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

Nadarajah Sivaneswaran
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
Departmenst of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

July 2004

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
WA-RD 588.1		

4. TITLE AND SUBTITLE	5. REPORT DATE
APPLICATION OF HDM-4 IN THE WSDOT HIGHWAY SYSTEM	July 2004
	6. PERFORMING ORGANIZATION CODE

7. AUTHORS	8. PERFORMING ORGANIZATION CODE
Jianhua Li, Stephen T. Muench, Joe P. Mahoney, George C. White, Linda M. Pierce, Nadarajah Sivaneswaran	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NO.
Washington State Transportation Center University of Washington, Box 354802 University District Building, 1107 NE 45th Street, Suite 535 Seattle, Washington (8504-7370	11. CONTRACT OR GRANT NUMBER Research Project T2695, Task 26

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Research Office Washington State Department of Transportation Transportation Building, MS 47370 Olympia, Washington 98504-7370 Project Manager: Keith Anderson, 360-709-5405	Final Research Report 14. SPONSORING AGENCY CODE

15. SUPPLIMENTARY NOTES

16. ABSTRACT

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.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
pavement management, pavement performance, models, HDM-4, vehicle operating costs, pavement preservation, pavement maintenance	

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE

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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 pavement maintenance and rehabilitation 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 polices 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.

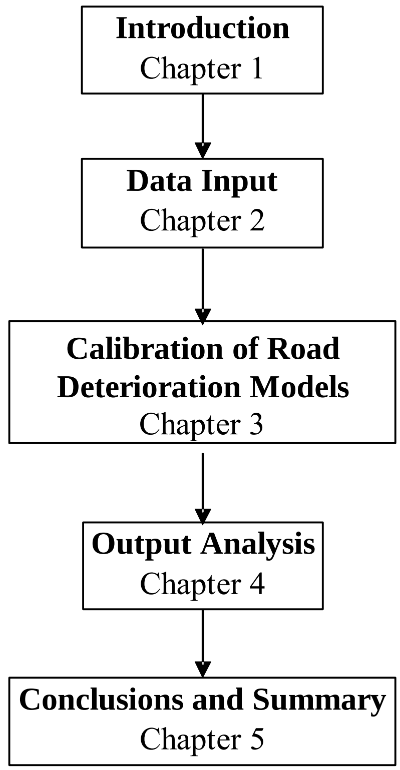

Figure 1: Report organization

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:

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

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

$$TCEC = (0.8TC3) + 0.445(0.\ 8TC2)^{1.15} + 0.13(0.\ 8TC1)^{1.35}$$

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

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

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

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^2 pavement block contains a fully developed longitudinal and a fully developed transverse crack. Therefore:

100% AC = (3+3) longitudinal cracks + (100/1.5) transverse cracks

= 6 * (100 ft.) + 66.7 * (3 ft. +3 ft.)

= 10 * (100 ft.)

= 10 longitudinal cracks (full 100-foot section length)

= 1000% of longitudinal cracking

And,

100%AC = 1000%LC

$$AC = 0.1LC \tag{2.2}$$

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.

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

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 ft = 0.03048 km

1 km = 3280.83 ft. (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 ¼ inch faulting or settlement

  FLT2 = percentage of panels with ¼ to ½ inch faulting or settlement

  FLT3 = percentage of panels with > ½ 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:

$$
\begin{aligned}
&CREC = CR3 + 0.24(CR2)^{1.16} + 0.0054(CR1)^{1.84} \\
&\mathrm{JSEC} = 0.075(\mathrm{JS3})^{1.14} + 0.0061(\mathrm{JS2})^{1.27} + 0.0034\,(\mathrm{JS1})^{1.03} \\
&\mathrm{PMEC} = 0.0069(\mathrm{PM1} + \mathrm{PM2} + \mathrm{PM3})^{1.45} \\
&\mathrm{FLTEC} = \mathrm{FLT3} + 0.0915(\mathrm{FLT2})^{1.46} + 0.00115(\mathrm{FLT1})^{2.32} \\
&\mathrm{PTEC} = 0.103(\mathrm{PT3})^{1.19} + 0.0079(\mathrm{PT2})^{1.55} + 0.00194\,(\mathrm{PT1})^{1.57} \\
&\mathrm{RSEC} = 0.052(\mathrm{RS3})^{1.29} + 0.0159(\mathrm{RS2})^{1.18} + 0.0014\,(\mathrm{RS1})^{1.18} \\
&\mathrm{EC} = \mathrm{CREC} + \mathrm{JSEC} + \mathrm{PMEC} + \mathrm{FLTEC} + \mathrm{PTEC} + \mathrm{RSEC} \\
&\mathrm{PSC} = 100 - 18.6(\mathrm{EC})^{0.43}
\end{aligned}
\tag{2.6}
$$

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).

$$\begin{aligned}&\text{CRACKSLABS (\%)} = (\text{CR1}+\text{CR2})\\&\text{FAULT (mm)} = 4.7625*\text{FLT1}+9.525*\text{FLT2}+12.7*\text{FLT3}\\&\text{SPALL\_JNTS (\%)} = \text{JS3}.\end{aligned} \tag{2.7}$$

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

Pavement Type	**Surface Material***	**ESAL** (ESAL / year/Elane)	**Number of Cases**
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) ≤ 50
- rut depth ≥ 10 mm
- roughness ≥ 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:

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

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

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

(b) Rutting

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

(c) Roughness

Same as WSDOT, HDM-4 triggers rehabilitation when IRI ≥ 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 ≥ 10%
- rut depth ≥ 10 mm
- roughness ≥ 3.5 m/km (AL-Omari and Darter, 1992).

<u>2.4.1.2: Work Effects of 45-mm Overlay</u>

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.

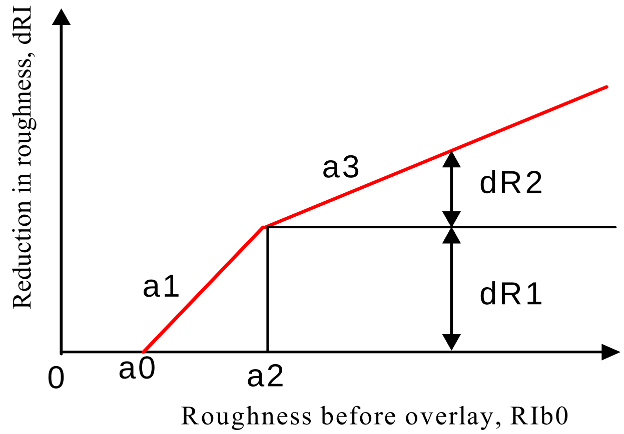

Figure 2: Works effects on roughness in HDM-4

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.

