

**Final Research Report**  
Research Project T2695, Task 26  
HDM-4 2004

**APPLICATION OF HDM-4  
IN THE WSDOT HIGHWAY SYSTEM**

by

Jianhua Li  
Research Assistant

Stephen T. Muench  
Assistant Professor

Joe P. Mahoney  
Professor

George C. White  
Research Engineer

Department of Civil and Environmental Engineering  
University of Washington

Linda M. Pierce  
State Pavement Engineer  
Washington State Department of Transportation

Nadarajah Sivanewaran  
State Pavement Management Engineer  
Washington State Department of Transportation

**Washington State Transportation Center (TRAC)**  
University of Washington, Box 354802  
1107 NE 45th Street, Suite 535  
Seattle, Washington 98105-4631

Prepared for  
**Washington State Transportation Commission**  
Department of Transportation  
and in cooperation with  
**U.S. Department of Transportation**  
Federal Highway Administration

July 2004

1. REPORT NO. <b>WA-RD 588.1</b>		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE  <b>APPLICATION OF HDM-4 IN THE WSDOT HIGHWAY SYSTEM</b>				5. REPORT DATE <b>July 2004</b>	
				6. PERFORMING ORGANIZATION CODE	
7. AUTHORS <b>Jianhua Li, Stephen T. Muench, Joe P. Mahoney, George C. White, Linda M. Pierce, Nadarajah Sivaneswaran</b>				8. PERFORMING ORGANIZATION CODE	
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>Washington State Transportation Center University of Washington, Box 354802 University District Building, 1107 NE 45<sup>th</sup> Street, Suite 535 Seattle, Washington (8504-7370)</b>				10. WORK UNIT NO.	
				11. CONTRACT OR GRANT NUMBER <b>Research Project T2695, Task 26</b>	
12. SPONSORING AGENCY NAME AND ADDRESS <b>Research Office Washington State Department of Transportation Transportation Building, MS 47370 Olympia, Washington 98504-7370 Project Manager: Keith Anderson, 360-709-5405</b>				13. TYPE OF REPORT AND PERIOD COVERED <b>Final Research Report</b>	
				14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES					
16. ABSTRACT <p>This project performed extensive study and systematic research on the application of the Highway Development and Management system (HDM-4) to the Washington State Department of Transportation (WSDOT) highway system. Data processing, testing, calibration, and analysis were executed to provide the WSDOT with a new budget planning tool. HDM-4 flexible pavement deterioration models were calibrated with the assistance of the Washington State Pavement Management System. A method to calibrate concrete pavement deterioration models is proposed. This research also explored the application of HDM-4 analysis at the project, program, and strategic levels. The applications include prediction of pavement conditions during a defined analysis period, calculation of required budgets for optimal pavement conditions and maximum economic indicators, establishment of optimized work programs under varying levels of constrained budgets, and other applications for WSDOT.</p>					
17. KEY WORDS <b>pavement management, pavement performance, models, HDM-4, vehicle operating costs, pavement preservation, pavement maintenance</b>				18. DISTRIBUTION STATEMENT	
19. SECURITY CLASSIF. (of this report)		20. SECURITY CLASSIF. (of this page)		21. NO. OF PAGES	22. PRICE



## **DISCLAIMER**

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Washington State Department of Transportation, or Federal Highway Administration. This report does not constitute a standard, specification, or regulation.



# TABLE OF CONTENTS

<b>1: INTRODUCTION .....</b>	<b>1</b>
1.1: Introduction to the Highway Development and Management System .....	1
1.1.1: Background .....	1
1.1.2: Functions .....	1
1.2: WSDOT Background .....	3
1.3: Research Objectives .....	5
1.4: Research Process .....	5
1.4.1: Data Preparation .....	5
1.4.2: Calibration .....	6
1.4.3: Output Analysis .....	6
1.5: Report Organization .....	7
<b>2: DATA INPUT .....</b>	<b>8</b>
2.1: Data Sources .....	8
2.1.1: Introduction to the WSPMS .....	8
2.1.2: Flexible Pavement Distress Data Conversion .....	8
2.1.3: Concrete Pavement Distress Data Conversion .....	13
2.2: Road Networks .....	16
2.3: Vehicle Fleets .....	18
2.4: Works Standards for Asphalt Concrete-Surfaced Flexible Pavements .....	19
2.4.1: 45-mm Overlay .....	20
2.4.2: Input Table for 45-mm Mill and Fill .....	26
2.4.3: Input Table for Pothole Patching .....	27
2.5: Road Works Standards for Concrete Pavements .....	27
2.5.1: Diamond Grinding .....	28
2.5.2: Reconstruction .....	29
2.6: Road Works Standards for BST-Surfaced Flexible Pavements .....	30
2.7: HDM-4 Configuration .....	31
2.7.1: Traffic Flow Patterns .....	31
2.7.2: Speed Flow Types .....	32
2.7.3: Climate Zones .....	35
<b>3: CALIBRATION OF ROAD DETERIORATION MODELS .....</b>	<b>40</b>
3.1: Calibration Classification .....	40
3.1.1: Surface Types .....	40
3.1.2: Traffic .....	41
3.1.3: Climate .....	41
3.2: Calibration Tool: LIMDEP .....	42
3.3: Calibration of Deterioration Models for Flexible Pavements .....	43
3.3.1: Primary Modeling Factors .....	43
3.3.2: Proposed Calibration Methodology .....	45
3.3.3: Determination of Calibration Coefficients .....	46
3.3.4: Simplified Deterioration Models for AC-Surfaced Flexible Pavements ...	50
3.3.5: Simplified Deterioration Models for BST-Surfaced Flexible Pavements .	57

3.3.6: Calibration Steps and Results .....	60
3.3.7: Validation of Modeling Factors .....	64
3.4: Calibration of Deterioration Models for Concrete Pavements .....	68
3.4.1: Proposed Calibration Methodology .....	68
3.4.2: Determination of Calibration Coefficients .....	69
3.4.3: Simplified Pavement Deterioration Models for Concrete Pavements .....	70
3.4.4: Fatal Errors in HDM-4 Outputs for Concrete Pavements.....	71
<b>4: OUTPUT ANALYSIS .....</b>	<b>76</b>
4.1: Project Level Analysis .....	76
4.1.1: Analysis Methods .....	76
4.1.2: Reports Generated.....	76
4.1.3: Analysis Results.....	77
4.2: Program Level Analysis.....	86
4.2.1: Multi-Year Forward Program .....	87
4.2.2: Life-Cycle Analysis .....	89
4.3: Strategic Level Analysis .....	90
4.3.1: Road Network Data .....	91
4.3.2: Optimized Road Maintenance and Development Plans .....	92
4.3.3: WSDOT Funds .....	92
4.3.4: Road Performance Under Varying Levels of Budgets .....	93
4.3.5: Economic Indicators Under Varying Levels of Budgets .....	98
4.3.6: Optimized Allocation of Defined Budgets .....	98
<b>5: CONCLUSIONS AND SUMMARY.....</b>	<b>102</b>
5.1: Conclusions.....	102
5.2: Summary .....	102
<b>REFERENCES.....</b>	<b>104</b>
<b>LIST OF APPENDICES .....</b>	<b>106</b>

# FIGURES

<u>Figure</u>	<u>Page</u>
1 Report organization.....	7
2 Works effects on roughness in HDM-4 .....	23
3 Works effects on roughness by WSDOT.....	23
4 Simulation of roughness performance after diamond grinding .....	28
5 Speed-flow relationships on multi-lane highways.....	33
6 Speed-flow curves with criteria .....	33
7 Speed-flow and percentage of time-spent-following flow relationships for directional segments with base conditions.....	34
8 Six climate zones of Washington state .....	38
9 Flexible pavement distress interaction.....	43
10 Faulting forecasting by different analysis periods.....	73
11 IRI forecasting by different analysis periods .....	73
12 HDM-4 distress data input interface .....	74
13 Roughness under two alternatives for concrete pavements .....	74
14 Roughness of I-405 MP 13.82-15.17 (D) under four alternatives .....	78
15 Average roughness of all I-405 flexible pavements .....	79
16 Cracking of SR 21 MP 130.4-153.0 (I) for 40 years .....	80
17 Average roughness of all I-5 flexible pavements for five years .....	89
18 Average volume capacity ratio of all I-5 flexible pavements for five years..	89
19 Roughness of all ACPs under varying budgets.....	94
20 Roughness of all BSTs under varying budgets.....	94
21 Surface damage of all ACPs under varying budgets .....	95
22 Surface damage of all BSTs under varying budgets.....	95
23 Roughness of all ACPs under WSDOT scenarios .....	97
24 Damaged area of all ACPs under WSDOT scenarios.....	97



## TABLES

<u>Table</u>	<u>Page</u>
1 Categories of road network input tables .....	17
2 Values of WP and Elane .....	18
3 Maintenance standard for 45-mm overlay .....	25
4 Maintenance standard for 45-mm mill and fill .....	26
5 Maintenance standard for pothole patching .....	27
6 Maintenance standard for diamond grinding .....	29
7 Maintenance standard for reconstruction .....	29
8 Maintenance standard for bituminous surface treatment .....	30
9 Volume composition in the commuter traffic flow pattern .....	31
10 Volume composition in the inter-urban/rural flow pattern .....	31
11 Volume composition in the seasonal flow pattern .....	31
12 FFS adjustment for lane width and shoulder width .....	32
13 FFS adjustment for access-point density .....	32
14 FFS adjustment for lateral clearance .....	33
15 Speed flow types in Washington state .....	34
16 Moisture categories .....	35
17 Temperature categories .....	35
18 Climate zones in HDM-4 .....	36
19 WSDOT's climate zones by county .....	39
20 Climate indices for six climate zones in Washington state .....	39
21 Climate indices for Western Washington and Eastern Washington .....	42
22 Climate categories of Washington state .....	42
23 Calibration factors in flexible pavement deterioration models .....	44
24 Sensitivity classes for RDWE factors .....	45
25 Values of ICA, ICW, ICT and IRV .....	49
26 Estimated factors for high ESAL ACPs .....	61
27 Estimated factors for medium ESAL ACPs .....	62

28	Estimated factors for low ESAL ACPs.....	63
29	Estimated factors for all BSTs .....	64
30	Climate index for one climate zone of Washington state .....	65
31	Maintenance standards for flexible pavements.....	66
32	Traffic composition and annual growth rate for ACPs.....	66
33	Validated calibration factors for flexible pavements .....	67
34	Calibration factors used in concrete pavement deterioration models .....	68
35	Main road network data for concrete pavement tests .....	72
36	Current conditions of I-405 MP 13.82-15.17 (D).....	79
37	Vehicle composition of I-405 MP 13.82-15.17 (D).....	79
38	Pavement conditions of SR 21 MP 130.4-153.0 (I).....	81
39	Traffic composition and growth rates of SR 21 MP 130.4-153.0 (I).....	81
40	Costs and schedule of 45-mm overlay for SR 405 MP 13.82-15.17 (D).....	82
41	Costs and schedule of 45-mm mill and fill for I-405 MP 13.82-15.17 (D)...	82
42	Costs and schedule of pothole patching for I-405 MP 13.82-15.17 (D).....	83
43	Summary of total annual costs for all I-405 flexible sections .....	84
44	Economic indicators for I-405 MP 13.85-15.17 (D).....	85
45	Total economic benefits for all I-405 flexible sections .....	86
46	Traffic composition and growth rates of I-5 .....	87
47	Optimized work program for all I-5 flexible sections for five years .....	88
48	WSDOT historical funds for pavement maintenance .....	92
49	WSDOT funding scenarios .....	96
50	Economic indicators under varying levels of budgets for all ACPs .....	98
51	Optimized work program under the current WSDOT budget for ACPs .....	99



## **1: INTRODUCTION**

### **1.1: INTRODUCTION TO THE HIGHWAY DEVELOPMENT AND MANAGEMENT SYSTEM (HDM-4)**

#### **1.1.1: Background**

The Highway Development and Management System (HDM-4), originally developed by the World Bank for international use, is a software tool for systematically addressing these issues. HDM-4 can provide road performance prediction, road treatment programming, funding estimates, budget allocation, project appraisal, policy impact studies, and a wide range of special applications. However, its effectiveness is dependant on its ability to accurately model and predict pavement performance, which is affected by numerous factors including structural design, materials, construction variability, traffic, vehicle operating costs, environmental considerations, as well as maintenance and rehabilitation practices. Therefore, in order to effectively use HDM-4, its predictive models must be calibrated to local conditions. While Tonga, Thailand, India, Canada and several other counties have calibrated some HDM-4 models to their local conditions, there is no evidence that this calibration is valid for Washington State. To date, there has been no thorough documented calibration and application of HDM-4 in the U.S. (Kerali et al., 2000b).

#### **1.1.2: Functions**

HDM-4 can be used for four basic functions: project analysis, program analysis, strategic analysis, and research and policy studies. They are briefly described as follows:

1. Project analysis evaluates one or more specific road project or investment options in short-term planning. By associating costs and benefits, the application analyzes

- individual sections with user-selected treatments and determines economic indicators for different investment options. It provides a detailed economic appraisal of each option by considering pavement structure performance, life-cycle predictions of road deterioration and maintenance effects, road-user costs and benefits, and economic comparisons of project alternatives.
2. Program analysis primarily prioritizes a defined list of candidate road projects into a one-year or multi-year roadwork and expenditure program under a constrained budget. A list of candidate road projects is selected as discrete segments defined by homogeneous physical properties. By using the life-cycle analysis method or the multi-year analysis method, the optimal combination of road works options maximizes Net Present Value (NPV) for the whole network, subject to the sum of treatment costs being less than the available budget.
  3. Strategic analysis examines a road network as a whole over the long term. This typically involves expenditure estimates for road network development and preservation under various budget and economic scenarios. Typical applications include fund requirements for specified target road maintenance standards, long-term forecasts on road network performance under varying levels of budgets, optimal allocation of funds to sub-networks, and policy studies.  
  
Strategic analysis aggregates individual road segments into various user-defined categories (e.g., combinations of traffic volume, pavement type and condition, climate zones). HDM-4 then analyzes each category over a defined time period.
  4. Policy studies include funding policies for competing needs, road-user charges for setting up road funds, impacts of road transport policy changes on energy

consumption, impact of axle load limits, and pavement preservation standards (Kerali, 2000a).

## **1.2: WSDOT BACKGROUND**

Pavement maintenance is a major and important process for state departments of transportation. For the Washington State Department of Transportation (WSDOT), this task covers approximately 18,000 lane-miles of pavements, 3,300 bridges, and 100,000 acres (WSDOT, 2001).

Currently, WSDOT applies pavement preservation on a “least life cycle cost” basis, but numerous factors such as structural design, materials applied, construction variability, traffic, environment, and maintenance/rehabilitation types can affect the prediction capability of pavement performance. Maintenance treatments and pavement preservation applied on a preventative basis can extend pavement life and lead to more cost-effective pavement performance, which, in turn, provides a more cost-effective expenditure of maintenance and preservation funds.

The WSDOT Fiscal Year (FY) 2001-2003 rehabilitation funds were \$267.4 million, but the current FY 2004-2005 budget is constrained to \$240 million—a reduction of 10.2%. With constrained budgets, what level of preservation and maintenance will result in optimized pavement conditions? What are the tradeoffs between increased/decreased preservation and maintenance budgets?

To address these issues, HDM-4 was introduced to improve the pavement maintenance/preservation process. The application of HDM-4 to the WSDOT road network can be beneficial at the project, program, and strategic levels.

At project level, HDM-4 is able to benefit WSDOT by the functions of more accurate prediction of pavement performance, quantification of pavement maintenance/preservation benefits, determination of what, when, and where for pavement maintenance/preservation, and examination of budget tradeoffs and impacts on pavement performance.

At the program level, HDM-4 can assist WSDOT in planning biennial road works and expenditure budgets. Once decision makers assign those budgets, HDM-4 can prioritize desired road works to make optimal use of available funds.

At a strategic level, HDM-4 is beneficial because it can

- forecast long-term road network performance based on proposed levels of budgets. This can provide decision makers with a clear and convincing picture of their fund level impacts
- determine budget requirements for a specified set of target road maintenance/preservation standards, which can provide a baseline optimal budget level to present to decision makers
- optimize fund allocations to sub-networks (e.g., by functional road classification or administrative region). This can help WSDOT better allocate existing funds to achieve the optimal benefits.

