ $25/ton @ 40% of project cost ≃ $44,000/ln-mi

For Ages 11 to 15 years: 0.15 ft AC overlay @ $25/ton @ 40% of project cost plus 25% for level-up and/or patching costs ≃ $55,000/ln-mi

For Ages 16 to 20 years: 0.20 ft AC overlay @ $25/ton @ 40% of project cost plus 25% for level-up and/or patching costs ≃ $72,300/ln-mi

To estimate user delay costs during construction it was assumed that 10,000 vehicles per day use the one lane-mile segment. The formula contained in the WSDOT Pavement Guide, Volume 2, SECTION 8.0, p. 8-11, was used to estimate such costs with

L = 1 mile
RS = 20 mph
IS = 55 mph
ADT = 10,000 vpd
PT = 100%
CP = 20 days

The project construction delay costs were estimated at ≈$40,000 for the lane-mile.

3.3 Calculation of VOCs

The VOCs were estimated in accordance with Section 3. It was assumed that 71.6 percent of the vehicles were passenger cars and pickups, 24.0 percent single unit trucks and buses, and 4.4 percent single trailer trucks. The following VOCs were calculated:

Year	$	Year	$
0-1	614	10-11	12,697
1-2	1,843	11-12	13,721
2-3	2,867	12-13	14,950
3-4	4,301	13-14	16,179
4-5	5,325	14-15	17,408
5-6	6,554	15-16	18,637
6-7	7,987	16-17	19,814
7-8	9,011	17-18	20,941
8-9	10,035		
9-10	11,469		

The change in IRI at the beginning and end of each year were used in the calculation for a specific year.

3.4 Calculation of Annual Costs

All "future" costs were converted to a present worth and then annualized. The following formulas were used:

$$PW = F\left[\frac{1}{(1+i)^n}\right]$$

and

$$A = PW\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

where PW = present worth
A = annual cost
n = number of years
i = discount rate (fixed at 4 percent)

The VOCs were accumulated for each year and adjusted to a present worth. Project specific costs were converted to a present worth for the year in which they occurred.

Using the process, the following annualized costs were estimated:

Time Between AC Overlays (n) (years)	Total Annualized Costs ($)
2	42,393
4	22,128
6	16,112
8	13,681
10	12,610
12	12,965
14	12,835
16	13,749
18	13,922

For these "typical" conditions, the minimum life cycle costs occur between 10 to 14 years after rehabilitation. These ages would occur within a PSC range of 70 to 40 (using the assumed PSC - Age relationship for Interstate ACP in the Olympic Region).

4. SUMMARY

Minimum life cycle costing illustrated by the example in this appendix supports the currently used WSDOT criterion of project due dates at a PSC of 50. The generated cost data tended to vary within a few hundred dollars annually between 10 to 14 years after rehabilitation. This range of "optimal" ages results in a PSC range of 70 to 40 and an IRI range of 2.2 to 3.4 (using the equations in this appendix).