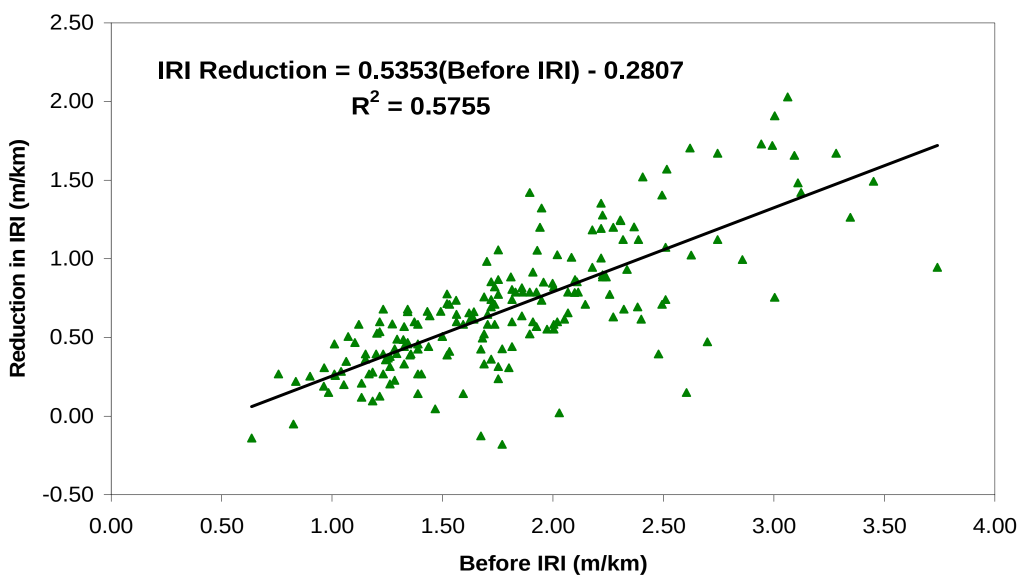

Figure 3: Works effects on roughness by WSDOT
[Source: WSDOT Material Laboratory, 2003]

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 a1 = a3 and a2 = a0. Therefore, a0 = 0.5244, a1 = 0.5353, a2 = 0.5244, and a3 = 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

General	Name:	45 mm Overlay
	Short Code:	45 OVER
	Intervention Type:	Responsive
Design	Surface Material:	Asphalted Concrete
	Thickness:	45 mm
	Dry Season a:	0.44
	CDS:	1
Intervention	Responsive Criteria:	Total cracked area ≥ 10%
		Rutting ≥ 10 mm
		IRI ≥ 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
Costs	**Overlay**	
	Economic:	19 dollars/m^2 *
	Financial:	19 dollars/m^2 *
	Patching	
	Economic:	47 dollars/m^2 *
	Financial:	47 dollars/m^2 *
	Edge Repair	
	Economic:	47 dollars/m^2
	Financial:	47 dollars/m^2
Effects	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

General	Name:	45 mm Mill & Fill
	Short Code:	45MF
	Intervention Type:	Responsive
Design	Surface Material:	Asphalted Concrete
	Depth of Mill:	45 mm
	Thickness:	45 mm
	Dry Season a:	0.44
	CDS:	1
Intervention	Responsive Criteria:	Total cracked area ≥ 10%
		Rutting ≥ 10 mm
		IRI ≥ 3.5 m/km
	Min. Interval:	-
	Max. Interval:	-
	Last Year:	2099
	Max Roughness:	16 m/km
	Min ADT:	0
	Max ADT:	500,000
Costs	**Overlay**	
	Economic:	30 dollars/m^2 *
	Financial:	30 dollars/m^2 *
	Patching	
	Economic:	47 dollars/m^2 *
	Financial:	47 dollars/m^2 *
	Edge Repair	
	Economic:	47 dollars/m^2 *
	Financial:	47 dollars/m^2 *
Effects	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

General	Name:	Pothole Patching
	Short Code:	POTPAT
	Intervention Type:	Responsive
Intervention	Responsive Criteria:	Potholing ≥ 0.01 no./km
	Min. Interval:	-
	Max. Interval:	-
	Last Year:	2099
	Max Roughness:	16 m/km
	Max Quantity:	5000 m^2/km/year
	Min ADT:	0
	Max ADT:	500,000
Costs	Economic:	47 dollars/m^2 *
	Financial:	47 dollars/m^2 *
Effects	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 ≥ 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.

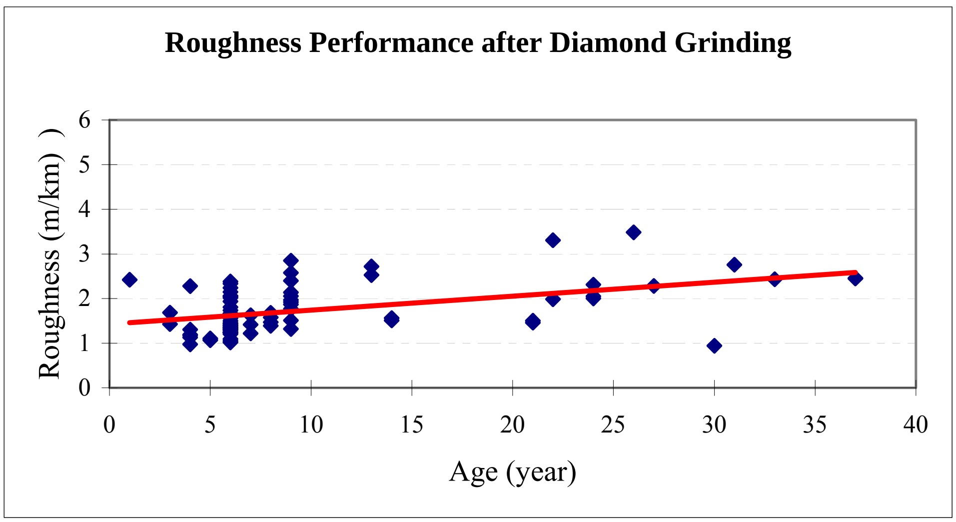

Figure 4: Simulation of roughness performance after diamond grinding

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

General	Name:	Diamond Grinding
	Short Code:	DG
	Intervention Type:	Responsive
Intervention	Responsive Criteria:	Faulting ≥ 6 mm
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	500,000
Costs	Economic:	1 dollars/m^2/mm *
	Financial:	1 dollars/ m^2/mm *
Effects	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 ≥ 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

General	Name:	Reconstruction
	Short Code:	RECON
	Intervention Type:	Responsive
Intervention	Responsive Criteria:	% of cracked slabs ≥ 10%
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	500,000
Costs	Economic:	169.9 dollars/m^2 *
	Financial:	169.9 dollars/m^2 *
Effects	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

General	Name:	Bituminous Surface Treatment
	Short Code:	BSTCRA
	Intervention Type:	Responsive
Design	Surface Material:	Double Bituminous Surface Dressing
	Thickness:	12.5mm
	Dry Season a:	0.2
	CDS:	1
Intervention	Responsive Criteria:	total cracked area ≥ 10%
	Min. Interval:	1
	Max. Interval:	100
	Max Roughness:	16 m/km
	Max ADT:	100,000
	BST Economic:	2.04 dollars/m^2 *
	BST Financial:	2.04 dollars/m^2 *
	Patching Economic:	47 dollars/m^2 *
	Patching Financial:	47 dollars/m^2 *
	Edge Repair Economic:	47 dollars/m^2 *
	Edge Repair Financial:	47 dollars/m^2 *
	Crack Seal Economic:	8.5 dollars/m^2 *
	Crack Seal Financial:	8.5 dollars/m^2 *
Effects	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

Period	Hours Per Year	Hourly Volume	% of AADT
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
Total	8760	1.0005	100

[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

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

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

Table 11: Volume composition in the seasonal flow pattern

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

[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]