These capabilities will be immediately beneficial to WSDOT. At the research and policy levels, WSDOT and decision makers can see the potential impacts of policy changes, including the impact of changes to the axle load limit, maintenance/preservation trigger standards, or pavement design standards (Kerali, 2000a).

### **1.3: RESEARCH OBJECTIVES**

Although HDM has been applied in more than 100 countries, most recorded applications have been in developing countries. In recent years, however, many industrialized countries have begun to adopt its economic approach and principles, but no thorough application has been documented in the U.S.

This research used HDM-4 to analyze the WSDOT highway facilities for systematic maintenance and rehabilitation. This analysis includes developing predictive strategies for the selection and timing of maintenance/preservation treatments, developing a detailed examination of road works standards, and developing a process for analyzing varying budget levels and their pavement impacts for the WSDOT highway system.

Because HDM-4 predicts future road performance from current and/or historical conditions, the reliability of its results depends upon how well input data represent actual conditions and how well HDM-4 predictions model actual behavior (Kerali, 2000a).

As the first thorough application of HDM-4 in the U.S., this research mainly focused on acquisition of data and calibration of deterioration models. The results will be a view of the effectiveness of various WSDOT preservation funding levels.

### **1.4: RESEARCH PROCESS**

WSDOT implementation of HDM-4 involves four major tasks: 1) data transfer from the Washington State Pavement Management System (WSPMS) and independent data gathering, 2) model calibration, and 3) output analyses.

#### **1.4.1: Data Preparation**

WSPMS contains a historical archive of WSDOT highway pavement condition



data. Most of the required input data for HDM-4 were obtained from the WSPMS either directly or indirectly. An automated method of data transfer between the WSPMS and HDM-4 were developed. This method is capable of directly transferring applicable values from an existing WSPMS database to a new HDM-4 database, and manipulating existing values from WSPMS to input into HDM-4. Since WSPMS data are dynamic, automatic data transfer is critical to HDM-4's current and future usability.

A large portion of the required HDM-4 data is essentially independent of WSPMS data. These data, such as climate zones, traffic-flow schemes and default pavement conditions, were developed and input into HDM-4.

#### **1.4.2: Calibration**

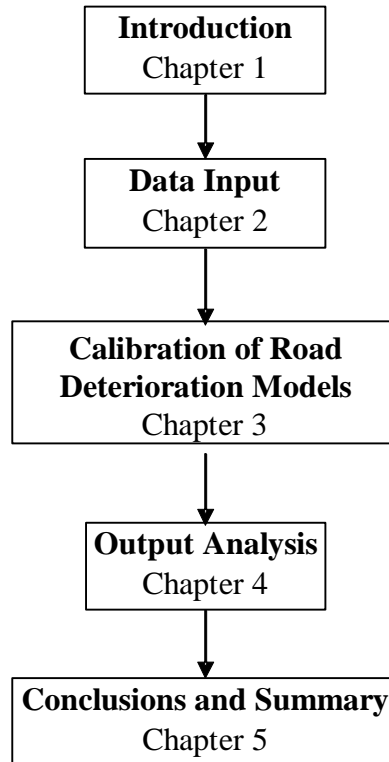
Although HDM-4 models were developed with broad-based applicability in diverse climates and conditions, the accuracy of the predicted pavement performance still depends on the extent of calibration, which was applied to adapt the default HDM-4 models to local conditions.

#### **1.4.3: Output Analysis**

HDM-4 has three levels of analysis: project level, program level, and strategic level. Each has different functions for pavement management. The HDM output results include costs, traffic, pavement deterioration conditions, pavement preservation effects, road-user effects, environmental effects, and various program and strategic reports (Kerali et al., 2000b). Further research, such as cost-benefit analyses, was carried out to confirm the feasibility of the final results.

## **1.5: REPORT ORGANIZATION**

Figure 1 shows the organization of this report.



**Figure 1: Report organization**

**Chapter 2** introduces ways to modify HDM-4 configurations and accommodate WSDOT inputs.

**Chapter 3** addresses detailed procedures for deterioration model calibration. Flexible and concrete pavements were modeled separately in HDM-4. Ways to adapt WSDOT's data to the HDM-4 deterioration models are also discussed.

**Chapter 4** describes HDM-4 applications at the analysis, program, and strategic levels for WSDOT.

**Chapter 5** draws the main conclusions of this research and summarizes the report.

## **2: DATA INPUT**

### **2.1: DATA SOURCES**

#### **2.1.1: Introduction to the WSPMS**

The WSPMS is both a historical archive of WSDOT highway pavement condition data and a tool to schedule and predict WSDOT road network preservation demands.

WSDOT collects and analyses the pavement distress conditions and updates the database every year. The most up-to-date version is WSPMS 2003, which records the road condition data of 2002.

The WSPMS organizes data into analysis units and project units. An analysis unit contains homogeneous pavement sections that are structurally uniform (same type of materials and thicknesses). Project units are established according to similar pavement performance criteria and made up of one or more analysis units (WSPMS, 2003).

Most calibration variables and road network input data for HDM-4 were derived from project units. Some specific calibration variables were generated from analysis units.

To convert the WSPMS data into an acceptable form for HDM-4 input, transformation rules are necessary. A wide range of data types are required for HDM-4, which include vehicle fleet characteristics, road maintenance and improvement standards, unit costs, and economic analysis factors. These are stored in the HDM-4 internal database. The physical attributes of the selected data objects must be exported to a data exchange file format defined for HDM-4, which is dBase file format [\*.DBF (IV)]. Additional details on inputting data into HDM-4 are discussed in sections 2.1.2 and 2.1.3.

#### **2.1.2. Flexible Pavement Distress Data Conversion**

HDM-4 models six types of flexible pavement distress: cracking, rut depth,

roughness, potholes, edge-break and raveling. Since WSDOT does not measure and record edge-break data, this research assumes edge break has a value. WSPMS represents rut depth, raveling, and roughness in the same way required by HDM-4 so that data can be used directly. WSDOT and HDM-4 characterize cracking using different methods, thus a conversion method from WSDOT to HDM-4 was developed. This is explained in section 2.1.2.1

### **2.1.2.1: WSDOT Characterization of Cracking**

WSDOT uses the pavement structural condition (PSC) to characterize flexible pavement cracking (Kay et al., 1993). WSDOT considers the following items for PSC determination. Note that since there are two wheel paths, a 100-foot lane actually has 200 feet of wheel paths for measurement purposes. Therefore, a measurement of 100 percent would mean that both wheel path lengths are completely cracked.

- **Alligator (fatigue) cracking (ACEC):** the percentage of the wheel path length that contains alligator cracks. Since there are two wheel paths, a 100-foot lane has 200 feet of wheel paths for measurement (i.e., a measurement of 100 percent means that both wheel path lengths are completely cracked).

Severity is divided into three levels:

AC1 = hairline

AC2 = spalled

AC3 = spalled and pumping

- **Longitudinal cracking (LCEC):** the percentage of a 100-foot section length that contains longitudinal cracking. Severity is divided into three levels:

LC1 = less than ¼ inch wide

LC2 = more than ¼ inch wide

LC3 = spalled

- **Transverse cracking (TCEC):** the number of transverse cracks per 100-foot section length. Severity is divided into three levels:

TC1 = less than ¼ inch wide

TC2 = more than ¼ inch wide

TC3 = spalled

- **Patching (PTEC):** WSDOT considers patching to be a structural defect and quantifies it using the percentage of the wheel path lengths that contains patches. The extent of patching is represented as the percentage of both wheel paths. Severity is divided into three levels:

PT1 = BST patching

PT2 = blade (cold mix) patching

PT3 = full depth patching

The total Equivalent Cracking (EC) is the sum of ACEC, LCEC, TCEC and PTEC. The calculation of PSC is:

$$ACEC = AC3 + 0.445(AC2)^{1.15} + 0.13(AC1)^{1.35}$$

$$LCEC = (0.1LC3) + 0.445(0.1LC2)^{1.15} + 0.13(0.1LC1)^{1.35}$$

$$TCEC = (0.8TC3) + 0.445(0.8TC2)^{1.15} + 0.13(0.8TC1)^{1.35}$$

$$PTEC = (PT3) + 0.445(0.75PT2)^{1.15} + 0.13(0.75PT1)^{1.35}$$

$$EC = ACEC + LCEC + TCEC + PTEC$$

$$PSC = 100 - 15.8(EC)^{0.5} \quad (2.1)$$

### **2.1.2.2: HDM-4 Characterization of Cracking**

HDM-4 uses the following factors to characterize flexible pavement cracking:

- **Total cracked area of the carriageway (ACA):** the percentage of the total carriageway surface area that is cracked.
- **Percentage of total cracking that is wide structural cracking (ACW):** the percentage of ACRA that constitutes wide structural cracking, defined as cracks greater than 3 mm wide.
- **Transverse thermal cracking (ACT):** the number of transverse thermal cracks per kilometer of roadway length. The number of transverse thermal cracks is capped by setting a time (in years), since thermal crack initiation, to reach the maximum amount of thermal cracking.

Unlike WSDOT, which uses wheel path length, HDM-4 quantifies cracking by the percentage of total carriageway area that is cracked.

### **2.1.2.3: Conversion Method**

In order to make HDM-4 results meaningful for WSDOT, HDM-4 must replicate, as closely as possible, the methods that WSDOT uses to trigger works standards.

Fortunately, rut depth and roughness use the same measurement definitions in both systems. Unfortunately, this is not the case with cracking. The following presents conversion methodologies for the various HDM 4 cracking categories:

#### **All Structural Cracking (ACA)**

WSMPS categories of alligator (fatigue) cracking and longitudinal cracking will be added to give a total area of cracking. No distinction between severity levels is made.

The wide structural cracking variable will account for severity throughout the area

concerned. In order to convert a linear crack to an area, each wheel path is assumed to be 3 feet wide, and a fully cracked 1.5 x 1.5 ft<sup>2</sup> pavement block contains a fully developed longitudinal and a fully developed transverse crack. Therefore:

$$\begin{aligned}
 100\% \text{ AC} &= (3+3) \text{ longitudinal cracks} + (100/1.5) \text{ transverse cracks} \\
 &= 6 * (100 \text{ ft.}) + 66.7 * (3 \text{ ft.} + 3 \text{ ft.}) \\
 &= 10 * (100 \text{ ft.}) \\
 &= 10 \text{ longitudinal cracks (full 100-foot section length)} \\
 &= 1000\% \text{ of longitudinal cracking}
 \end{aligned}$$

And,

$$\begin{aligned}
 100\% \text{ AC} &= 1000\% \text{ LC} \\
 \text{AC} &= 0.1 \text{ LC}
 \end{aligned} \tag{2.2}$$

Assume that two wheel paths defined by WSDOT constitutes 50% of the total pavement area (2 wheel paths = 6 feet wide, assume the lane is 12 feet wide). Therefore, WSDOT percentages are divided by 2 to match HDM-4 percentages.

$$\text{ACA} = \frac{\text{AC1} + \text{AC2} + \text{AC3}}{2} + 0.1 * \frac{\text{LC1} + \text{LC2} + \text{LC3}}{2} \tag{2.3}$$

### **Wide Structural Cracking Area (ACW)**

WSPMS categories of alligator (fatigue) cracking and longitudinal cracking at severity level “medium” or “high” are added to give a total area of wide structural cracking. Since WSPMS “medium” severity level is defined by cracks at least 6 mm wide, all “medium” severity cracks count as wide structural cracking. Since WSPMS “high” severity level cracks are more advanced and in poorer condition than “medium” severity level cracks, all “high” severity cracks count as wide structural cracking.

$$ACA = \frac{AC2 + AC3}{2} + 0.1 * \frac{LC2 + LC3}{2} \quad (2.4)$$

### **Transverse Thermal Cracking (ACT)**

The WSPMS category of transverse cracking can be converted to an HDM-4 definition for “transverse thermal cracking” by applying a constant to convert from cracks-per-100 feet to cracks-per-kilometer:

$$ACT = 32.81(TC1 + TC2 + TC3)$$

$$100 \text{ ft} = 0.03048 \text{ km}$$

$$1 \text{ km} = 3280.83 \text{ ft.} \quad (2.5)$$

### **Patching**

WSPMS uses patching as a contributor to PSC, but HDM-4 models patching independent of cracking. To avoid confusion, the contribution of patching to PSC will be ignored. This is a reasonable assumption because the incidence of pavement patching on WSDOT roads is relatively low (Muench, 2003b).

### **2.1.3: Concrete Pavement Distress Data Conversion**

HDM-4 characterizes concrete pavement deterioration differently than the WSPMS. Therefore, a method of converting WSPMS distress characterization to HDM-4 characterization must be developed. This section outlines conversion methodologies for pavement distress.

#### **2.1.3.1: WSDOT Characterization**

WSDOT uses PSC to characterize concrete pavement deterioration (Kay et al., 1993), and the following items are considered in PSC determination:



- **Slab cracking (CREC):** the percentage of slabs that are cracked. Severity is divided into three levels:

CR1 = percentage of slabs with 1 crack per panel

CR2 = percentage of slabs with 2 or 3 cracks per panel

CR3 = percentage of slabs with 4 or more crack per panel

- **Joint and crack spalling (JSEC):** the percentage of joints and cracks that are spalled. Severity is divided into three levels:

JS1 = percentage of joints/cracks with 1/8 – 1 inch spalls

JS2 = percentage of joints/cracks with 1 – 3 inch spalls

JS3 = percentage of joints/cracks with > 3 inch spalls

- **Pumping and blowing (PMEC):** the percentage of joints and cracks that are pumping. Severity is divided into three levels:

PM1 = percentage of joints/cracks pumping (slight shoulder depression, little or no staining)

PM2 = percentage of joints/cracks pumping (moderate shoulder depression, obvious staining)

PM3 = percentage of joints/cracks pumping (severe shoulder depression, significant staining)

- **Faulting and settlement (FLTEC):** the percentage of all panels that exhibit joints or cracks that are faulting or settling. Three severity levels are:

FLT1 = percentage of panels with 1/8 to 1/4 inch faulting or settlement

FLT2 = percentage of panels with 1/4 to 1/2 inch faulting or settlement

FLT3 = percentage of panels with > 1/2 inch faulting or settlement

- **Patching (PTEC):** the percentage of panels in the travel lane that are patched. Severity is divided into three levels:
  - PT1 = percentage of panels patched (1 to 9 percent of surface covered)
  - PT2 = percentage of panels patched (10 to 24 percent of surface covered)
  - PT3 = percentage of panels patched (> 25 percent of surface covered)
- **Raveling and scaling (RSEC):** the percentage of panels that exhibit raveling, scaling, map cracking, or crazing. Severity is divided into three levels:
  - RS1 = percentage of pavement surface with slight raveling or scaling
  - RS2 = percentage of pavement surface with moderate raveling or scaling
  - RS3 = percentage of pavement surface with severe raveling or scaling

PSC is calculated by Equation 2.6:

$$CREC = CR3 + 0.24(CR2)^{1.16} + 0.0054(CR1)^{1.84}$$

$$JSEC = 0.075(JS3)^{1.14} + 0.0061(JS2)^{1.27} + 0.0034(JS1)^{1.03}$$

$$PMEC = 0.0069(PM1 + PM2 + PM3)^{1.45}$$

$$FLTEC = FLT3 + 0.0915(FLT2)^{1.46} + 0.00115(FLT1)^{2.32}$$

$$PTEC = 0.103(PT3)^{1.19} + 0.0079(PT2)^{1.55} + 0.00194(PT1)^{1.57}$$

$$RSEC = 0.052(RS3)^{1.29} + 0.0159(RS2)^{1.18} + 0.0014(RS1)^{1.18}$$

$$EC = CREC + JSEC + PMEC + FLTEC + PTEC + RSEC$$

$$PSC = 100 - 18.6(EC)^{0.43}$$

(2.6)

### **2.1.3.2: HDM-4 Characterization**

HDM-4 uses the following to characterize concrete pavement deterioration:

- **Cracked slabs (CRACKSLABS):** the percentage of slabs that are cracked.

- **Faulting (FAULT):** the average fault height in millimeters.
- **Spalled joints (SPALL\_JNTS):** the percentage of joints that are spalled.  
Spalling is assumed to be 75 to 100 mm
- **Panel failures per km (FAILURESKM):** the number of failed panels per kilometers of roadway.

### 2.1.3.3: Proposed Conversion Methods

HDM-4 counts low and medium severity levels of cracking and high severity level of spalling. For faulting, WSPMS measures it in terms of the percentage of slabs that are faulted, but HDM-4 measures it in terms of the average height of the faults. Thus, the conversion from WSPMS to HDM-4 is listed as follows (Muench, 2003c).

$$\text{CRACKSLABS (\%)} = (\text{CR1} + \text{CR2})$$

$$\text{FAULT (mm)} = 4.7625 * \text{FLT1} + 9.525 * \text{FLT2} + 12.7 * \text{FLT3}$$

$$\text{SPALL\_JNTS (\%)} = \text{JS3}. \tag{2.7}$$

## 2.2: ROAD NETWORKS

In HDM-4, road networks store characteristics of road sections, which are the fundamental unit of the analysis. Each road network contains a detailed listing of each road section chosen for analysis. Sections, links, and nodes are the three data entities supported within the road network:

- **Sections** are lengths of roads over which physical characteristics are reasonably constant. Sections defined in this research will follow the definition of project units in WSPMS, where each section has uniform pavement layers, geometry, and traffic conditions over its entire length.

- **Links** comprise one or more sections over which traffic is reasonably constant. Links defined in this research are state route numbers.
- **Nodes** are used to mark intersections where links have a significant change in traffic, carriageway characteristics, or administrative boundaries.

Road network data must be in a dBASE IV format to be imported into HDM-4.

Bridge decks were not considered for this research because WSDOT treats bridges in a separate management system. Because of the data scale limited by HDM-4 computation power, road network data of all state highways are divided into five categories according to different pavement types, surface types, and/or 18 kip Equivalent Single Axle Loads (ESALs). These are listed in Table 1.

**Table 1: Categories of road network input tables**

<b>Pavement Type</b>	<b>Surface Material*</b>	<b>ESAL (ESAL / year/Elane)</b>	<b>Number of Cases</b>
Flexible	AC	High: (500000+)	374
Flexible	AC	Medium: (250000,500000]	512
Flexible	AC	Low: (0, 250000]	1595
Flexible	BST	--	412
Concrete	Concrete pavement	--	615

\*AC denotes asphalt concrete, which is hot mix asphalt, BST indicates bituminous surface treatments.

Because this research only concerns WSDOT highways, in this report, ACP represents the AC-surfaced WSDOT flexible highway, BST stands for the BST-surfaced WSDOT flexible highway, concrete pavements indicates the WSDOT concrete highway.

*Elane* is the effective number of lanes for the road section:

$$Elane = \frac{1}{WP} \tag{2.8}$$

where WP is the lane distribution factor. WP accounts for the distribution of traffic loads on the design lane, which is defined by the 1993 AASHTO Guide. Values adopted by this

research are listed in Table 2.

**Table 2: Values of WP and Elane**

Number of Lanes in Each Direction	Lane distribution factor (WP)		Elane
	1993 ASSHTO Guide	Values adopted	
1	100	100	1
2	80-100	90	1.111
3	60-80	70	1.429
4	50-75	65	1.538
5	-	-	2
≥6	-	-	3

Appendix B1 addresses the data conversion methods from the WSPMS and data definitions for project level analysis. Appendices B2, B3, B4, B5 and B6 are the road network input for all high ESAL ACPs, medium ESAL ACPs, low ESAL ACPs, BSTs, and concrete pavements, correspondingly.

### **2.3: VEHICLE FLEETS**

Vehicle fleets are used to store vehicle characteristics for calculating speeds, operating costs, travel times, and other vehicle effects. WSDOT uses a simplified version of the Federal Highway Administration (FHWA) vehicle classification system, which includes four categories:

1. passenger car
2. single-unit truck. Includes FHWA classes 4, 5, 6 and 7. WSDOT assumes 0.40 ESALs per truck.
3. double-unit truck. Includes FHWA classes 8, 9 and 10. WSDOT assumes 1.00 ESALs per truck.
4. train. Includes FHWA classes 11, 12 and 13. WSDOT assumes 1.75 ESALs per truck (FHWA, 2001).

Appendices C1, C2, C3, and C4 define all vehicle fleet input data for cars, single units, double units, and trains, respectively. Most of the data are not directly available from any single data source. Data sources for this research are listed in Appendix C5. When the data are imported to HDM-4, they can be stored in the HDM-4 internal database as Appendix C6.

#### **2.4: WORKS STANDARDS FOR ASPHALT CONCRETE (AC) SURFACED FLEXIBLE PAVEMENTS**

Road work standards can be used in all three analysis levels. Two kinds of work are defined in HDM-4 for flexible pavements. Improvement standards comprise pavement reconstruction, lane addition, lane upgrading, partial widening, and realignment. Maintenance standards are applied to meet specific objectives that are related to functional characteristics of the road network system. Works for crack sealing, fog seal, edge repair, patching, drainage, edge repair, overlay and flexible pavement reconstruction are included in maintenance standards. Unlike HDM-4, WSDOT classifies road works into two categories: 1) preservation and 2) maintenance, which are both defined as maintenance works in HDM-4. For AC-surfaced flexible pavements, three basic types of road works are normally adopted by WSDOT (WSDOT, 2002). They are

1. 45-mm overlay
2. 45-mm mill and fill
3. pothole patching

To keep all HDM-4 inputs and output reports consistent, this research names all three road works standards as maintenance standards.

### **2.4.1: 45-mm Overlay**

Although other thicknesses have been used, WSDOT typically uses a 45-mm thickness (WSDOT, 2002).

#### **2.4.1.1: Triggers of Rehabilitation Efforts**

##### **WSDOT Characterization**

WSDOT triggers its rehabilitation efforts (termed “preservation”) on the basis of any of the following conditions (Kay, 1993):

- pavement structural condition (PSC)  $\leq 50$
- rut depth  $\geq 10$  mm
- roughness  $\geq 3.5$  m/km

This scheme is heavily weighted toward PSC; therefore, most rehabilitation efforts are triggered by the PSC value. This was done intentionally because rehabilitation triggered by PSC will result in roads that are rehabilitated earlier in their life cycles before an accumulation of defects causes substantial increases in roughness and overall structural deterioration.

##### **HDM-4 Characterization**

HDM-4 uses the following to characterize flexible pavement cracking:

- **Total cracked area of the carriageway (ACA):** the percentage of the carriageway surface area that is cracked.
- **Percentage of total cracking that is wide structural cracking (ACW):** the percentage of ACRA that constitutes wide structural cracking, which is defined as cracks  $> 3$  mm wide.

- **Transverse thermal cracking (ACT):** the number of transverse thermal cracks per kilometer of roadway length. The number of transverse thermal cracks is capped by setting a time (in years) since thermal crack initiation, to reach the maximum number of thermal cracking.

Unlike WSDOT, which uses wheel path area, HDM-4 quantifies cracking by the percentage of the total carriageway area that is cracked.

### **Conversion of WSDOT Rehabilitation Standards to HDM-4**

#### **(a) Cracking**

WSDOT triggers rehabilitation when PSC = 50. Therefore, HDM-4 maintenance trigger levels should simulate this as closely as possible. The only cracking trigger available in HDM-4 is “total carriageway cracking.” Therefore, several assumptions need to be made to convert a PSC trigger level to a total cracking area level:

1. Most cracking is at the AC1 and LC1 levels.
2. When AC2/3 or LC2/3 cracking occurs, it is generally at a much lower level.
3. Transverse cracks do not trigger maintenance.

Straightforward calculations show a relationship between PSC and cracking.

WSDOT triggers rehabilitation at varying lengths of cracking, depending upon the breakdown of severity, so rehabilitation is triggered when:

$$AC1 + AC2 + AC3 + 0.1(LC1 + LC2 + LC3) = 20\% \quad (2.9)$$

Because HDM-4 total pavement area = 2 x (WSDOT wheel path area), trigger rehabilitation in HDM-4 when:

$$ACA \geq 10\% \quad (2.10)$$



### **(b) Rutting**

This value is set the same as WSDOT. HDM-4 triggers rehabilitation when the average rut depth  $\geq 10$  mm.

### **(c) Roughness**

Same as WSDOT, HDM-4 triggers rehabilitation when IRI  $\geq 3.5$  m/km.

In summary, the triggered distress values to set up road works for WSDOT are one of the following:

- total carriageway cracked  $\geq 10\%$
- rut depth  $\geq 10$  mm
- roughness  $\geq 3.5$  m/km (AL-Omari and Darter, 1992).

#### **2.4.1.2: Work Effects of 45-mm Overlay**

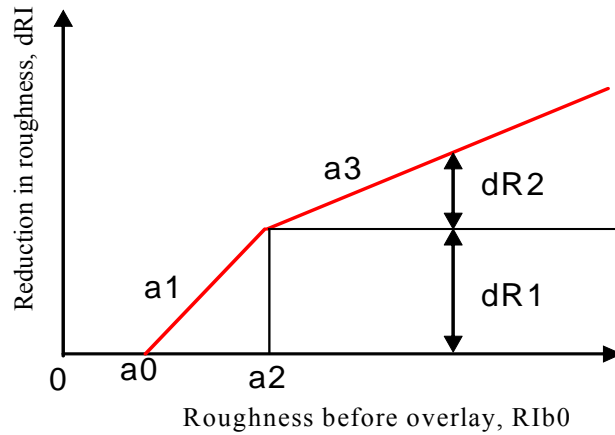
The HDM-4 work-effects model for overlays includes several models for the effects of overlay rehabilitation. These models can be divided into the following:

- **User defined:** Models that accept user input to determine overlay effects
- **Derived:** Models that use existing data to determine overlay effects.

HDM-4 models overlay effects on roughness, rutting, surface texture, and skid resistance. The following discussion focuses on the models for each effect and presents the selected model for use in WSDOT road network.

### **(a) Roughness**

A generalized bilinear model is used for roughness reduction effects in HDM-4. Assuming a bilinear relationship (a line with an inflection point), users may enter their own values for key constants in the relationship.



**Figure 2: Works effects on roughness in HDM-4**

where,

dRI: roughness after overlay (m/km)

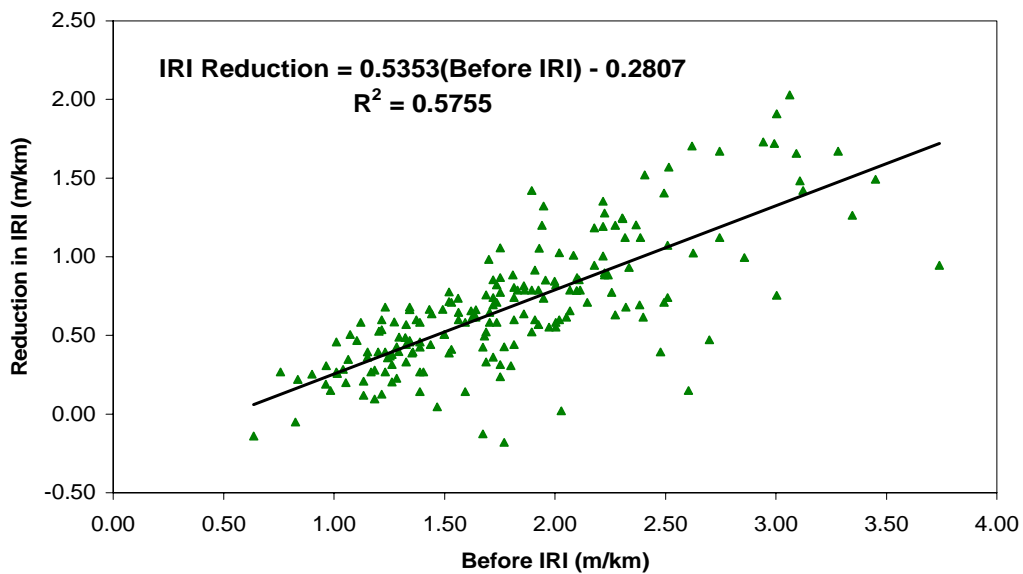
a0: minimum roughness after overlay (m/km)

a1: slope of the first line

a2: intersection point of the two lines (bilinear mode) (m/km)

a3: slope of the second line. A0 to a3 are user-definable factors.

Figure 3 shows WSDOT data for overlays from 1999 to 2001.



**Figure 3: Works effects on roughness by WSDOT**  
[Source: WSDOT Material Laboratory, 2003]

The model in Figure 3 is linear. Although HDM-4 only allows users to specify a bilinear model (see Figure 2), a linear one can be made by setting  $a_1 = a_3$  and  $a_2 = a_0$ . Therefore,  $a_0 = 0.5244$ ,  $a_1 = 0.5353$ ,  $a_2 = 0.5244$ , and  $a_3 = 0.5353$ .

**(b) Rutting**

A derived method resets rut depth to a user-defined percentage of pre-overlay rut depth. On the basis of WSDOT experimental results after overlay rehabilitation, the value of 0 percent is used in HDM-4 rutting reduction models for WSDOT case studies (Corley-Lay, 1998).

**(c) Surface Texture**

The HDM-4 derived method resets surface texture to a predetermined value, depending upon the surface material (= 0.7 mm in almost all cases). HDM-4 surface texture models for an overlay rehabilitation uses 0.7 mm. (Jayawickrama et al., 1998).

**(d) Skid Resistance**

HDM-4 resets surface texture to 0.50 mm in all cases. The value is also used in HDM-4 surface texture models for overlay rehabilitation (Muench, 2003a).

**2.4.1.3: Input Table for 45-mm Overlay**

A 45-mm overlay without milling is typical for medium or low traffic sections in Washington State. On the basis of WSDOT's criteria and the previously stated works-effect analysis, the HDM-4 input data for the 45-mm overlay maintenance standard is listed in Table 3.

**Table 3: Maintenance standard for 45-mm overlay**

<b>General</b>	Name:	45 mm Overlay
	Short Code:	45 OVER
	Intervention Type:	Responsive
<b>Design</b>	Surface Material:	Asphalted Concrete
	Thickness:	45 mm
	Dry Season a:	0.44
	CDS:	1
<b>Intervention</b>	Responsive Criteria:	Total cracked area $\geq$ 10%
		Rutting $\geq$ 10 mm
		IRI $\geq$ 3.5 m/km
	Min. Interval:	1
	Max. Interval:	9999
	Last Year:	2099
	Max Roughness:	16 m/km
	Min ADT:	0
	Max ADT:	500,000
<b>Costs</b>	<b>Overlay</b>	
	Economic:	19 dollars/m <sup>2</sup> *
	Financial:	19 dollars/m <sup>2</sup> *
	<b>Patching</b>	
	Economic:	47 dollars/m <sup>2</sup> *
	Financial:	47 dollars/m <sup>2</sup> *
	<b>Edge Repair</b>	
	Economic:	47 dollars/m <sup>2</sup>
	Financial:	47 dollars/m <sup>2</sup>
<b>Effects</b>	Roughness:	Use generalized bilinear model
	a0 =	0.5244
	a1 =	0.5353
	a2 =	0.5244
	a3 =	0.5353
	Rutting:	Use rutting reset coefficient = 0
	Texture Depth:	Use default values (0.7 mm)
	Skid Resistance:	Use default value (0.5 mm)

[\*Costs are derived from data provided by WSDOT]

## 2.4.2: Input Table for 45-mm Mill and Fill

**Table 4: Maintenance standard for 45-mm mill and fill**

<b>General</b>	Name:	45 mm Mill & Fill
	Short Code:	45MF
	Intervention Type:	Responsive
<b>Design</b>	Surface Material:	Asphalted Concrete
	Depth of Mill:	45 mm
	Thickness:	45 mm
	Dry Season a:	0.44
	CDS:	1
<b>Intervention</b>	Responsive Criteria:	Total cracked area $\geq 10\%$
		Rutting $\geq 10$ mm
		IRI $\geq 3.5$ m/km
	Min. Interval:	-
	Max. Interval:	-
	Last Year:	2099
	Max Roughness:	16 m/km
	Min ADT:	0
	Max ADT:	500,000
<b>Costs</b>	<b>Overlay</b>	
	Economic:	30 dollars/m <sup>2</sup> *
	Financial:	30 dollars/m <sup>2</sup> *
	<b>Patching</b>	
	Economic:	47 dollars/m <sup>2</sup> *
	Financial:	47 dollars/m <sup>2</sup> *
	<b>Edge Repair</b>	
	Economic:	47 dollars/m <sup>2</sup> *
	Financial:	47 dollars/m <sup>2</sup> *
<b>Effects</b>	Roughness:	Use generalized bilinear model
	a0 =	0.5244
	a1 =	0.71
	a2 =	0.5244
	a3 =	0.71
	Rutting:	Use rutting reset coefficient = 0
	Texture Depth:	Use default values (0.7 mm)
	Skid Resistance:	Use default value (0.5 mm)

[\*Costs are derived from data provided by WSDOT]

This type of maintenance is normally used on Interstate routes with high traffic conditions in Washington State. Unlike the 45-mm overlay, the 45-mm mill and fill has improved effects on cracking, so the reduction in roughness is greater. Expressed in the same way as the 45-mm overlay, a1 and a3 are equal to 0.71, instead of 0.5353 based on work reported by Raymond (2002). Additionally, the work costs of milling and filling are added to the overlay costs. The inputs to HDM-4 are listed in Table 4.