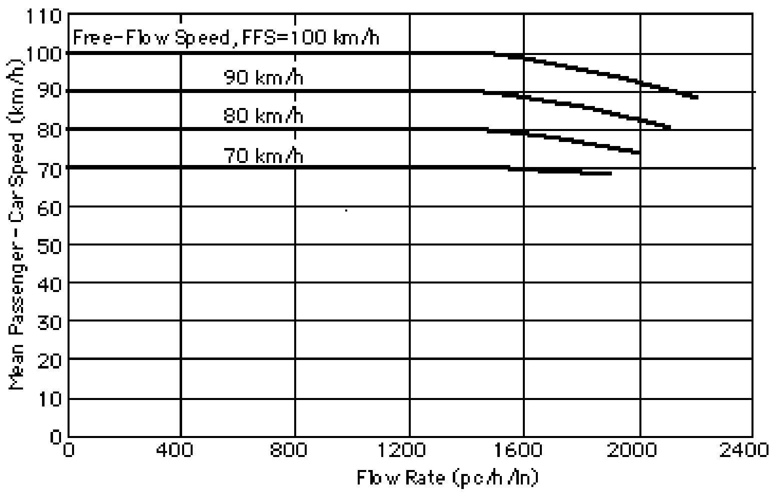

Figure 5: Speed-flow relationships on multi-lane highways
[Source: Highway Capacity Manual 2000, Exhibit 12-1]

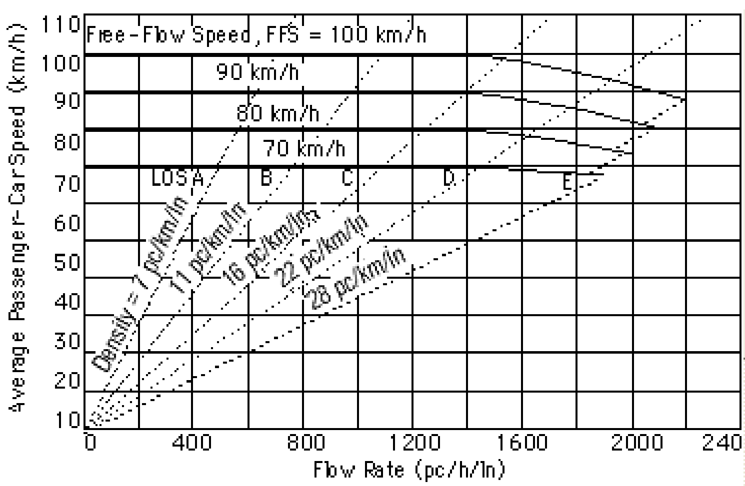

Figure 6: Speed-flow curves with criteria
[Source: Highway Capacity Manual 2000, Exhibit 21-3]

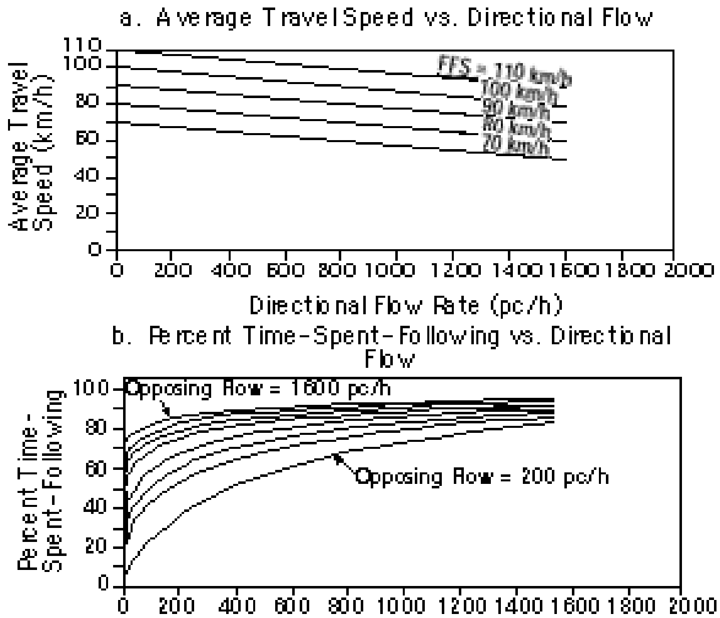

Figure 7: Speed-flow and percentage of time-spent-following flow relationships for directional segments with base conditions
[Source: Highway Capacity Manual 2000, Exhibit 12-7]

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** (Qnom)	**FFS** (Km/hr)	**Jam Speed** (km/hr)	**Max Acceleration Noise** (m/s^2)
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

Moisture Category	Description	Thornthwaite Moisture Index	Annual Precipitation (mm)
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

Temperature Category	Description	Temperature Range (°C)
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

Climate Zone	Tropical	Subtropical -hot	Subtropical -cool	Temperate -cool	Temperate -freezing
Arid	X	X	X	X	X
Semi-arid	X	X	X	X	X
Sub-humid	X	X	X	X	X
Humid	X	X	X	X	X
Per-humid	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_h: humidity index

I_a: 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 (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:

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

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

Zone	Olympic	Northwest	North Central	Eastern	Southwest	South Central
County	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.edusummary/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

Zone Name	Moisture			Temperature			
	Moisture Index	Duration of dry season	Mean monthly precipitation (mm)	Mean Temp. (ºC)	Temp. Range (ºC)	Days T>32ºC (89.6ºF)	Freeze Index (ºC-days)
Olympic	144.77	0.5386	111.98	9.77	9.21	0	11.73
Northwest	75.09	0.5924	65.89	10.60	8.64	0	0.99
North Central	26.02	0.8296	20.26	10.13	12.30	9.4	465.33
Eastern	58.64	0.7052	41.20	8.57	12.66	2	562.77
Southwest	163.46	0.5036	127.95	10.73	9.92	0	3.13
South Central	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 (ºC)**	10.37	9.64
	Temp Range (ºC)	9.26	12.83
	Days T>32ºC (89.6ºF)	0.00	7.73
	Freeze Index (ºC-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).

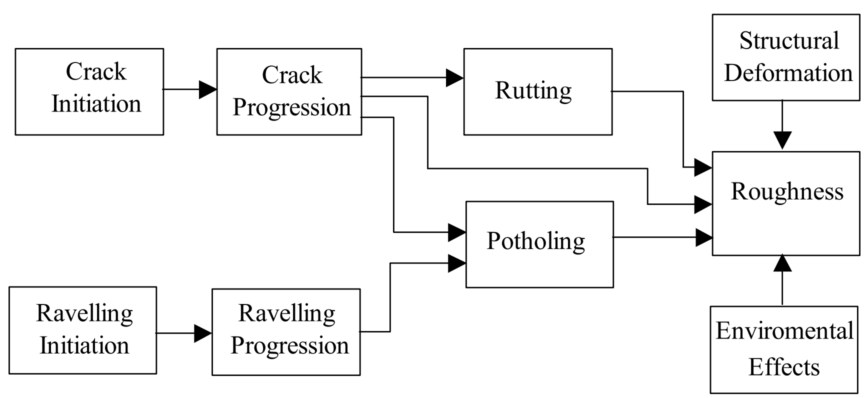

Figure 9: Flexible pavement distress interaction
[Source: HDM-4 Volume-5]

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

Deterioration model	Calibration factor
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

Sensitivity Level	Impact	Impact Elasticity	Factor
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
			Cracking progression factor
S-III	Low	0.05-0.2	Subgrade CBR (with SN)
			Surface thickness (with SN)
			Heavy axles volume
			Potholing area
			Rut depth mean
			Rut depth standard deviation
			Rut depth progression factor
			Roughness general factor
S-IV	Negligible	<0.05	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:

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

where:

K_y: calibration factor of distress type Y

ΔY: 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 $Y_a, a_0, a_1, a_2, \ldots, a_n, X_1, X_2, \ldots$, and X_m are given, $f()$ acts as one independent variable of the dependent variable ΔY. The non-linear models are converted to simple linear relationship between the dependent variable ΔY 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 (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):

$$\text{WW:} \quad PASS = \frac{365 * 3\% * AADT}{10^3 * Number\ Of\ Direction}$$

$$\text{EW:} \quad PASS = \frac{365 * 8\% * AADT}{10^3 * Number\ Of\ Direction}$$

(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):

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

- **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.

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

- **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 ≥ AGE4 and condition year ≥ 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 ≤ 40 years, since longer AC service lifes 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

Surface Material	Climate	ICA (year)	ICW (year)	ICT (year)	IRV (year)
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).

<u>3.3.4: Simplified Deterioration Models for AC-Surfaced Flexible Pavements</u>

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).

<u>*3.3.4.1: Wet/Dry Season SNP Ratio*</u>

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,

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

where:

$f = \dfrac{Wet\ season\ SNP}{Dry\ season\ SNP}$. 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.

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

ACRAa=ACAa+ACTa

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)

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

If HSOLD>0 (that is overlays)

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

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.

$$ICW = k_{ciw}\left(2.04 + 0.98ICA\right) \tag{3.9}$$

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

$$SCA=ACA_a \tag{3.10}$$

If $ACA_a>0$,

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

Otherwise:

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

where:

$$ACA_a = MAX\ (ACA_a,\ 0.5) \tag{3.13}$$

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

ACA_a: ACA at the start of the analysis year;

K_{cpa}: 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

$$SCW = ACW_a \tag{3.14}$$

If $ACW_a > 0$

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

Otherwise:

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

where:

$$ACW_a = MAX\ (ACW_a,\ 0.5) \tag{3.17}$$

dACW: incremental change of ACW during the analysis year;

ACW_a: 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:

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

where:

Kcit: calibration factor for initiation of transverse thermal cracking.

(f) Progression of Transverse Thermal Cracking (NCT)

If HSOLD=0

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

If HSOLD>0

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

(3.21)

where:

dNCT = 20*dACT

PNCT = 20*PACT (3.22)

If $ACT_a > 0$, $\delta t_T = 1$ Otherwise, $\delta t_T = MAX\left\{0, MIN\left[\left(AGE2 - ICT\right), 1\right]\right\}$

K_{cpt}: calibration factor for progression of thermal cracking

dNCT: incremental change in number of thermal cracking in analysis year (n^o/km) dACT: incremental change in ACT in analysis year (%)

PNCT: number of thermal cracks before last overlay (n^o/km)

NCT_a: 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

$$\Delta \text{RDST}=\text{K}_{\text{rst}}\left(1.1291SNP^{-1.14}YE4^{0.11}\right)=\text{K}_{\text{rst}}X_1 \tag{3.23}$$

Otherwise:

$$\Delta \text{RDST}=\text{K}_{\text{rst}}\left[1.1291SNP^{-1.14}YE4^{0.11}+0.0000248SNP^{-0.84}YE4^{0.14}MMP^{1.07}ACX_a^{1.11}\right]=Krst*X_1 \tag{3.24}$$

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 (%);

$$ACX_a=0.62ACA_a+0.39ACW_a \tag{3.25}$$

MMP: mean monthly precipitation (mm/month). MMP of WW equals 101.94, and EWequals 27.98.

(c) Plastic Deformation

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

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

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

where:

K_{rsw}: calibration factor for surface wear;

ΔRDW : 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,

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

Otherwise:

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

where:

ΔRDM : incremental change in rut depth in the analysis year (mm).

3.3.4.4: Raveling

(a) Initiation of Raveling (IRV)

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

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

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

where:

If $ARV_a > 0$, $\delta t_v = 1$; (3.32)

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

$ARV_a = MAX\ (ARV_a,\ 0.5)$ (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_{snpk} instead of the default value 1.0.

3.3.4.6: Roughness

Use $K_{snpk} = 0$, then

$$\begin{aligned}\Delta RI &= K_{gp}\left[\Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_t\right] + \Delta RI_e \\ &= K_{gp}\left[\Delta RI_s + \Delta RI_c + \Delta RI_r\right] + 0.035 * K_{gm} RI_a \\ &= K_{gp}\left[134 e^{0.035 K_{gm} AGE3}\left(1 + SNP\right)^{-5} YE4 + 0.0066 \Delta ACRA + 0.088 * \Delta RDS\right] + 0.035 * K_{gm} RI_a\end{aligned}$$

(3.35)

where:

ΔRI_s: Roughness increase during the analysis year due to structural deterioration

ΔRI_c: Roughness increase during the analysis year due to cracking

ΔRI_r: Roughness increase during the analysis year due to rutting

ΔRI_t: Roughness increase during the analysis year due to potholing, use 0

ΔRI : Roughness increase during the analysis year

K_{gp}: Calibration factor for roughness progression

K_{gm}: Calibration factor for environmental

ΔRDS : Increase in standard deviation of rut depth during the analysis year:

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

(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)

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

3.3.5.2: Initiation of Wide Structural Cracking

If HSOLD=0

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

If HSOLD>0

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

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:

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

If HSOLD>0

If ACA_a>0,

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

Otherwise:

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

3.3.5.4: Progression of Wide Structural Cracking

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

$$SCW = ACW_a \tag{3.46}$$

If HSOLD=0

If $ACW_a > 0$

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

Otherwise:

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

If HSOLD>0

If $ACW_a > 0$

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

Otherwise:

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

3.3.5.5: Initiation of Transverse Thermal Cracking

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

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,

$$\Delta RDM = \Delta RDW = K_{rsw} X_3 \tag{3.52}$$

Otherwise:

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

3.3.5.8: Initiation of Raveling

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

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}	*WW*	0.10053	3594.903	248
	EW	2.51061	64.210	104
K_{cpt}		0.11289	4.413	212
K_{rid}	*Age4<=1*	0.12434	0.572	28
K_{rpd}	*Age4<=1*	0.04491	0.131	28
K_{rsw}	*Age4<=1*	1.18374	1.557	28
K_{rst}	*Age4>1*	1.76939	3.413	343
K_{rpd}	*Age4>1*	0.00818	0.300	343
K_{rsw}	*Age4>1*	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}	*WW*	0.10055	1901.345	309
	EW	1.66277	19.464	146
K_{cpt}		0.26529	5.254	266
K_{rid}	*Age4<=1*	0.12434	0.572	28
K_{rpd}	*Age4<=1*	0.04491	0.131	28
K_{rsw}	*Age4<=1*	1.18374	1.557	28
K_{rst}	*Age4>1*	0.31945	2.154	255
K_{rpd}	*Age4>1*	0.17583	5.329	255
K_{rsw}	*Age4>1*	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}	*WW*	0.10074	6751.605	946
	EW	1.88127	34.588	422
K_{cpt}		0.37150	7.411	709
K_{rid}	*Age4<=1*	0.12434	0.572	28
K_{rpd}	*Age4<=1*	0.04491	0.131	28
K_{rsw}	*Age4<=1*	1.18374	1.557	28
K_{rst}	*Age4>1*	0.60274	6.791	1268
K_{rpd}	*Age4>1*	0.29016	5.199	1268
K_{rsw}	*Age4>1*	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}	*WW*	0.04338	6499.995	257
	EW	3.29640	77.269	118
K_{cpt}		0.62233	6.206	353
K_{rid}	*Age4<=1*	--	--	0
K_{rpd}	*Age4<=1*	--	--	0
K_{rsw}	*Age4<=1*	--	--	0
K_{rst}	*Age4>1*	0.22147	4.756	352
K_{rpd}	*Age4>1*	0.00000	0.000	352
K_{rsw}	*Age4>1*	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 ≤ ESAL/Elane/year ≤ 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

Climate	
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 ºC
Average Temperature range	9.97 ºC
Days T>32 ºC	1.55 days
Freeze Index	99.44 ºC-days
Percentage of Time Driven	
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

Asphalt Concrete-Surfaced Flexible Pavements
-Base Alternative (Do Nothing)
-Pothole Patching
-45-mm Overlay
Bituminous Treatment-Surfaced Flexible Pavements
-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 (%)**
ACP		
Car	87.11	1.66
Single Unit	6.11	1.66
Double Unit	5.37	1.66
Train	1.41	1.66
BST		
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 ≥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 ≥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

Calibration Factor	Deterioration model
Kjp_c	Cracking calibration factor
$Kjpn_f$	Faulting calibration factor in pavements without dowels
$Kjpd_f$	Faulting calibration factor in pavements with dowels
Kjp_s	Joint spalling calibration factor
Kjp_r	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:

Predicted Distress**:** $Y' = K_y' * f\,(Y_a, a_0, a_1, a_2, \ldots, a_n, X_1, X_2, \ldots, X_m)$ (3.55)

where:

K_y': default calibration factor of distress type Y given by HDM-4 (1.0);

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

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, 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 Ky.

$$Y = K_y * Y' \tag{3.56}$$

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 (Ec): 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

$CRACKING_t = Kjp_c$ * Function (Slab thickness, Joint spacing, Concrete flexural strength, Climate)

where:

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

Kjp_c: Calibration factor of cracking (default value 1.0).

3.4.3.2: Faulting

$FAULT_t = Kjpn_f$ * Function (Drainage condition, Base type, Shoulder/lane width, Joint spacing, Slab thickness)

where:

$FAULT_t$: Average faulting at time t;

$Kjpn_f$: Calibration factor of faulting (default value 1.0).

3.4.3.3: Spalling

$SPALL_t = Kjr_s$ * Function (Age, Seal type, Material characteristics, Joint spacing)

where:

$SPALL_t$: Spalling at time t (%);

Age: Age since pavement construction (years);

Kjr_s: Calibration factor of spalling (default value 1.0).

3.4.3.4: Roughness

$ROUGHNESS_t$ = Kjp_r * Function ($ROUGHNESS_0$, Fault, Spall, Crack, Joint Spacing)

where:

$ROUGHNESS_t$: Roughness at time t;

$ROUGHNESS_0$: Roughness at the timne of pavement construction;

Kjp_r: 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

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

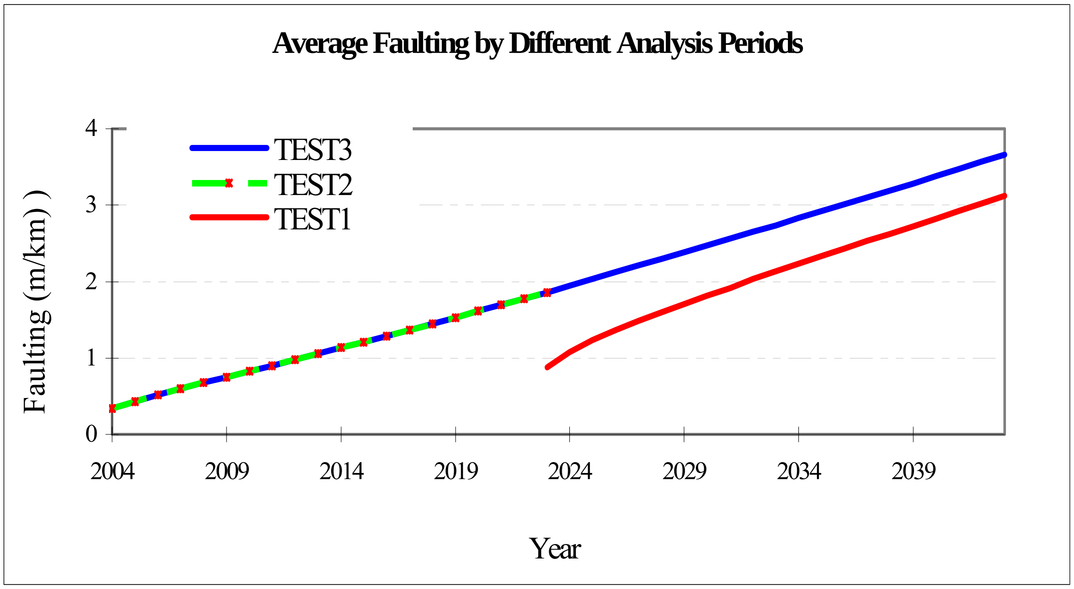

Figure 10: Faulting forecasting by different analysis periods

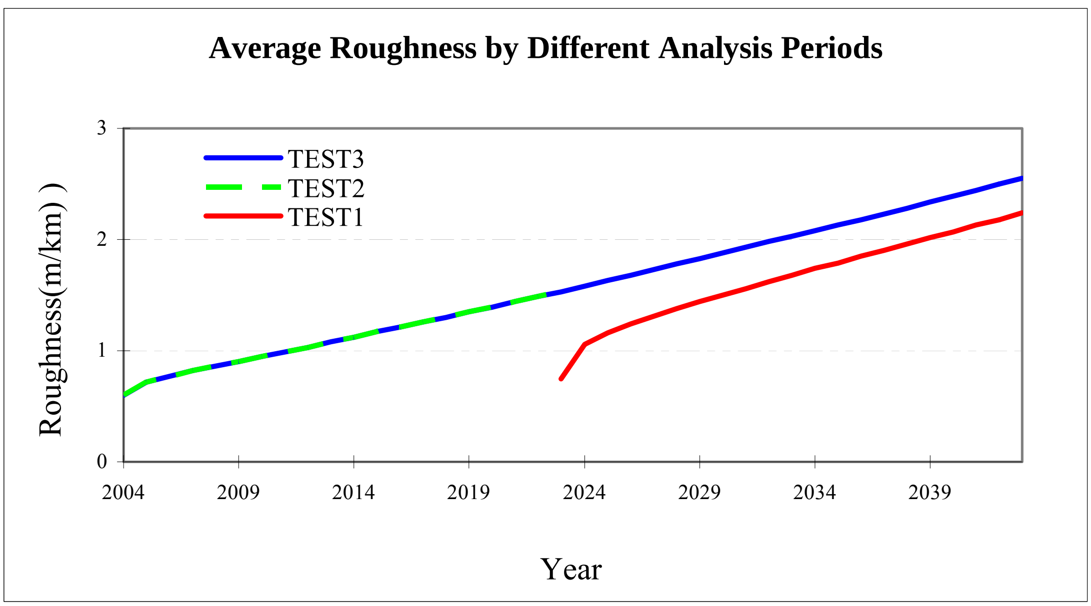

Figure 11: IRI forecasting by different analysis periods

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.