### **2.4.3: Input Table for Pothole Patching**

WSDOT patches a pothole as soon as it appears. The criteria and related factors of input to this maintenance standard are listed in Table 5.

**Table 5: Maintenance standard for pothole patching**

<b>General</b>	Name:	Pothole Patching
	Short Code:	POTPAT
	Intervention Type:	Responsive
<b>Intervention</b>	Responsive Criteria:	Potholing $\geq 0.01$ no./km
	Min. Interval:	-
	Max. Interval:	-
	Last Year:	2099
	Max Roughness:	16 m/km
	Max Quantity:	5000 m <sup>2</sup> /km/year
	Min ADT:	0
	Max ADT:	500,000
<b>Costs</b>	Economic:	47 dollars/m <sup>2</sup> *
	Financial:	47 dollars/m <sup>2</sup> *
<b>Effects</b>	Distress Repaired:	100 (%) (potholing only)

[\*Costs are derived from data provided by WSDOT]

## **2.5 ROAD WORKS STANDARDS FOR CONCRETE PAVEMENTS**

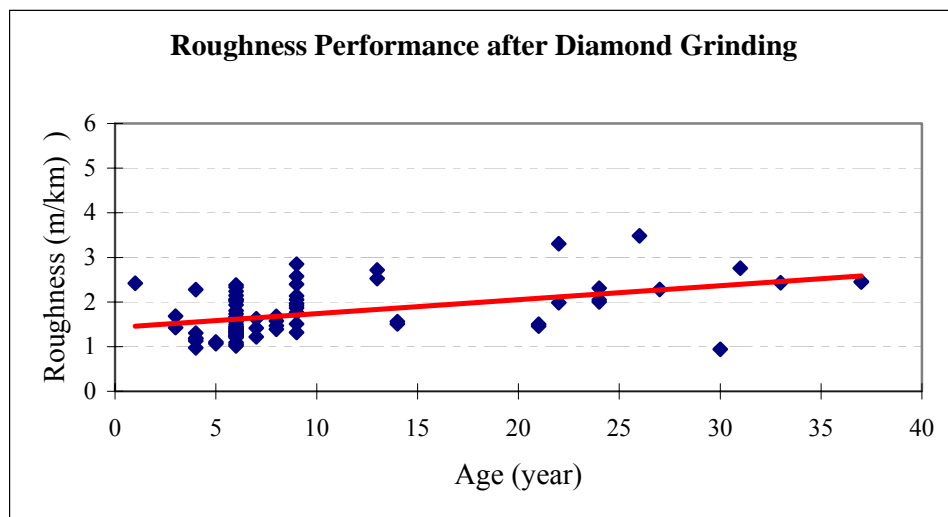
Road works standards adopted by WSDOT are diamond grinding, dowel bar retrofit, and reconstruction. Unlike flexible pavements, all road works for concrete

pavements are defined as maintenance standards by HDM-4. For the same reason described in section 2.4, all three of the above standards were considered to be maintenance standards in this research. In the current HDM-4 version 1.3, dowel bar retrofit can intervene only as scheduled activity—not as a responsive intervention.

### **2.5.1: Diamond Grinding**

In HDM-4, diamond grinding rehabilitation works are triggered by faulting. The criterion for triggering diamond grinding is faulting  $\geq 6$  mm.

HDM-4 measures the works effects of diamond grinding by roughness after works, but no direct roughness value is available. Figure 4 shows selected concrete sections in WSPMS 2003 that have been rehabilitated by diamond grinding. Each point represents one section.



**Figure 4: Simulation of roughness performance after diamond grinding**

A linear model was taken to regress roughness progression. On the basis of the data in Figure 4, the linear model is regressed as  $IRI = 0.0312 * Age + 1.4283$ . This model represents the road performance after diamond grinding. The intercept is the roughness measured immediately following the diamond grinding. roughness = 1.4283 m/km.

**Table 6: Maintenance standard for diamond grinding**

<b>General</b>	Name:	Diamond Grinding
	Short Code:	DG
	Intervention Type:	Responsive
<b>Intervention</b>	Responsive Criteria:	Faulting $\geq$ 6 mm
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	500,000
<b>Costs</b>	Economic:	1 dollars/m <sup>2</sup> /mm *
	Financial:	1 dollars/ m <sup>2</sup> /mm *
<b>Effects</b>	Grinding thickness:	8 mm
	Roughness:	1.4283 m/km

[\*Costs are derived from data provided by WSDOT]

**2.5.2: Reconstruction**

HDM-4 triggers reconstruction works similarly to WSDOT, when the total carriageway is cracked  $\geq$  10 percent, and it measures the works effects of reconstruction by the percentage of the slab replaced after works. For WSDOT, all slabs will be replaced. Thus, the works standard for reconstruction is shown in Table 7:

**Table 7: Maintenance standard for reconstruction**

<b>General</b>	Name:	Reconstruction
	Short Code:	RECON
	Intervention Type:	Responsive
<b>Intervention</b>	Responsive Criteria:	% of cracked slabs $\geq$ 10%
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	500,000
<b>Costs</b>	Economic:	169.9 dollars/m <sup>2</sup> *
	Financial:	169.9 dollars/m <sup>2</sup> *
<b>Effects</b>	Slabs replaced:	100%

[\*Costs are derived from data provided by WSDOT]



**2.6: ROAD WORKS STANDARDS FOR BST-SURFACED FLEXIBLE PAVEMENTS**

BST-surfaced flexible pavements are usually used in low traffic locations and normally rehabilitated every five to ten years in accordance with WSDOT budget conditions and planning. The only maintenance standard is bituminous surface treatment. HDM-4 can trigger this work only as a result of cracking. The related input factors are listed in Table 8.

**Table 8: Maintenance standard for bituminous surface treatment**

<b>General</b>	Name:	Bituminous Surface Treatment
	Short Code:	BSTCRA
	Intervention Type:	Responsive
<b>Design</b>	Surface Material:	Double Bituminous Surface Dressing
	Thickness:	12.5mm
	Dry Season a:	0.2
	CDS:	1
<b>Intervention</b>	Responsive Criteria:	total cracked area $\geq$ 10%
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	100,000
	<b>BST</b> Economic:	2.04 dollars/m <sup>2</sup> *
	<b>BST</b> Financial:	2.04 dollars/m <sup>2</sup> *
	<b>Patching</b> Economic:	47 dollars/m <sup>2</sup> *
	<b>Patching</b> Financial:	47 dollars/m <sup>2</sup> *
	<b>Edge Repair</b> Economic:	47 dollars/m <sup>2</sup> *
<b>Edge Repair</b> Financial:	47 dollars/m <sup>2</sup> *	
<b>Crack Seal</b> Economic:	8.5 dollars/m <sup>2</sup> *	
<b>Crack Seal</b> Financial:	8.5 dollars/m <sup>2</sup> *	
<b>Effects</b>	Roughness:	Use user defined method
	Roughness:	2 m/km
	Mean rut depth:	0 mm
	Texture Depth:	0.7mm
	Skid Resistance:	0.5mm

[\*Costs are derived from data provided by WSDOT]

## **2.7: HDM-4 CONFIGURATION**

Configuration data are traffic flow patterns, speed flow types, and climate. These data are collected to adapt the basic characteristics to WSDOT conditions.

### **2.7.1: Traffic Flow Patterns**

Traffic flow patterns model the temporal variations in traffic. HDM-4 uses traffic flow pattern data to model congestion effects on vehicle speeds and vehicle operation costs. The traffic flow types are defined by three steps:

1. Choose typical routes from the WSPMS.
2. Find the routes and mile posts (MPs) in the table.
3. Calculate the volume percentage of different daily time periods.

**Table 9: Volume composition in the commuter traffic flow pattern**

<b>Period</b>	<b>Hours Per Year</b>	<b>Hourly Volume</b>	<b>% of AADT</b>
Morning Peak (6:30-10:00am)	1277.5	0.093	32.5
Off Peak (10:00am-3:30pm)	2007.5	0.032	17.5
Evening Peak (3:30-7:30pm)	1460	0.1	40
Night (7:30pm-6:30am)	4015	0.009	10
<b>Total</b>	<b>8760</b>	<b>1.0005</b>	<b>100</b>

[Source: <http://www.wsdot.wa.gov/mapsdata/tdo/PDF%20and%20ZIP%20Files/peak2000.pdf>, 2000]

**Table 10: Volume composition in the inter-urban/rural flow pattern**

<b>Period</b>	<b>Hours Per Year</b>	<b>Hourly Volume</b>	<b>% of AADT</b>
Day Time (7:30am-7:00pm)	4197.5	0.07	80
Night Time (7:00pm-7:30am)	4562.5	0.016	20
<b>Total</b>	<b>8760</b>	<b>1.005</b>	<b>100</b>

[Source: <http://www.wsdot.wa.gov/mapsdata/tdo/PDF%20and%20ZIP%20Files/peak2000.pdf>, 2000]

**Table 11: Volume composition in the seasonal flow pattern**

<b>Periods</b>	<b>Hours Per Year</b>	<b>Hourly Volume</b>	<b>% of AADT</b>
Day Time (7:30am-7:00pm)	4197.5	0.072	82.5
Night Time (7:00pm-7:30am)	4562.5	0.014	17.5
<b>Total</b>	<b>8760</b>	<b>1.003</b>	<b>100</b>

[Source: <http://www.wsdot.wa.gov/mapsdata/tdo/PDF%20and%20ZIP%20Files/peak2000.pdf>, 2000]

### **2.7.2: Speed Flow Types**

Speed flow types model the effects of traffic volume on speeds. HDM-4 uses speed flow data to conduct economic analyses for road capacity improvements. For individual project segments, the free-flow speeds (FFS) are to be adjusted for the width of lanes, access point density, and lateral clearance. Lane widths are adjusted for two-lane roads as illustrated in Table 12. Adjustments for lateral clearance and access point density for four-lane highways can be made on the basis of tables 13 and 14, respectively. Given figures 5, 6, and 7 for four-lane and two-lane highways, the changes result in more accurate values for free-flow speeds and, subsequently, for free-flow capacities and for ultimate capacities.

**Table 12: FFS adjustment for lane width and shoulder width**

Lane Width (m)	Reduction in FFS (km/hr)			
	Shoulder Width (m)			
	[0.0, 0.6)	[0.6, 1.2)	[1.2, 1.8)	[1.8, +∞)
[2.7, 3.0)	10.3	7.7	5.6	3.5
[3.0, 3.3)	8.5	5.9	3.8	1.7
[3.3, 3.6)	7.5	4.9	2.8	0.7
[3.6, +∞)	6.8	4.2	2.1	0

[Source: Highway Capacity Manual 2000]

**Table 13: FFS adjustment for access-point density**

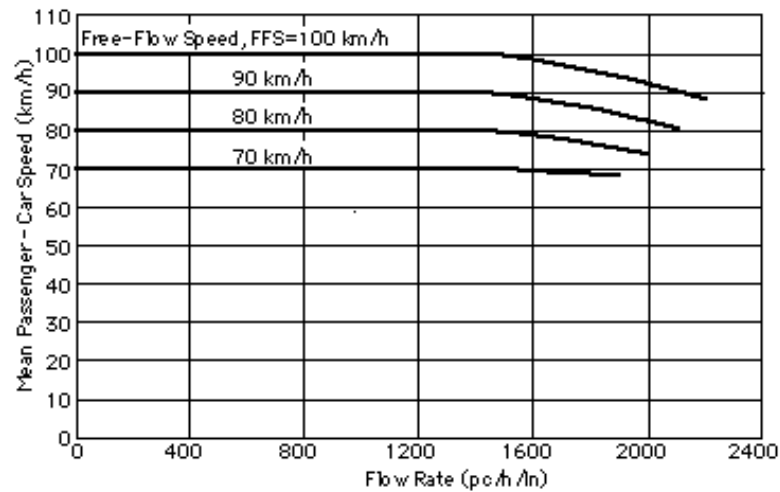
Access Points per km	Reduction in FFS (km/hr)
0	0
6	4
12	8
18	12
≥24	16

[Source: Highway Capacity Manual 2000]

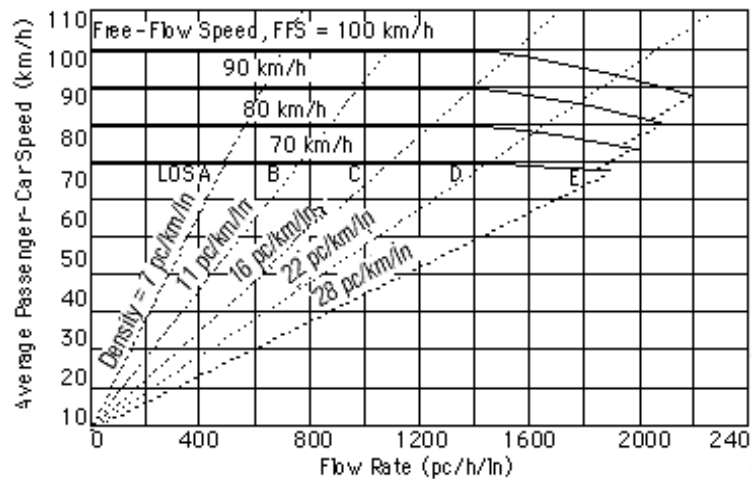
**Table 14: FFS adjustment for lateral clearance**

Four-lane Highways		Six-lane Highways	
Total Lateral Clearance (m)	Reduction in FFS (km/h)	Total Lateral Clearance (m)	Reduction in FFS (km/h)
3.6	0	3.6	0
3	0.6	3	0.6
2.4	1.5	2.4	1.5
1.8	2.1	1.8	2.1
1.2	3	1.2	2.7
0.6	5.8	0.6	4.5
0	8.7	0	6.3

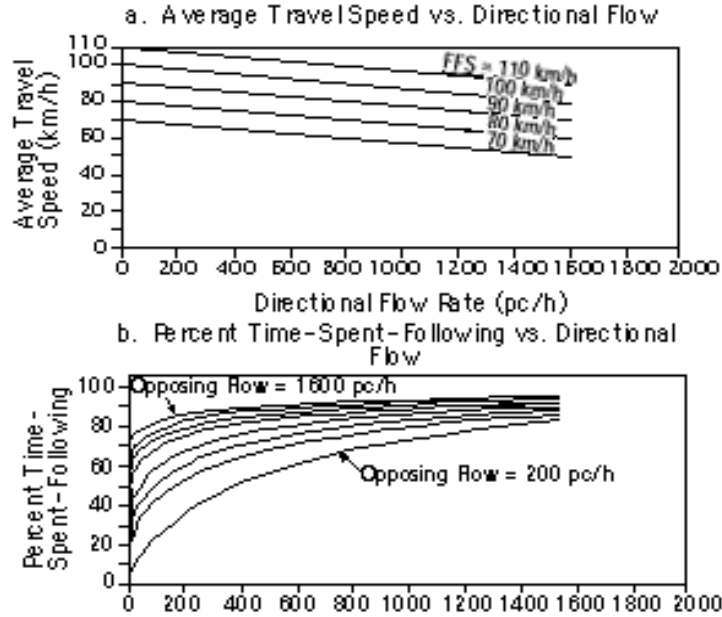
[Source: Highway Capacity Manual 2000]



**Figure 5: Speed-flow relationships on multi-lane highways**  
[Source: Highway Capacity Manual 2000, Exhibit 12-1]



**Figure 6: Speed-flow curves with criteria**  
[Source: Highway Capacity Manual 2000, Exhibit 21-3]



**Figure 7: Speed-flow and percentage of time-spent-following flow relationships for directional segments with base conditions**  
 [Source: Highway Capacity Manual 2000, Exhibit 12-7]

For basic conditions, FFS's are approximately 11km/hr above the 65 and 70 km/hr speed limit, and approximately 8 km/hr above the 80-90 km/hr speed limit. This can be used to calculate approximate free-flow speeds, the free flow capacities, and the ultimate capacities. The speed-flow types of studied highways are listed as Table 15.