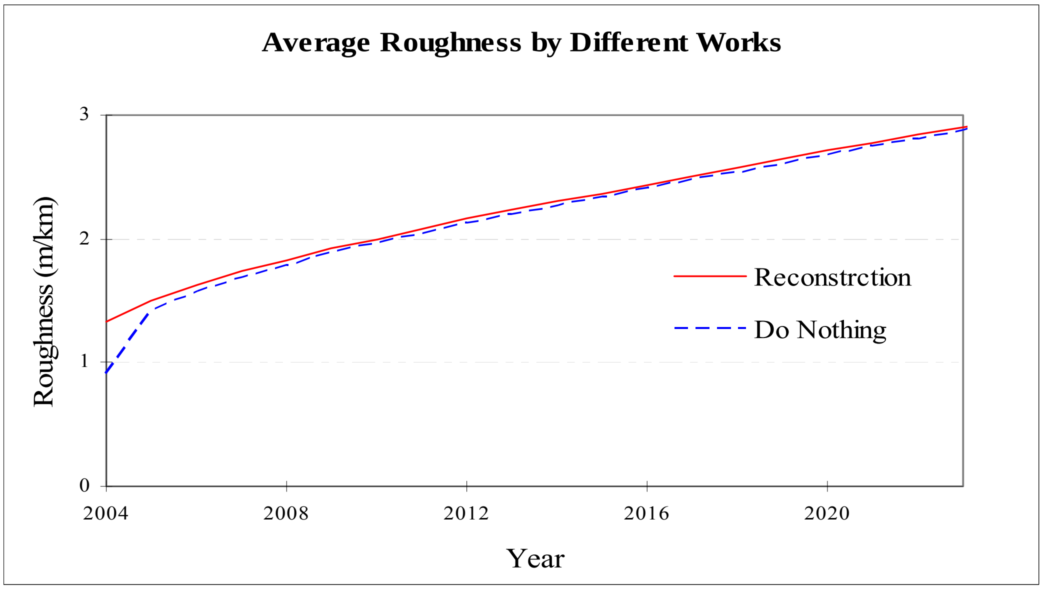

Figure 12: Roughness under two alternatives for concrete pavements

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.

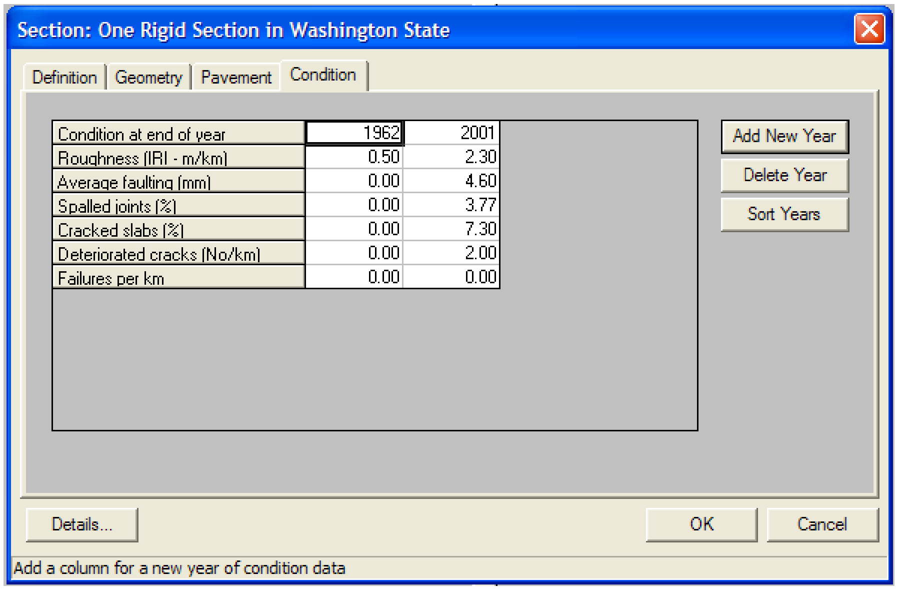

Figure 13: HDM-4 distress data input interface

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.

4: OUTPUT ANALYSIS

As stated in Chapter 1, HDM-4 output analyses include three levels: 1) project level, 2) program level, and 3) strategic level.

4.1: PROJECT LEVEL ANALYSIS

A "Project" is defined as several road works, or more than one road section, grouped together in one contract. Project title, road network, or vehicle fleet information can create a project. Work standards, general traffic composition and growth rate, extra benefits, and costs must be specified to start a project analysis. Project analysis predicts pavement conditions and costs during a user-specified time period. The costs include capital investment, road maintenance works, and vehicle operation costs. Accident costs and emission costs may also be included (Kerali, 2000). All road agency costs in this research are financial, which exclude the costs of overhead, taxes, project engineering, and safety from the total road work economic costs.

4.1.1: Analysis Methods

Options for analyzing investment are provided by section or project. In analysis by section, economic indicators (such as NPV and IRR) are calculated individually for each section alternative; analysis by project will group alternatives to perform an economic analysis, and a base alternative is compared for each project alternative to give annual total economic indicators.

4.1.2: Reports Generated

The goal of project level analysis is to identify the most cost-effective solutions by comparing several project alternatives. HDM-4 project level analysis can generate the following types of reports:

- traffic condition forecasting, which includes AADT, traffic volume, and volume/capacity ratio
- road deterioration condition prediction, which includes roughness, pavement distress conditions, and roadwork lists
- road-user cost estimation, which includes an accident-rate summary, cargo holding hours, crew hours, fuel consumption, labor hours, lubricant hours, overhead costs, parts consumption, vehicle speed
- environmental effects
- comparison of the project alternatives
- input data, which can be used for checking and review.

4.1.3: Analysis Results

All ACP sections on I-405 and all BST sections on SR 21 are used as examples of project level analyses. Pavement preservation alternatives used for ACPs are: 1) base alternative (do nothing), 2) pothole patching, 3) 45-mm overlay, and 4) 45-mm mill and fill. The alternatives for BSTs are: 1) base alternative (do nothing), and 2) bituminous surface treatment. Functions are performed as described in the following groups.

4.1.3.1: Pavement Distress Forecasting

In a defined analysis period, distress conditions analyzed at the project level under different maintenance alternatives are generated.

(a) AC-Surfaced Flexible Pavements

As an example, Figure 14 shows the roughness changes during a 40-year analysis period of section I-405 MP 13.82 – 15.17 (D), which was constructed in 1957 and overlaid in 1994. Other related information about this 1.35-mile-long section is listed in Tables 36 and 37.

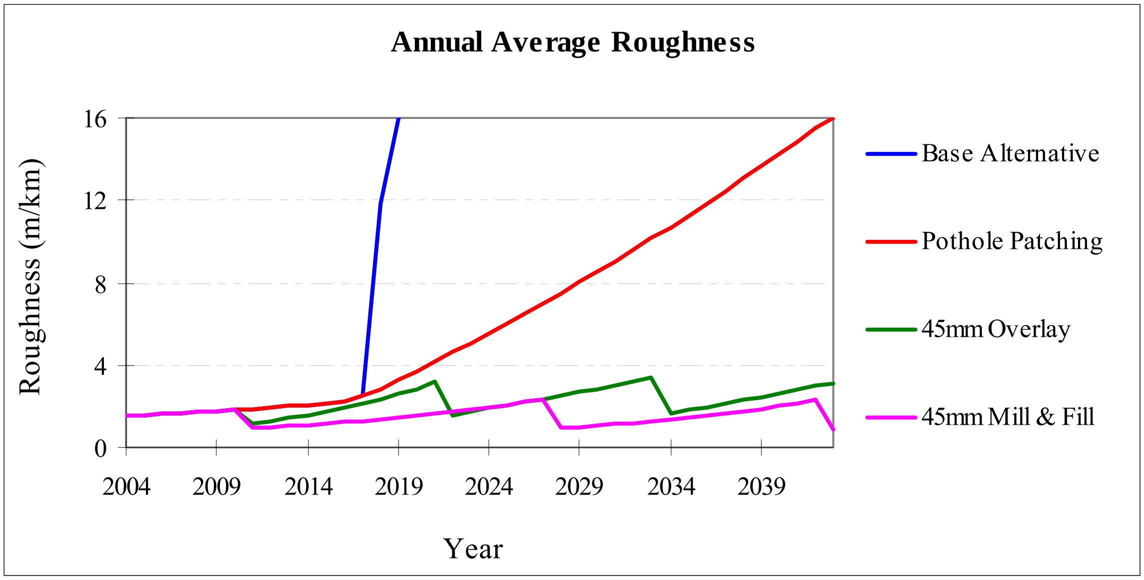

Figure 14: Roughness of I-405 MP 13.82 – 15.17 (D) under four alternatives

The figure illustrates the following conclusions for this specific section:

- Without any maintenance to the road (the base alternative), the roughness will increase to 16 m/km (the maximum allowed by HDM-4) in year 2018, which is 24 years from the last overlay.
- By only patching potholes, the roughness will increase to 4 m/km in year 2021 and 10 m/km in year 2041.
- 45-mm mill and fill has the best works effects on roughness, and it lasts longer than 45-mm overlays.

Table 36: Current conditions of I-405 MP 13.82 – 15.17 (D)

Current Surface Thickness	46 mm
Base Thickness	152 mm
IRI	1.54 m/km
ACRA	0.04%
Pothole	0
Rut Depth	5 mm
Skid resistance	1
MT AADT	97,813
Number of Lanes	3

[Source: WSPMS 2003]

With an annual traffic growth rate of 1.48 %, traffic compositions are as follows:

Table 37: Vehicle composition of I-405 MP 13.82 – 15.17 (D)

Vehicle	Composition (%)
Car	92.7
Single Unit	3.4
Double Unit	3.5
Train	0.4

[Source: WSPMS 2003]

A project level analysis "by project" considers all I-405 flexible sections as one project. Figure 15 shows the result of average roughness (weighted by each section length) for 40 years.

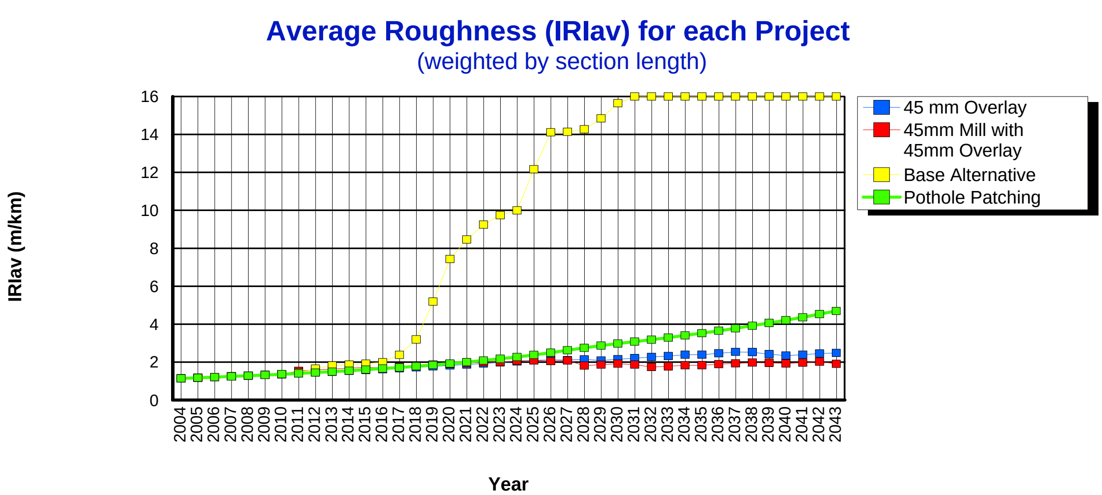

Figure 15: Average roughness of all I-405 flexible pavements (from HDM-4 screen)

(b) BST-Surfaced Flexible Pavements

A BST section, SR 21 MP 130.4 – 153.0 (I), was analyzed in HDM-4 during a 40-year analysis period. This section was constructed in 1955 and resurfaced in 1975, 1984, 1992, and 1999, and other related data are listed in Tables 38 and 39. According to theses input information, HDM-4 estimated the pavement conditions, such as roughness, raveling, cracking, rut depth, and number of potholes. Figure 16 shows the cracking (percentage of total carriageway area).

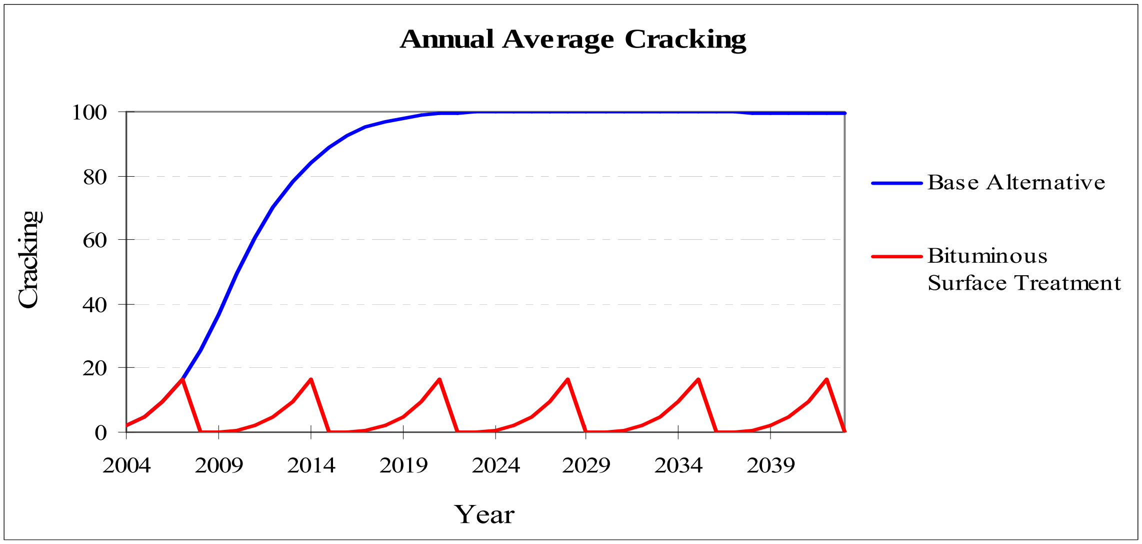

Figure 16: Cracking of SR 21 MP 130.4 – 153.0 (I) for 40 years

Note that the "base alternative" is "do nothing," and "bituminous surface treatment" is defined in Chapter 2.