**Table 15: Speed flow types in Washington State**

Speed-Flow Type	Ultimate Capacity (PCSE/lane/hr)	Free-Flow Capacity (PCSE/lane/hr)	Nominal Capacity (Q <sub>nom</sub> )	FFS (Km/hr)	Jam Speed (km/hr)	Max Acceleration Noise (m/s <sup>2</sup> )
Four-Lane Road	1900-2200	800-1300	0.95	70-110	65-80	0.6
Two-Lane Narrow	850-1600	150	0.7	60-100	30-60	0.7
Two-Lane Standard	1600-1650	150-250	0.9	70-100	40-60	0.65
Two-Lane Wide	1600-1700	150-250	0.9	70-110	40-60	0.6

The above table does not differentiate between urban and rural highways. In general, the free-flow speed in rural freeways is about 8km/hour higher than those of urban highways. However, this is the result of varying speed limits (Zhang et al., 2001).

### **2.7.3: Climate Zones**

Climate data is used to model its effects on road performance and user costs.

#### **2.7.3.1: Climate Data Parameter Definitions**

HDM-4's climate data input provides two categories: moisture and temperature.

The default moisture categories include arid, semi-arid, sub-humid, humid, and per-humid. Temperature categories comprise tropical, subtropical-hot, subtropical-cool, temperate-cool, and temperate-freezing (Odoki, 2000). Tables 16 and 17 list the definitions of those categories.

**Table 16: Moisture categories**

<b>Moisture Category</b>	<b>Description</b>	<b>Thornthwaite Moisture Index</b>	<b>Annual Precipitation (mm)</b>
Arid	Very low rainfall, high evaporation	-100 to -61	<300
Semi-arid	Low rainfall	-60 to -21	300 to 800
Sub-humid	Moderate rainfall or strongly seasonal rainfall	-20 to +19	800 to 1600
Humid	Moderate warm seasonal rainfall	+20 to +100	1500 to 3000
Per-humid	High rainfall or very many wet-surface days	>100	>2400

[Source: HDM-4 Series, Volumes 5. The World Road Association (PIARC), 1999]

**Table 17: Temperature categories**

<b>Temperature Category</b>	<b>Description</b>	<b>Temperature Range (°C)</b>
Tropical	Warm temperatures in small range	20 to 35
Sub-tropical – hot	High day, cool night temperatures, hot-cold seasons	-5 to 45
Sub-tropical – cool	Moderate day temperatures, cool winters	10 to 30
Temperate – cool	Warm summer, shallow winter freeze	-20 to 25
Temperate – freeze	Cool summer, deep winter freeze	-40 to 20

[Source: HDM-4 Series, Volumes 5. The World Road Association (PIARC), 1999]

Among the 25 moisture and temperature combinations, two of them are not applicable to Washington State. Therefore, a matrix was developed from the classifications to create 23 unique climate zones, as shown in Table 18.

**Table 18: Climate zones in HDM-4**

<b>Climate Zone</b>	<b>Tropical</b>	<b>Subtropical -hot</b>	<b>Subtropical -cool</b>	<b>Temperate -cool</b>	<b>Temperate -freezing</b>
<b>Arid</b>	X	X	X	X	X
<b>Semi-arid</b>	X	X	X	X	X
<b>Sub-humid</b>	X	X	X	X	X
<b>Humid</b>	X	X	X	X	X
<b>Per-humid</b>	X	X	X	N/A	N/A

Each temperature and moisture category possesses data parameter definitions. In HDM-4, the following data parameters are required (Odoki, 2000).

**Moisture**

- Mean monthly precipitation (mm/month)
- Thornthwaite Moisture Index (MI)

$$MI = I_h - 0.6 * I_a = \frac{100 * SWAT - 60 * DWAT}{NWAT} \tag{2.12}$$

where:

MI: Thornthwaite Moisture Index

I<sub>h</sub>: humidity index

I<sub>a</sub>: aridity index

SWAT: excess of water (mm)

DWAT: water deficiency (mm)

NWAT: necessary water (mm)

- Dry season duration as a proportion of a year

$$(365-p)/365 \tag{2.13}$$

where p is the number of days of precipitation.

## Temperature

- Mean annual temperature (°C)
- Temperature range (TRANGE) (°C): the mean monthly ambient temperature range. Its calculation is based on the temperature ranges for each of the twelve months of the year, hence the difference between the maximum and minimum temperature of each month.
- Number of days per year the temperature exceeds 32°C
- Freezing index (FI) (°C - days): the difference between the mean ambient temperature and 0°C (degrees per day). The freezing index is negative when the ambient temperature is below 0°C and positive otherwise.

The freezing index is calculated as:

$$FI = \sum_{i=1}^{ndays} ABS[MIN(TEMP, 0)] \quad (2.14)$$

where:

FI: freezing index

TEMP: temperature (°C)

ndays: number of days in one freezing season

- Percentage of driving times on snow-covered roads (%)
- Percentage of driving times on water-covered roads (%)

### **2.7.3.2: Six Climate Zones in Washington State**

WSDOT Regions were used to define six climate zones: Northwest, Olympic, Southwest, North Central, Eastern, and South Central. The partition of six climate zones is shown in Figure 8 and follows regional boundaries.





**Figure 8: Six climate zones of Washington state**  
 [Source: <http://www.wsdot.wa.gov>]

The above six climate zone definitions are based on historical weather data from observation stations. Several stations in each zone were selected so that each station has at least one of the following characteristics:

- high moisture
- low temperature
- high road density
- loosely based on the six climate-zone classifications.

To look up the climate data for a segment of roadway, the county data listed in the WSPMS should be cross-referenced. Table 19 lists WSDOT’s climate zones by county.

**Table 19: WSDOT’s climate zones by county**

<b>Zone</b>	<b>Olympic</b>	<b>Northwest</b>	<b>North Central</b>	<b>Eastern</b>	<b>Southwest</b>	<b>South Central</b>
<b>County</b>	Clallam	San Juan	Okanogan	Ferry	Pacific	Kittitas
	Jefferson	Island	Chelan	Stevens	Wahkiakum	Yakima
	Grays Harbor	Whatcom	Douglas	Pend Oreille	Lewis	Walla Walla
	Mason	Skagit	Grant	Lincoln	Cowlitz	Benton
	Kitsap	Snohomish		Spokane	Clark	Franklin
	Thurston	King		Adams	Skamania	Klickitat
	Pierce			Whitman		Columbia
						Garfield
						Asotin

Climate data from each county are listed in Appendix A [Source: <http://www.wrcc.dri.edu/summary/mapwa.html>]. A uniform moisture and temperature for each county were developed by averaging the individual climate factors.

**Table 20: Climate indices for six climate zones in Washington State**

<b>Zone Name</b>	<b>Moisture</b>			<b>Temperature</b>			
	Moisture Index	Duration of dry season	Mean monthly precipitation (mm)	Mean Temp. (°C)	Temp. Range (°C)	Days T>32°C (89.6°F)	Freeze Index (°C-days)
<b>Olympic</b>	144.77	0.5386	111.98	9.77	9.21	0	11.73
<b>Northwest</b>	75.09	0.5924	65.89	10.60	8.64	0	0.99
<b>North Central</b>	26.02	0.8296	20.26	10.13	12.30	9.4	465.33
<b>Eastern</b>	58.64	0.7052	41.20	8.57	12.66	2	562.77
<b>Southwest</b>	163.46	0.5036	127.95	10.73	9.92	0	3.13
<b>South Central</b>	28.24	0.785	22.48	10.21	13.53	11.8	400.03

### **3: CALIBRATION OF ROAD DETERIORATION MODELS**

Road deterioration models simulate future changes from current and/or historical road conditions, and each model develops and progresses at different rates in different environments. Therefore, the models should be calibrated to Washington State local conditions. Coefficients included in the models are used to adjust the deterioration rates to different types of surface material. Furthermore, the models include a number of user-definable calibration factors to fit the models to the local conditions. The reliability of these factors depends on the accuracy of the input data and how well the prediction models represent local conditions (Odoki et al., 2000).

Thus, calibration of the models includes three primary elements: data preparation, determination of the optimal calibration factors by regression, and validation.

#### **3.1: CALIBRATION CLASSIFICATION**

In order to properly calibrate deterioration models, homogeneous road sections, (in terms of physical attributes and conditions) must be identified. Therefore, different pavement groups are defined so that calibration factors for each group can be obtained. These calibration factors are related to the conditions of climate and environment, traffic, pavement history, road geometry, pavement structural characteristics, and material properties. The primary explanatory variables for flexible pavement deterioration were evaluated to determine the variables needed to define the pavement groups.

##### **3.1.1: Surface Types**

HDM uses two general classes of models for pavement performance prediction based on the road surface classes: incremental models for flexible pavements and

absolute models for concrete pavements. Incremental models predict the change in condition from an initial state, and absolute models predict the condition at a particular point in time. Furthermore, flexible and concrete pavements manifest various kinds of distresses, so they must be calibrated independently.

WSDOT flexible pavements use two types of surface material: asphalt concrete (AC) and 2) bituminous surface treatment (BST). The geometric standards and material properties for these two flexible pavement types vary considerably, so they were calibrated in different classes. Therefore, based on the surface materials, WSDOT highways were divided into three calibration classes:

- AC-surfaced flexible pavements (ACPs)
- BST-surfaced flexible pavements (BSTs)
- Concrete pavements (Odoki et al., 2000).

### **3.1.2: Traffic**

Traffic is measured by ESALs in this research. Specifically, annual quantities of ESALs divided by Elane. Because concrete pavements are normally used for high traffic and BSTs for low traffic loads, only ACPs were divided into three classes according to traffic usage: high, medium, and low as listed in Table 1.

### **3.1.3: Climate**

Climatic conditions for flexible pavements have been classified into six climate regions according to the moisture and temperature classifications in Tables 16 and 17.

The Cascade mountain range separates Washington State into two significantly different climate zones, Western Washington (WW) and Eastern Washington (EW). WW includes the Northwest, Olympic, and Southwest regions. EW includes the North Central,

Eastern, and South Central regions. By averaging the climate indices of the three zones of each class, the corresponding climatic values are shown in Table 21.

**Table 21: Climate indices for Western Washington and Eastern Washington**

Climate Zone		Western Washington	Eastern Washington
Moisture	Moisture Index	127.77	37.64
	Duration of dry season	0.54	0.77
	Mean monthly precipitation (mm)	101.94	27.98
Temperature	Mean Temperature (°C)	10.37	9.64
	Temp Range (°C)	9.26	12.83
	Days T>32°C (89.6°F)	0.00	7.73
	Freeze Index (°C-days)	5.29	476.04

On the basis of the climate indices in Table 21, as well as temperatures and moisture classes defined by HDM-4, WW and EW can be categorized as Table 22.

**Table 22: Climate categories of Washington state**

Climate Category	Moisture Category	Temperature Category
Western Washington	Per-humid	Temperate cool
Eastern Washington	Semi-arid	Temperate freeze

Table 22 is used for choosing factors to be used in the calibration equations. Those factors are described in sections 3.3.3 and 3.3.4.

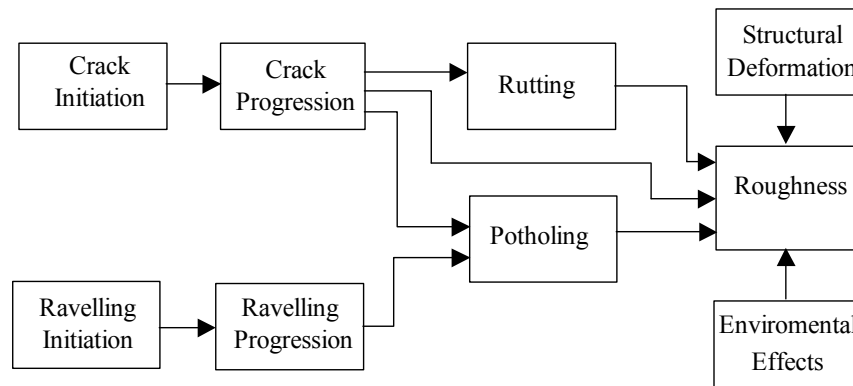
### **3.2: CALIBRATION TOOL: LIMDEP**

LIMDEP is econometric software developed by Econometric Software, Inc., that can estimate linear and nonlinear regression models, as well as limited and qualitative dependent variable models for cross-section, time-series, panel-data, and user-specified models (Greene, 1995). It was used to estimate the optimal calibration factors for large amounts of local condition data based on models generated by HDM-4.

### **3.3: CALIBRATION OF DETERIORATION MODELS FOR FLEXIBLE PAVEMENTS**

#### **3.3.1: Primary Modeling Factors**

Eight types of flexible pavement distresses are modeled in HDM-4. They are 1) cracking, 2) raveling, 3) potholing, 4) edge-breaking, 5) rutting, 6) surface texture, 7) skid resistance and 2) roughness. The first five types have high-to-medium sensitivity level effects on the prediction models; therefore, emphasis is given to the related calibration factors. Because of limited data and low sensitivity to the prediction models, skid resistance and surface texture were not calibrated. Rather, the HDM-4 default values were used. Interactions among the distresses, as defined by HDM-4, are illustrated in Figure 9. All distresses ultimately have effects on roughness, so roughness can represent the condition as a whole (Odoki, 2000).



**Figure 9: Flexible pavement distress interaction**  
[Source: HDM-4 Volume-5]

The key variables used in the road-deterioration models are related to the conditions of climate and environment, traffic, pavement history, road geometry, pavement structural characteristics, and material properties. These are described in Chapter 2. HDM-4 uses 24 factors to represent these conditions, as listed in Table 23.

**Table 23: Calibration factors in flexible pavement deterioration models**

<b>Deterioration model</b>	<b>Calibration factor</b>
Wet/dry season SNP ratio	$K_f$
Drainage deterioration factor	$K_{ddf}$
Drain life factor	$K_{drain}$
All structural cracking-initiation	$K_{cia}$
Wide structural cracking-initiation	$K_{ciw}$
All structural cracking- progression	$K_{cpa}$
Wide structural cracking- progression	$K_{cpw}$
Transverse thermal cracking - initiation	$K_{cit}$
Transverse thermal cracking - progression	$K_{cpt}$
Rutting-initial densification	$K_{rid}$
Rutting - structural deterioration	$K_{rst}$
Rutting - plastic deformation	$K_{rpd}$
Rutting - surface wear	$K_{rsw}$
Ravelling - initiation	$K_{vi}$
Ravelling - progression	$K_{vp}$
Pothole - initiation	$K_{pi}$
Pothole - progression	$K_{pp}$
Edge - break	$K_{eb}$
Roughness - enviromental coefficient	$K_{gm}$
Roughness - SNPK	$K_{snpk}$
Roughness - progression	$K_{gp}$
Texture depth - progression	$K_{td}$
Skid resistance	$K_{sfc}$
Skid resistance - speed effects	$K_{sfcs}$

Depending upon their different effects on pavement performance, these factors are categorized into four sensitivity classes by HDM-4, as shown in Table 24.

**Table 24: Sensitivity classes for RDWE factors**

<b>Sensitivity Level</b>	<b>Impact</b>	<b>Impact Elasticity</b>	<b>Factor</b>
S-I	High	>0.5	Structural number
			Modified structural number
			Traffic volume
			Deflection
			Roughness
S-II	Moderate	0.2-0.5	Annual loading
			Age
			All cracking area
			Wide cracking area
			Roughness-environment factor
			Cracking initiation factor
S-III	Low	0.05-0.2	Cracking progression factor
			Subgrade CBR (with SN)
			Surface thickness (with SN)
			Heavy axles volume
			Potholing area
			Rut depth mean
			Rut depth standard deviation
			Rut depth progression factor
S-IV	Negligible	<0.05	Roughness general factor
			Deflection with (SNC)
			Subgrade compaction
			Rainfall (with $K_{ge}$ )
			Raveling area
			Raveling factor

(Note: When SN is given, deflection has negligible impacts.)

[Source: HDM-4, Volume 5]

Calibrating HDM-4 for WSDOT focused first on S-I level factors, with a lesser priority given to lower sensitivity level factors. Some low, or negligible, sensitivity factors were not calibrated. Instead, a default value of 1.0 was used, especially when related data were not available.

### **3.3.2: Proposed Calibration Methodology**

Calibration of a deterioration model is intended to find the adjustment factors that



will make model predictions as accurate as possible. The general expression used for the calibration of deterioration models is:

$$\Delta Y = K_y * f(Y_a, a_0, a_1, a_2, \dots, a_n, X_1, X_2, \dots, X_m) \quad (3.1)$$

**where:**

$K_y$ : calibration factor of distress type Y

$\Delta Y$ : incremental change of distress type Y in the analysis year

$Y_a$ : deterioration value at the beginning of the analysis year

$a_i$ : default coefficient values given by models and decided by factors of climate and environment, traffic, pavement history, road geometry, pavement structural characteristics, or material properties.

$X_i$ : input factors of climate, traffic, pavement history, road geometry, pavement structural characteristics, and material properties.

$f()$ : non-linear function, which may include various non-linear operations such as logarithm, exponential and polynomial etc.

If the values of  $Y_a, a_0, a_1, a_2, \dots, a_n, X_1, X_2, \dots,$  and  $X_m$  are given,  $f()$  acts as one independent variable of the dependent variable  $\Delta Y$ . The non-linear models are converted to simple linear relationship between the dependent variable  $\Delta Y$  and the independent variable  $f()$ . Only the total roughness deterioration model cannot be transformed to a linear model. Section 3.3.4 illustrates the specific methodology used to determine the corresponding factors of roughness. Then, road deterioration models of each calibration category were regressed independently in LIMDEP.

### **3.3.3: Determination of Calibration Coefficients**

Proposed values for HDM-4 calibration variables are as follows (Odoki, 2000):

- **CDS** (Construction defects indicator for bituminous surfacing): use 1.0, since the surface condition of the studied sections is supposed to be at an optimal binder content.
- **CDB** (Base construction defects indicator): use 0.5 for construction defect conditions as given values in HDM-4.
- **COMP** (Relative compaction (%)): use 100 for the assumption of a full compliance in all layers.
- **CRT** (Crack retardation time due to maintenance (years)): use 0, since WSDOT seldom does preventive treatments such as fog seal or joint sealing.
- **CRP** (Cracking progression retardation due to preventative treatment):  

$$CRP = 1 - 0.12 * CRT = 1 \quad (3.2)$$
- **RRF** (Raveling retardation factor due to maintenance): use 1.0 as defaults.
- **PASS** (Annual number of vehicles with studded tires in one direction (1000s)): assume 3 % of the annual number of vehicle passes has studded tires for Western Washington and 8% for Eastern Washington. PASS can be calculated by Equation (3.3):

$$\begin{aligned}
 \text{WW: } PASS &= \frac{365 * 3\% * AADT}{10^3 * \text{Number Of Direction}} \\
 \text{EW: } PASS &= \frac{365 * 8\% * AADT}{10^3 * \text{Number Of Direction}}
 \end{aligned}
 \quad (3.3)$$

- **YE4** (Annual number of equivalent standard axles (millions/lane): WSDOT assumes 0.4 ESALs per single-unit truck, 1.00 ESALs per double-unit truck, and 1.75 ESALs per train. Then, YE4 can be calculated as (WSPMS, 2003):

$$YE4 = \frac{0.4 * Single-unit + 1.00 * Double-unit + 1.75 * Train}{10^6 * ELANE} \quad (3.4)$$

- **YAX** (Annual number of axles of all motorized vehicle types in the analysis year (millions/lane)): assume standard axles of passenger cars (PC), single-unit trucks, double-unit trucks, and trains are 2, 2, 5, and 6, respectively.

$$YAX = \frac{2 * PC + 2 * Single-unit + 5 * Double-unit + 6 * Train}{10^6 * ELANE} \quad (3.5)$$

- **HSNEW** (Thickness of the most recent surfacing (mm)): it is the overlay thickness, which is 45 mm for WSDOT.

- **AGE**

AGE1 (Preventive treatment age (years)):  
= Analysis year – Year of the last prevention

AGE2 (Surfacing age (years))  
= Analysis year – Year of the last surfacing

AGE3 (Rehabilitation age (years))  
= Analysis year – Year of the last rehabilitation

AGE4 (Base construction age (years))  
= Analysis year – Year of the last construction

HDM-4 constrains  $AGE1/AGE2/AGE3 \geq AGE4$  and condition year  $\geq$

Year of last construction, where condition year equals 2002, since all distress data of this research were measured in 2002.

- **Time to initiation of cracking or raveling:**

**ICA** (Initiation time of all structural cracking)

**ICW** (Initiation time of wide structural cracking)

**ICT** (Initiation time of thermal cracking)

### **IRV** (Initiation time of raveling)

Initiation of cracking or raveling is the time when the distress area is 0.5% of the total carriageway surface area. Ideally, the calculation steps are:

1. Select the specific distress data, surface age, and section length from the road network input table defined in Chapter 2.
2. Group sections with AC or BST surface.
3. Select AC sections with surface age  $\leq 40$  years, since longer AC service lives are unrealistic. Select BST sections with surface age no greater than 30 years, since BST pavements rarely can serve longer than 30 years.
4. Choose sections whose distress area is 0.5% of the total carriage way area.
5. Weigh surface ages by section length.

A range from 0.4% to 0.6% was chosen instead of 0.5%. Cracking data of AC sections were grouped by climate zones of WW and EW because cracking and raveling are highly sensitive to climate. Table 25 illustrates the results.

**Table 25: Values of ICA, ICW, ICT and IRV**

<b>Surface Material</b>	<b>Climate</b>	<b>ICA (year)</b>	<b>ICW (year)</b>	<b>ICT (year)</b>	<b>IRV (year)</b>
AC	WW	8.95	11.21	10.06	6.33
	EW	5.54	7.00	5.70	
BST	All	3.86	5.67	4.33	4.89

- **CCT** (Coefficient of thermal cracking): CCT is used to predict ICT for different climate conditions. CCT of WW equals 100, and CCT of EW is 2.
- **NCTeq** (Maximum number of thermal cracks (no/km)): use 0 for WW and 20 for EW.

- **Teq** (Time since initiation to reach NCTeq): use 50 for WW and 7 for EW (Odoki et al., 2000).

### **3.3.4: Simplified Deterioration Models for AC-Surfaced Flexible Pavements**

HDM-4 classifies AC-surfaced flexible pavements into five categories, while WSDOT highways take two: 158 sections of AMGB (asphalt mix on granular base), and 1714 sections of AMAP (asphalt mix on asphalt pavements). The coefficient (not the calibration factors) values proposed by HDM-4 were selected base on surface materials (Odoki, 2000).

#### **3.3.4.1: Wet/Dry Season SNP Ratio**

Use 1.0 as a drainage factor for the good drainage condition of the WSDOT routes. Use 0.0 as the pothole area at the start of the analysis year because potholes will be patched as soon as they appear as a practice of WSDOT. Then,

$$f = K_f \left[ 1 - 0.075 \left( 1 - e^{-0.01MMP} \right) \left( 1 + 0.02ACRA_a \right) \right] \quad (3.6)$$

where:

$f = \frac{\text{Wet season SNP}}{\text{Dry season SNP}}$ . Use 1.0 since season does not have much of an effect on SNP in Washington state for unstabilized base and thick, hot mix asphalt layers (normally thicker than 150 mm).

$K_f$ : Calibration factor for wet/dry season SNP ratio.

$ACRA_a$ : Total area of carriageway cracked at the beginning of the analysis year.

$$ACRA_a = ACA_a + ACT_a$$

MMP: Mean monthly precipitation (mm). Western Washington uses 101.94 and Eastern Washington uses 27.98, as determined in Chapter 2.

### **3.3.4.2: Cracking**

#### **(a) Initiation of All Structural Cracking (ICA)**

In general, WSDOT uses unstabilized base material, so the related road deterioration model is simplified by using the proposed coefficients.

If HSOLD=0 (that is original surfacing)

$$ICA = K_{cia} \left( 4.21e^{0.14SNP - 17.1 \left( \frac{YE4}{SNP^2} \right)} \right) \quad (3.7)$$

If HSOLD>0 (that is overlays)

$$ICA = K_{cia} \left\{ \left[ \text{MAX} \left( 4.21e^{0.14SNP - 17.1 \left( \frac{YE4}{SNP^2} \right)}, 1.125 \right) \right] \right\} \quad (3.8)$$

where:

$K_{cia}$ : calibration factor for initiation of all structural cracking.

#### **(b) Initiation of Wide Structural Cracking (ICW)**

Since HDM-4 surface type AMAP (asphalt mix on asphalt pavements) is representative of more than 90% of WASOT ACPs, coefficients proposed by HDM-4 for AMAP were used.

$$ICW = k_{ciw} (2.04 + 0.98ICA) \quad (3.9)$$

where:

$K_{ciw}$ : calibration factor for initiation of all structural cracking.

#### **(c) Progression of All Structural Cracking (ACA)**

WSDOT measures cracking in wheel paths, but HDM-4 measures it in the total roadway. Assume that the wheel paths are 50 percent of the total roadway area. Because

of WSDOT's definition, ACA can never be greater than 100 percent, ACA in HDM-4 can never be greater than 50 percent, and then

$$SCA = ACA_a \quad (3.10)$$

If  $ACA_a > 0$ ,

$$dACA = k_{cpa} \left[ \left( 0.2996 + ACA_a^{0.28} \right)^{\frac{1}{0.28}} - ACA_a \right] \quad (3.11)$$

Otherwise:

$$dACA = k_{cpa} \left[ \left( 0.2996 * MAX(0, MIN[(AGE2 - ICA), 1]) + ACA_a^{0.28} \right)^{\frac{1}{0.28}} - ACA_a \right] \quad (3.12)$$

where:

$$ACA_a = MAX(ACA_a, 0.5) \quad (3.13)$$

dACA: incremental changes of ACA during the analysis year (%);

ACA<sub>a</sub>: ACA at the start of the analysis year;

K<sub>cpa</sub>: calibration factor for initiation of all structural cracking.

#### (d) Progression of Wide Structural Cracking (ACW)

As ACA, ACW of Washington State routes can never be greater than 50%, so

$$SCW = ACW_a \quad (3.14)$$

If  $ACW_a > 0$

$$dACW = K_{cpw} MIN \left[ (ACA_a + dACA - ACW_a), \left( (1.161 + ACW_a^{0.45})^{\frac{1}{0.45}} - ACW_a \right) \right] \quad (3.15)$$

Otherwise:

$$dACW = K_{cpw} MIN \left[ (ACA_a + dACA - ACW_a), \left( (1.161 * MAX\{0, MIN[AGE2 - ICW], 1\} + ACW_a^{0.45})^{\frac{1}{0.45}} - ACW_a \right) \right] \quad (3.16)$$

where:

$$ACW_a = MAX(ACW_a, 0.5) \quad (3.17)$$

dACW: incremental change of ACW during the analysis year;

ACW<sub>a</sub>: ACW at the start of the analysis year.

**(e) Initiation of Transverse Thermal Cracking (ICT)**

If HSOLD=0

$$ICT = K_{cit} * MAX(1, CCT) = K_{cit} * CCT \quad (3.18)$$

Otherwise:

$$ICT = K_{cit} * MAX[1, (CCT - 0.1)] = K_{cit} (CCT - 0.1) \quad (3.19)$$

where:

K<sub>cit</sub>: calibration factor for initiation of transverse thermal cracking.

**(f) Progression of Transverse Thermal Cracking (NCT)**

If HSOLD=0

$$dNCT = K_{cpt} * MAX \left\{ 0, MIN \left[ (NCT_{eq} - NCT_a), \left( \frac{2NCT_{eq} (AGE3 - ICT - 0.5)}{(T_{eq})^2} \right) \right] \right\} * \delta t_T \quad (3.20)$$

If HSOLD>0

$$dNCT = K_{cpt} * MIN \left\{ (NCT_{eq} - NCT_a), MAX \left[ MIN(0.25 PNCT, (PNCT - NCT_a)), \left( \frac{2NCT_{eq} (AGE3 - ICT - 0.5)}{(T_{eq})^2} \right), 0 \right] \right\} * \delta t_T$$

(3.21)

where:

$$dNCT = 20 * dACT$$

$$PNCT = 20 * PACT \quad (3.22)$$

If ACT<sub>a</sub>>0,  $\delta t_T = 1$  Otherwise,  $\delta t_T = MAX \{0, MIN [(AGE2 - ICT), 1]\}$

K<sub>cpt</sub>: calibration factor for progression of thermal cracking

dNCT: incremental change in number of thermal cracking in analysis year (n<sup>0</sup>/km)



- dACT: incremental change in ACT in analysis year (%)
- PNCT: number of thermal cracks before last overlay (n°/km)
- NCT<sub>a</sub>: number of thermal cracks at the start of analysis year.

### **3.3.4.3: Rut Depth**

#### **(a) Initial Densification**

The initial densification depends upon the degree of relative compaction of the base and selected subgrade layers. The construction and compact works are quite good in Washington state, so  $K_{rid} = 0$ .

#### **(b) Structural Deterioration -- $K_{rst}$**

If  $ACA+ACT=0$

$$\Delta RDST = K_{rst} (1.1291SNP^{-1.14}YE4^{0.11}) = K_{rst} X_1 \quad (3.23)$$

Otherwise:

$$\Delta RDST = K_{rst} \left[ 1.1291SNP^{-1.14}YE4^{0.11} + 0.0000248SNP^{-0.84}YE4^{0.14}MMP^{1.07}ACX_a^{1.11} \right] = K_{rst} * X_1 \quad (3.24)$$

where:

$K_{rst}$ : calibration factor for structural deformation;

$\Delta RDST$ : incremental change in structural deformation in the analysis year (mm);

$ACX_a$ : area of indexed cracking at the beginning of the analysis year (%);

$$ACX_a = 0.62ACA_a + 0.39ACW_a \quad (3.25)$$

MMP: mean monthly precipitation (mm/month). MMP of WW equals 101.94, and

EWequals 27.98.

#### **(c) Plastic Deformation**

$$\Delta RDPD = K_{rpd} (2.46YE4Sh^{-0.78}HS^{0.71}) = K_{rpd} X_2 \quad (3.26)$$

where:

$K_{rpd}$ : calibration factor for plastic deformation;

$\Delta RDPD$ : incremental change in plastic deformation in the analysis year (mm);

Sh: speed of trucks (km/h), assume Sh=SpeedLimit-15;

HS: total thickness of bituminous surface, HS=HSOLD+HSNEW.

#### (d) Surface Wear

Most roads in Washington are seldom salted, then

$$\Delta RDW = K_{rsw} \left[ 0.0000248 PASS * W^{-0.46} S^{1.22} \right] = K_{rsw} * X_3 \quad (3.27)$$

where:

$K_{rsw}$ : calibration factor for surface wear;

$\Delta RDW$ : incremental change in rut depth for studded tires in the analysis year (mm);

W: road width that includes carriageway and shoulder (m);

S: average traffic speed, assuming it equals the speed limit.

#### (e) Total Rut Depth

If AGE4<=1,

$$\Delta RDM = \Delta RDPD + \Delta RDW = K_{rpd} X_2 + K_{rsw} X_3 \quad (3.28)$$

Otherwise:

$$\Delta RDM = \Delta RDST_{uc} + \Delta RDPD + \Delta RDW = K_{rst} X_1 + K_{rpd} X_2 + K_{rsw} X_3 \quad (3.29)$$

where:

$\Delta RDM$ : incremental change in rut depth in the analysis year (mm).

#### 3.3.4.4: Raveling

##### (a) Initiation of Raveling (IRV)

$$IRV = K_{vi} \left( 100 e^{-0.156YAX} \right) \quad (3.30)$$

where:

$K_{vi}$ : calibration factor for raveling initiation.

### **(b) Progression of Raveling (ARV)**

Similarly to ACA, Washington state routes can never have sections with ARV greater than 50 percent, so

$$dARV = K_{vp} \left[ \left( (0.36 + 1.8YAX) \delta t_v + ARV_a^{0.352} \right)^{1/0.352} - ARV_a \right] \quad (3.31)$$

where:

$$\text{If } ARV_a > 0, \delta t_v = 1; \quad (3.32)$$

$$\text{Otherwise, } \delta t_v = \text{MAX} \left\{ 0, \text{MIN} \left[ (AGE2 - IRV), 1 \right] \right\} \quad (3.33)$$

$$ARV_a = \text{MAX} (ARV_a, 0.5) \quad (3.34)$$

$K_{vp}$ : calibration factor for raveling progression;

DARV: incremental change in ARV during the analysis year (%).

#### **3.3.4.5: Factors Not Calibrated**

This research emphasizes high sensitivity level factors. For factors that have low or negligible sensitivity levels and factors that necessary data are not available, default values of 1.0 given by HDM-4 were used. These factors are

- pothole initiation and progression -  $K_{pi}$
- edge-break -  $K_{eb}$
- skid resistance -  $K_{sfc}$
- skid resistance of speed effects -  $K_{sfcs}$
- texture depth progression -  $K_{td}$
- drainage life factor -  $K_{ddf}$

An exception is  $K_{snpk}$ , the calibration factor for Structural Number of Pavement (SNP). It describes the cracking effects on the pavement structure. Because the structural

conditions of all Washington state routes are fairly good, this research will use 0 for  $K_{\text{snpk}}$  instead of the default value 1.0.

### **3.3.4.6: Roughness**

Use  $K_{\text{snpk}} = 0$ , then

$$\begin{aligned}
 \Delta RI &= K_{gp} [\Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_t] + \Delta RI_e \\
 &= K_{gp} [\Delta RI_s + \Delta RI_c + \Delta RI_r] + 0.035 * K_{gm} RI_a \\
 &= K_{gp} \left[ 134e^{0.035K_{gm}AGE^3} (1 + SNP)^{-5} YE4 + 0.0066\Delta ACRA + 0.088 * \Delta RDS \right] + 0.035 * K_{gm} RI_a
 \end{aligned}
 \tag{3.35}$$

where:

$\Delta RI_s$ : Roughness increase during the analysis year due to structural deterioration

$\Delta RI_c$ : Roughness increase during the analysis year due to cracking

$\Delta RI_r$ : Roughness increase during the analysis year due to rutting

$\Delta RI_t$ : Roughness increase during the analysis year due to potholing, use 0

$\Delta RI$ : Roughness increase during the analysis year

$K_{gp}$ : Calibration factor for roughness progression

$K_{gm}$ : Calibration factor for environmental

$\Delta RDS$ : Increase in standard deviation of rut depth during the analysis year:

$$\begin{aligned}
 \Delta RDS &= RDS_b - RDS_a \\
 RDS_b &= \left[ \text{MAX} (0.3, 0.9 - 0.04RDM_b) \right] RDM_b \\
 RDS_a &= \left[ \text{MAX} (0.3, 0.9 - 0.04RDM_a) \right] RDM_a
 \end{aligned}
 \tag{3.36}$$

### **3.3.5: Simplified Deterioration Models for BST-Surfaced Flexible Pavements**

Some of the default coefficients for BSTs are given differently than those for ACPs. The related models are listed below, and variables used have the same meaning as the variables for ACPs (Odoki, 2000).

**3.3.5.1: Initiation of All Structural Cracking**

If HSOLD=0 (that is original surfacing)

$$ICA = K_{cia} \left( 13.2e^{-20.7\left(\frac{YE4}{SNP^2}\right)} \right) \quad (3.37)$$

If HSOLD>0 (that is overlays)

$$ICA = K_{cia} \left\{ \left[ \text{MAX} \left( 13.2e^{-20.7\left(\frac{YE4}{SNP^2}\right)}, 9.9 \right) \right] \right\} \quad (3.38)$$

**3.3.5.2: Initiation of Wide Structural Cracking**

If HSOLD=0

$$ICW = k_{ciw} \text{MAX} \left[ (2.66 + 0.88ICA), 1.16ICA \right] \quad (3.39)$$

If HSOLD>0

$$ICW = k_{ciw} (1.85 + ICA) \quad (3.40)$$

**3.3.5.3: Progression of All Structural Cracking**

The ACA of Washington state routes can never be greater than 50 percent, so

$$SCA = ACA_a \quad (3.41)$$

If HSOLD=0

If  $ACA_a > 0$ ,

$$dACA = k_{cpa} \left[ \left( 0.5632 + ACA_a^{0.32} \right)^{\frac{1}{0.32}} - ACA_a \right] \quad (3.42)$$

Otherwise:

$$dACA = k_{cpa} \left[ \left( 0.5632 * \text{MAX} (0, \text{MIN} [(AGE2 - ICA), 1]) + ACA_a^{0.32} \right)^{\frac{1}{0.32}} - ACA_a \right] \quad (3.43)$$

If HSOLD>0

If  $ACA_a > 0$ ,

$$dACA = k_{cpa} \left[ \left( 0.8194 + ACA_a^{0.34} \right)^{\frac{1}{0.34}} - ACA_a \right] \quad (3.44)$$

Otherwise:

$$dACA = k_{cpa} \left[ \left( 0.8194 * \text{MAX} (0, \text{MIN} [(AGE2 - ICA), 1]) + ACA_a^{0.34} \right)^{\frac{1}{0.34}} - ACA_a \right] \quad (3.45)$$

#### **3.3.5.4: Progression of Wide Structural Cracking**

The ACW of Washington state routes can never be greater than 50 percent, so

$$SCW = ACW_a \quad (3.46)$$

If HSOLD=0

If  $ACW_a > 0$

$$dACW = K_{cpw} \text{MIN} \left[ (ACA_a + dACA - ACW_a), \left( (0.625 + ACW_a^{0.25})^4 - ACW_a \right) \right] \quad (3.47)$$

Otherwise:

$$dACW = K_{cpw} \text{MIN} \left[ (ACA_a + dACA - ACW_a), \left( (0.625 * \text{MAX} \{0, \text{MIN} [AGE2 - ICW], 1\} + ACW_a^{0.25})^4 - ACW_a \right) \right] \quad (3.48)$$

If HSOLD>0

If  $ACW_a > 0$

$$dACW = K_{cpw} \text{MIN} \left[ (ACA_a + dACA - ACW_a), \left( (1.19 + ACW_a^{0.35})^{\frac{1}{0.35}} - ACW_a \right) \right] \quad (3.49)$$

Otherwise:

$$dACW = K_{cpw} \text{MIN} \left[ (ACA_a + dACA - ACW_a), \left( (1.19 * \text{MAX} \{0, \text{MIN} [AGE2 - ICW], 1\} + ACW_a^{0.35})^{\frac{1}{0.35}} - ACW_a \right) \right] \quad (3.50)$$

#### **3.3.5.5: Initiation of Transverse Thermal Cracking**

$$ICT = K_{cit} * \text{MAX} (100, CCT) = 100K_{cit} \quad (3.51)$$

### **3.3.5.6: Plastic Deformation of Rut Depth**

$\Delta RDPD = 0 \Rightarrow K'_{rpd}$  can be any value.

### **3.3.5.7: Total Rut Depth**

If AGE4 ≤ 1,

$$\Delta RDM = \Delta RDW = K_{rsw} X_3 \quad (3.52)$$

Otherwise:

$$\Delta RDM = \Delta RDST_{uc} + \Delta RDW = K_{rst} X_1 + K_{rsw} X_3 \quad (3.53)$$

### **3.3.5.8: Initiation of Raveling**

$$IRV = K_{vi} \left( 10.5 e^{-0.156YAX} \right) \quad (3.54)$$

## **3.3.6: Calibration Steps and Results**

The overall computational logic for regressing deterioration models for each distress type can be summarized in the following steps:

- Derive the variables from the road network input data.
- Exclude outliers.
- Divide the whole dataset into several sub-tables according to the calibration category defined in Section 3.1.
- Export the tables to (\*.csv) format that can be recognized by LIMDEP.
- Regress the models in different categories in LIMDEP.

Tables 26, 27, 28, and 29 give the values that were regressed in LIMDEP with the highest R-square based on local variables and models defined by HDM-4 in four categories. T-statistics refer to the values of the corresponding variables.

**Table 26: Estimated factors for high ESAL ACPs**

Calibration Factor	Class	Estimated Factor	T-statistic	Number of Observations
$K_{cia}$		1.74678	36.462	352
$K_{ciw}$		1.02038	512.290	352
$K_{cpa}$		0.69499	9.527	342
$K_{cpw}$		0.03395	4.215	345
$K_{cit}$	<i>WW</i>	0.10053	3594.903	248
	<i>EW</i>	2.51061	64.210	104
$K_{cpt}$		0.11289	4.413	212
$K_{rid}$	<i>Age4&lt;=1</i>	0.12434	0.572	28
$K_{rpd}$	<i>Age4&lt;=1</i>	0.04491	0.131	28
$K_{rsw}$	<i>Age4&lt;=1</i>	1.18374	1.557	28
$K_{rst}$	<i>Age4&gt;1</i>	1.76939	3.413	343
$K_{rpd}$	<i>Age4&gt;1</i>	0.00818	0.300	343
$K_{rsw}$	<i>Age4&gt;1</i>	0.31953	3.232	343
$K_{vi}$		0.17650	15.488	352
$K_{vp}$		0.01731	2.472	345
$K_{gm}$		0.49995	5.988	341
$K_{gp}$		0.14342	2.718	341



**Table 27: Estimated factors for medium ESAL ACPs**

Calibration Factor	Class	Estimated Factor	T-statistic	Number of Observations
$K_{cia}$		1.28748	47.465	461
$K_{ciw}$		1.01866	559.489	455
$K_{cpa}$		0.33471	13.510	418
$K_{cpw}$		0.47516	13.736	425
$K_{cit}$	<i>WW</i>	0.10055	1901.345	309
	<i>EW</i>	1.66277	19.464	146
$K_{cpt}$		0.26529	5.254	266
$K_{rid}$	<i>Age4&lt;=1</i>	0.12434	0.572	28
$K_{rpd}$	<i>Age4&lt;=1</i>	0.04491	0.131	28
$K_{rsw}$	<i>Age4&lt;=1</i>	1.18374	1.557	28
$K_{rst}$	<i>Age4&gt;1</i>	0.31945	2.154	255
$K_{rpd}$	<i>Age4&gt;1</i>	0.17583	5.329	255
$K_{rsw}$	<i>Age4&gt;1</i>	0.53993	5.564	255
$K_{vi}$		0.12145	37.323	455
$K_{vp}$		0.00742	3.672	425
$K_{gm}$		0.66950	8.371	328
$K_{gp}$		0.15754	1.653	328

**Table 28: Estimated factors for low ESAL ACPs**

Calibration Factor	Class	Estimated Factor	T-statistic	Number of Observations
$K_{cia}$		1.26660	107.273	1368
$K_{ciw}$		1.01951	989.111	1368
$K_{cpa}$		0.50630	21.133	1273
$K_{cpw}$		0.44102	22.639	1199
$K_{cit}$	<i>WW</i>	0.10074	6751.605	946
	<i>EW</i>	1.88127	34.588	422
$K_{cpt}$		0.37150	7.411	709
$K_{rid}$	<i>Age4&lt;=1</i>	0.12434	0.572	28
$K_{rpd}$	<i>Age4&lt;=1</i>	0.04491	0.131	28
$K_{rsw}$	<i>Age4&lt;=1</i>	1.18374	1.557	28
$K_{rst}$	<i>Age4&gt;1</i>	0.60274	6.791	1268
$K_{rpd}$	<i>Age4&gt;1</i>	0.29016	5.199	1268
$K_{rsw}$	<i>Age4&gt;1</i>	1.03010	9.028	1268
$K_{vi}$		0.08604	95.111	1368
$K_{vp}$		0.02824	6.964	1213
$K_{gm}$		0.76619	12.757	1281
$K_{gp}$		0.29695	2.600	1281

**Table 29: Estimated factors for all BSTs**

Calibration Factor	Class	Estimated Factor	T-statistic	Number of Observations
$K_{cia}$		0.36716	49.634	376
$K_{ciw}$		0.99222	--	376
$K_{cpa}$		0.49920	9.452	353
$K_{cpw}$		0.50040	9.452	353
$K_{cit}$	<i>WW</i>	0.04338	6499.995	257
	<i>EW</i>	3.29640	77.269	118
$K_{cpt}$		0.62233	6.206	353
$K_{rid}$	<i>Age4&lt;=1</i>	--	--	0
$K_{rpd}$	<i>Age4&lt;=1</i>	--	--	0
$K_{rsw}$	<i>Age4&lt;=1</i>	--	--	0
$K_{rst}$	<i>Age4&gt;1</i>	0.22147	4.756	352
$K_{rpd}$	<i>Age4&gt;1</i>	0.00000	0.000	352
$K_{rsw}$	<i>Age4&gt;1</i>	2.05351	9.469	352
$K_{vi}$		0.89950	231.770	376
$K_{vp}$		0.10260	2.046	353
$K_{gm}$		0.98860	7.692	353
$K_{gp}$		0.11181	1.196	353

### **3.3.7: Validation of Modeling Factors**

Calibration factors were chosen by maximizing R-squared in LIMDEP. All deterioration model factors were further accessed by the process of validation. Validation was used to determine how well the models represent the real system and to adjust model factors with real observations.

#### **3.3.7.1: Validation Data Preparation**

At the project unit, WSPMS 2003 consists of 3,508 sections (excluding bridges), including 2,893 flexible sections and 615 concrete sections. To simplify the validation process, these sections were merged into 42 typical sections (24 flexible sections and 18 concrete sections) according to the following classification:

- Pavement types (flexible, concrete)
- Traffic volume (high, medium, low)
  - High: when ESAL/Elane/year > 500,000
  - Low: when ESAL/Elane/year < 250,000
  - Medium: when  $250,000 \leq \text{ESAL/Elane/year} \leq 500,000$
- Surface material (AC, BST)
- Pavement condition (good, fair, poor)
  - Good: when rut depth < 5mm and ACA < 1.00%
  - Poor: when rut depth >10mm or ACA > 5.00%
  - Fair: between good and poor
- Road class (interstate, non-interstate).

Climate zones are merged into one, as shown in Table 30.

**Table 30: Climate index for one climate zone of Washington state**

<i>Climate</i>	
Moisture Index	109.75
Duration of dry season	0.59 (as a fraction of a year)
Mean monthly precipitation	97.15 mm
Mean temperature	10.22 °C
Average Temperature range	9.97 °C
Days T>32 °C	1.55 days
Freeze Index	99.44 °C-days
<i>Percentage of Time Driven</i>	
On snow covered roads	0
On water covered roads	20

[Source: WSPMS 2003]

According to the classification, all road network variables for the 42 sections were set as the medians of corresponding project level sections. Therefore, these 42 sections can represent the main characteristics of all WSDOT highways. Results based on these

typical sections are thereby valid and can be used in all project level sections.

The assigned standards follow the routine works of WSDOT as Table 31:

**Table 31: Maintenance standards for flexible pavements**

<b><i>Asphalt Concrete-Surfaced Flexible Pavements</i></b>
-Base Alternative (Do Nothing)
-Pothole Patching
-45-mm Overlay
<b><i>Bituminous Treatment-Surfaced Flexible Pavements</i></b>
-Base Alternative (Do Nothing)
-BST

Vehicle composition and annual growth rate also need to be confirmed on the selected road sections in the given year. Medians for specific surface types are applied as shown in Table 32:

**Table 32: Traffic composition and annual growth rate for ACPs**

Vehicle Type	Traffic Composition (%)	Annual Growth Rate (%)
<b><i>ACP</i></b>		
Car	87.11	1.66
Single Unit	6.11	1.66
Double Unit	5.37	1.66
Train	1.41	1.66
<b><i>BST</i></b>		
Car	83.14	1.72
Single Unit	9.05	1.72
Double Unit	5.72	1.72
Train	2.09	1.72

**3.3.7.2: Validation Criteria**

The following heuristic values from WSDOT were set as the validation criteria.

- For validation of AC surfaced flexible pavements models, roads should be overlaid about every 12 years when cracking  $\geq 10$  percent. At that time

roughness is smaller than 3.5m/km and rut depth is close to 10 mm.

- For validation of BST-surfaced flexible pavements models, roads should be resealed about every 6 years, when cracking  $\geq 10$  percent. At that time roughness is lower than 3.5m/km and rut depth is close to 10mm. But the average road conditions are worse than that of ACPs.

### **3.3.7.3: Validation Results**

The validation results are listed in Table 33. These factors will be used for future analysis in Chapter 4. Note that the results in Table 33 differ from the calibration factors in Tables 26, 27, 28 and 29. The factors in these Tables are not validated.

**Table 33: Validated calibration factors for flexible pavements**

Calibration Factors	ACP			BST
	Traffic			
	High	Med	Low	
$K_{cia}$	1.00	0.84	0.76	0.20
$K_{ciw}$	0.40	0.40	0.40	0.30
$K_{cpa}$	0.71	0.78	0.82	0.50
$K_{cpw}$	0.11	0.30	0.45	0.50
$K_{cit}$	0.10	0.10	0.10	0.04
$K_{cpt}$	0.20	0.20	0.20	0.62
$K_{rid}$	0.12			0.01
$K_{rst}$	0.15			0.22
$K_{rpd}$	0.01			0.02
$K_{rsw}$	0.32			2.05
$K_{gm}$	0.70			1.00
$K_{gp}$	1.62			0.70
$K_{vi}$	1.00			1.00
$K_{vp}$	0.04			1.00
$K_{pi}$	1.00	1.10	3.00	1.00
$K_{pp}$	0.10	0.08	0.40	1.00
$K_{snpk}$	0.00			0.00

### **3.4: CALIBRATION OF DETERIORATION MODELS FOR CONCRETE PAVEMENTS**

The deterioration models for concrete pavements in HDM-4 are basically absolute models. Absolute models make predictions based on conditions at a particular point in time (Odoki, 2000). HDM-4 sets this point of time as the construction year for concrete pavement deterioration models.

WSDOT uses jointed plain concrete pavement. Table 34 lists related calibration factors used in those deterioration models.

**Table 34: Calibration factors used in concrete pavement deterioration models**

<b>Calibration Factor</b>	<b>Deterioration model</b>
K <sub>jp<sub>c</sub></sub>	Cracking calibration factor
K <sub>jp<sub>n</sub><sub>f</sub></sub>	Faulting calibration factor in pavements without dowels
K <sub>jp<sub>d</sub><sub>f</sub></sub>	Faulting calibration factor in pavements with dowels
K <sub>jp<sub>s</sub></sub>	Joint spalling calibration factor
K <sub>jp<sub>r</sub></sub>	Roughness progression calibration factor

[Source: HDM-4 Volume 4]

#### **3.4.1: Proposed Calibration Methodology**

The general expression used for the deterioration models of concrete pavements in HDM-4 is as following:

$$\text{Predicted Distress: } Y' = K'_y * f(Y_a, a_0, a_1, a_2, \dots, a_n, X_1, X_2, \dots, X_m) \quad (3.55)$$

where:

K'<sub>y</sub>: default calibration factor of distress type Y given by HDM-4 (1.0);

Y': predicted value of distress types Y by HDM-4;

a<sub>i</sub>: default coefficient values given by models and decided by factors of climate and environment, traffic, pavement history, road geometry, pavement structural characteristics or material properties;

$X_i$ : input factors of climate, traffic, road geometry, pavement history, pavement structural characteristics and material properties.

The optimal calibration factors were obtained by following the steps below:

- Use default value 1.0 as the calibration factors.
- Run HDM-4 in Project Level for one-year forecasting from 2002. Export
- Export the predicted distress values of 2003 from the output reports.
- Exclude outliers.
- Regress the pavement deterioration models in LIMDEP for  $K_y$ .

$$Y = K_y * Y' \quad (3.56)$$

where:

$Y$ : Value of distress type  $Y$  in WSPMS 2003;

$Y'$ : HDM-4 predicted value for distress type  $Y$  by using default calibration factors;

$K_y$ : Calibration factor of distress type  $Y$ .

### **3.4.2: Determination of Calibration Coefficients**

The proposed values for calibration coefficients are listed as follows:

- Subgrade  $k$  static modulus of reaction: 54 mpa/m.
- Modulus of elasticity of concrete ( $E_c$ ): 27500 Mpa (4,000,000 psi).
- Modulus of rupture (flexural strength) of concrete: 5 Mpa (725 psi).
- Thermal coefficient of concrete: 0.000006 for gravel aggregate type.
- Shrinkage coefficient: 0.00045 in/in.
- Dowels diameter: 38 mm.



- Joint seal material: asphalt because WSDOT PCC joints are usually hot pour liquid sealant – asphalt.
- Use corrosion coated or not: yes because WSDOT dowel bars are epoxy coated or stainless steel.

### **3.4.3: Simplified Pavement Deterioration Models for Concrete Pavements**

WSDOT concrete pavements are generally jointed plain without load transfer dowels, and the corresponding pavement deterioration models are listed as follows:

#### **3.4.3.1: Thermal Cracking**

$CRACKING_t = K_{jpc} * \text{Function (Slab thickness, Joint spacing, Concrete flexural strength, Climate)}$

where:

$CRACKING_t$ : Cracking at time t (% of total carriageway);

$K_{jpc}$ : Calibration factor of cracking (default value 1.0).

#### **3.4.3.2: Faulting**

$FAULT_t = K_{jpnf} * \text{Function (Drainage condition, Base type, Shoulder/lane width, Joint spacing, Slab thickness)}$

where:

$FAULT_t$ : Average faulting at time t;

$K_{jpnf}$ : Calibration factor of faulting (default value 1.0).

#### **3.4.3.3: Spalling**

$SPALL_t = K_{jrs} * \text{Function (Age, Seal type, Material characteristics, Joint spacing)}$

where:

SPALL<sub>t</sub>: Spalling at time t (%);

Age: Age since pavement construction (years);

K<sub>jr</sub>: Calibration factor of spalling (default value 1.0).

#### **3.4.3.4: Roughness**

ROUGHNESS<sub>t</sub> = K<sub>jp</sub> \* Function (ROUGHNESS<sub>0</sub>, Fault, Spall, Crack, Joint Spacing)

where:

ROUGHNESS<sub>t</sub>: Roughness at time t;

ROUGHNESS<sub>0</sub>: Roughness at the time of pavement construction;

K<sub>jp</sub>: Calibration factor of roughness (default value 1.0).

#### **3.4.4: Fatal Errors in HDM-4 Outputs for Concrete Pavements**

The HDM-4 concrete pavement deterioration models do not function properly, which essentially renders the whole concrete pavement portion of HDM-4 non-functional. This conclusion is drawn from a large number of tests based on various pavement conditions, traffic conditions, and calibration factors. The errors are summarized as follows:

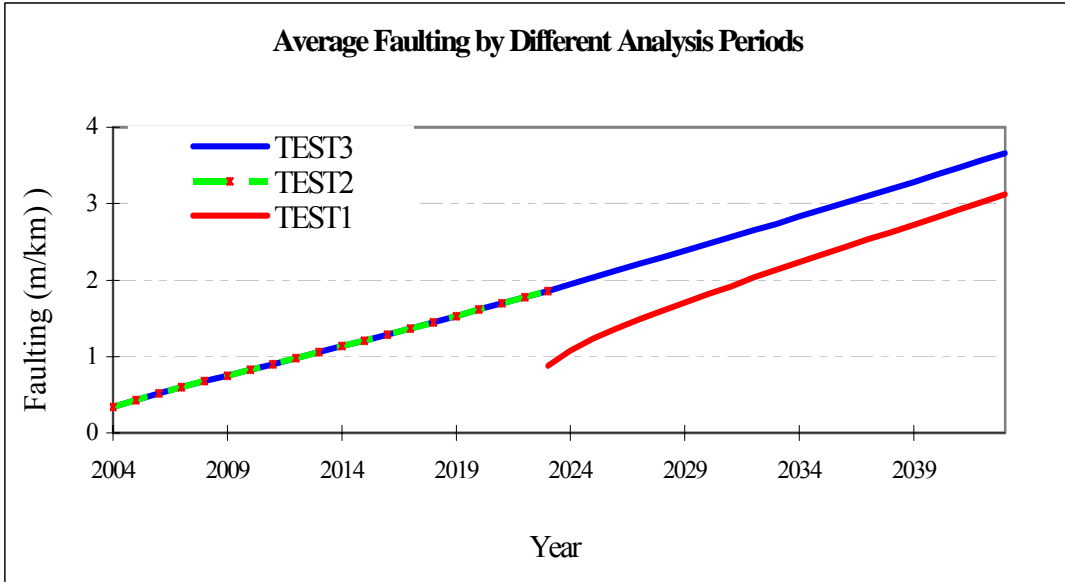
1. Regardless of the selected calibration factors, values of cracking and spalling never change. They always equal the values input for the construction year during the whole service life. Even when calibration factors are set at the maximum value of 20, the results do not change.
2. HDM-4 reports do not output values of deteriorated cracks and failures, even though the related deterioration models are given by HDM-4.

3. Prediction of faulting and roughness is not reliable. As an example, a typical concrete pavement section is input into HDM-4 for testing. Table 40 shows the main characteristics. Three different analysis periods were tested on this section:
- TEST 1: 20 years from 2004 to 2023
  - TEST 2: 21 years from 2023 to 2043
  - TEST 3: 40 years from 2004 to 2043

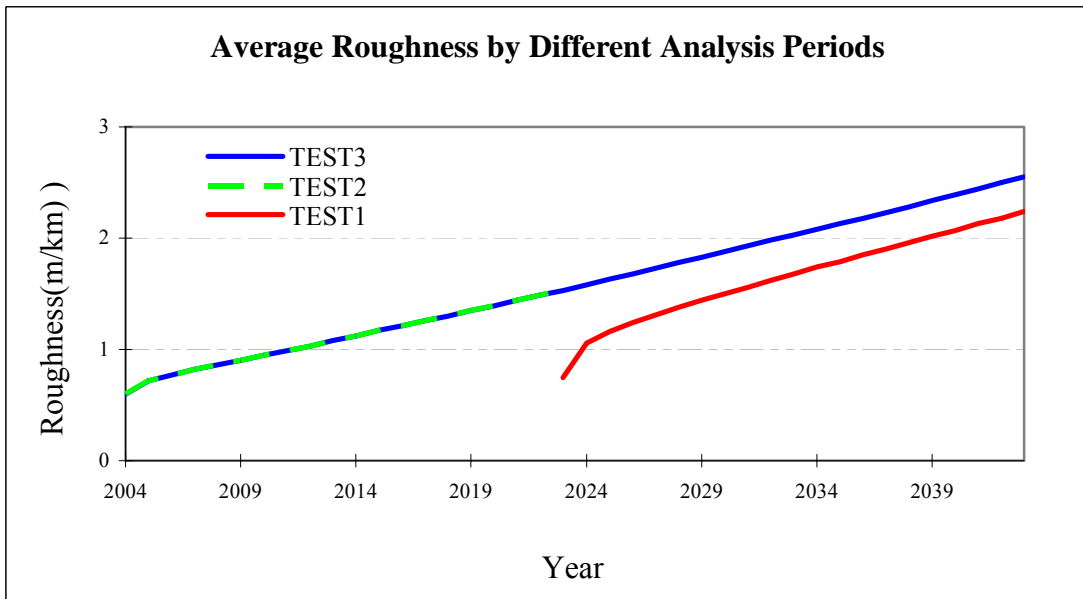
Because the analysis was performed on the same section, and traffic growth rates were set to 0, all tests should have had the same distress conditions in 2023. However, faulting and roughness in TEST 2 were significantly lower than those of TEST 1 from 2023 to 2043. Faulting and roughness estimated by HDM-4 are illustrated in Figures 10 and 11, respectively. Unreasonably low faulting and roughness values are always predicted by HDM-4 at the beginning of any analysis period. Therefore, the faulting and roughness performance forecasted by HDM-4 is not stable and reliable.

**Table 35: Main road network data for concrete pavement tests**

<b>Speed Flow Type</b>	Four Lane Wide
<b>Traffic Flow Type</b>	Urban
<b>Road Class</b>	Interstate
<b>Number of Lanes</b>	2
<b>AADT</b>	60000
<b>Speed Limit (km/hr)</b>	95
<b>Subgrade Type</b>	1 (Granular)
<b>Base Type</b>	0 (Asphalt Treated)
<b>Base Thickness (mm)</b>	225
<b>Construction Year</b>	1962
<b>Calibration Factors</b>	1 (default)
<b>Traffic Growth Rate</b>	0.00

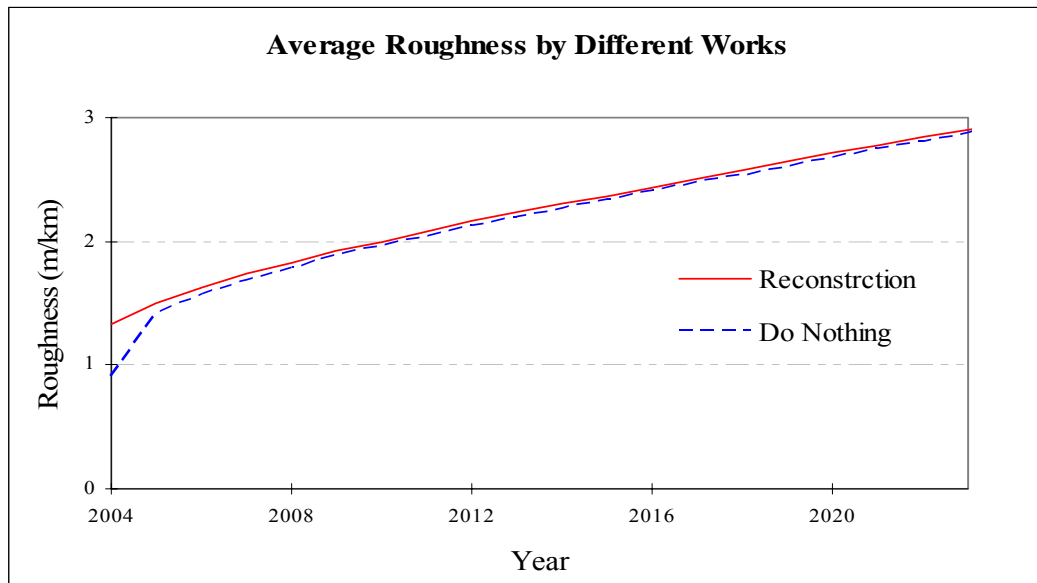


**Figure 10: Faulting forecasting by different analysis periods**



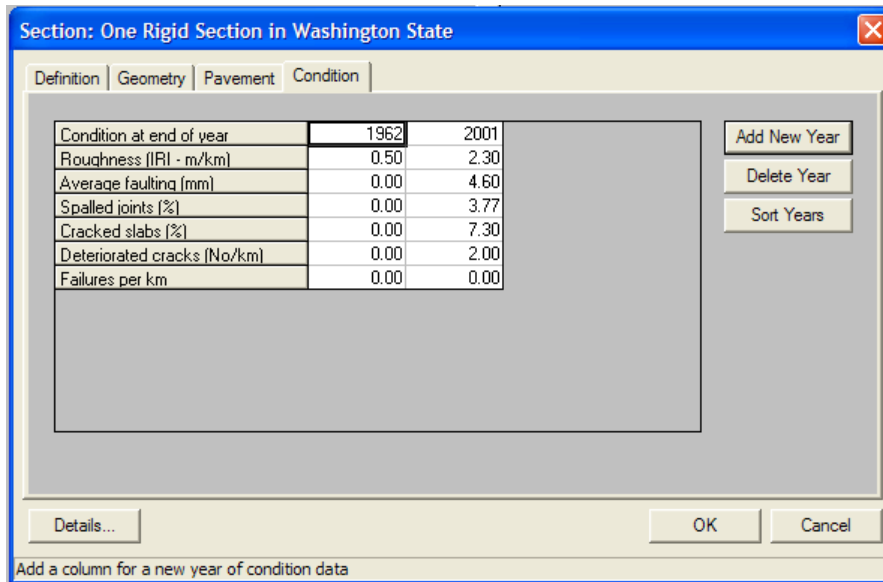
**Figure 11: IRI forecasting by different analysis periods**

4. Two preservation standards were input into HDM-4 and analyzed on the same section: reconstruction and do nothing. If “reconstruction” is never triggered in a specific analysis period, the pavement distress conditions should be the same as “do nothing.” But as seen in Figure 12, produced by HDM-4, the roughness values of the two alternatives are totally different, especially in the beginning of the analysis period. This is unreasonable.



**Figure 12: Roughness under two alternatives for concrete pavements**

5. In the input interface shown in Figure 13, although the distress data in a specific year can be added manually in the second column, only the first column is used, which is restricted by HDM-4. Therefore, the interface is futile.



**Figure 13: HDM-4 distress data input interface**

6. Some maintenance standards, such as reconstruction (or slab replacement), can only be triggered by cracking, but the estimated cracking stay at the same value as the construction year, so this maintenance standard is invalid.

Therefore, it is concluded that the HDM-4's concrete module is not yet functional. It cannot be applied until improvements and careful tests have taken place. Thus, the concrete module is NOT included in the later research.