Table 38: Pavement conditions of SR 21 MP 130.4 – 153.0 (I)

Current Surface Thickness	15 mm
Previous Surface Thickness	85 mm
IRI	2.42 m/km
ACRA	0.82%
Raveling	0.62%
Pothole	0 NPT
Rut Depth	4 mm
Skid resistance	1
MT AADT	537
Number of Lanes	2 (Both direction)

[Source: WSPMS 2003]

Table 39: Traffic composition and growth rates of SR 21 MP 130.4 – 153.0 (I)

Vehicle Type	**Traffic Composition(%)**	**Annual Growthrate(%)**
Car	75.17	3.86
Single Unit	2.45	3.86
Double Unit	13.29	3.86
Train	9.09	3.86

[Source: WSPMS 2003]

4.1.3.2: Road Agency Costs of Maintenance

(1) By Section

By choosing the “By Section” option for project analysis, HDM-4 can illustrate the direct maintenance costs and work schedule for each section and for each specific road maintenance alternative.

Tables 40, 41, and 42 show schedules for the optimal works for I-405 MP 13.82 – 15.17 (D), with economic indicators spanning 40 years. The distress types following the maintenance alternatives in tables 40 and 41 point out the types that trigger road works. Costs are road agency costs without consideration for discount rates.

During this 40-year analysis period, maintenance of 45-mm overlay and 45-mm mill & fill are triggered three times, but the latter serves one to three years longer than the former in each case.

Table 40: Costs and schedule of 45-mm overlay for I-405 MP 13.82 – 15.17 (D)

Year	Description	Road Agency Cost ($)	Work Quantity (m^2)
2010	45mm Overlay - Cracking	452,293	23,805
2021	45 mm Overlay - Rutting	452,293	23,805
2032	45 mm Overlay - Rutting	452,293	23,805
Total cost for the section:		1,356,879	

Table 41: Costs and schedule of 45-mm mill and fill for I-405 MP 13.82 – 15.17 (D)

Year	Description	Road Agency Cost ($)	Work Quantity (m^2)
2010	45mm Mill & Fill - Cracking	714,147	23,805
2027	45mm Mill & Fill - Rutting	714,147	23,805
2040	45mm Mill & Fill - Rutting	714,147	23,805
Total cost for the section:		2,142,441	

Table 42: Costs and schedule of pothole patching for I-405 MP 13.82 – 15.17 (D)

Year	Description	Road Agency Cost ($)	Work Quantity (m^2)
2015	Pothole Patching	236	5.0
2016	Pothole Patching	306	6.5
2017	Pothole Patching	385	8.2
2018	Pothole Patching	469	10.0
2019	Pothole Patching	550	11.7
2020	Pothole Patching	625	13.3
2021	Pothole Patching	693	14.7
2022	Pothole Patching	753	16.0
2023	Pothole Patching	805	17.1
2024	Pothole Patching	849	18.1
2025	Pothole Patching	887	18.9
2026	Pothole Patching	919	19.6
2027	Pothole Patching	945	20.1
2028	Pothole Patching	966	20.6
2029	Pothole Patching	983	20.9
2030	Pothole Patching	997	21.2
2031	Pothole Patching	1,007	21.4
2032	Pothole Patching	1,015	21.6
2033	Pothole Patching	1,021	21.7
2034	Pothole Patching	1,026	21.8
2035	Pothole Patching	1,029	21.9
2036	Pothole Patching	1,031	21.9
2037	Pothole Patching	1,032	22.0
2038	Pothole Patching	1,033	22.0
2039	Pothole Patching	1,034	22.0
2040	Pothole Patching	1,034	22.0
2041	Pothole Patching	1,035	22.0
2042	Pothole Patching	1,035	22.0
2043	Pothole Patching	1,035	22.0
Total cost for the section:		24,733	

(2) By Project

If using the "By Project" option, HDM-4 will treat all given sections as one project and calculate annual road agency costs for each alternative. Under each alternative, work schedules are optimized to gain the greatest economic advantage. Table 43 lists all related costs for all I-405 flexible pavements over a period of 40 years.

Table 43: Summary of total annual costs for all I-405 flexible sections

Year	Road Agency Cost ($)		
	45mm Mill & Fill	45mm Overlay	Pothole Patching
2006	513,396	325,151	0
2008	2,043,711	1,294,350	0
2009	566,052	358,500	0
2010	9,350,097	5,921,728	512
2011	4,067,676	2,576,195	714
2012	0	0	907
2013	542,412	343,528	1,172
2014	0	0	1,503
2015	573,156	362,999	2,962
2016	0	0	4,198
2017	0	0	5,023
2018	0	0	7,436
2019	0	0	8,966
2020	2,043,711	1,294,350	10,314
2021	1,007,046	637,796	11,624
2022	513,396	325,151	12,798
2023	5,072,928	3,212,854	14,241
2024	955,260	604,998	15,258
2025	3,775,371	2,391,068	16,162
2026	1,873,188	1,186,352	16,966
2027	0	0	17,649
2028	1,300,032	823,354	18,223
2029	542,412	343,528	18,694
2030	0	0	19,074
2031	0	0	19,379
2032	3,623,913	2,295,145	19,621
2033	0	0	19,811
2034	4,067,676	2,576,195	19,957
2035	0	0	20,067
2036	566,052	358,500	20,147
2037	1,468,656	930,149	20,204
2038	439,200	278,160	20,243
2039	1,785,795	1,131,004	20,270
2040	1,989,576	1,260,065	20,288
2041	0	0	20,300
2042	1,873,188	1,186,352	20,307
2043	2,563,689	1,623,670	20,313
Total	**53,117,589**	**33,641,140**	**465,300**

4.1.3.3: Optimum Maintenance Standards

(1) By Section

A project analysis "by section" estimates works effects and economic indicators for each section. The most effective alternative is the one with the highest indicators. An example using section I-405 MP 13.82 - 15.17 (D) is illustrated in Table 44.

The Economic Indicators Summary Report gives a summary of costs, discounted Net Present Value (NPV), and Internal Rate of Return (IRR) by project alternatives. The discount rate is 4 percent.

Table 44: Economic indicators for I-405 MP 13.85 – 15.17 (D)

Alternative	Increase in Agency Cost	Decrease in User Cost	Net Present Value (NPV)	Internal Rate of Return (IRR)
Base Alternative	0.00	0.00	0.00	0.00
Pothole Patching	0.01	206.77	206.76	No Solution
45mm Overlay	0.67	249.13	**248.46**	**93.2**
45mm Mill & Fill	1.06	249.13	248.07	82.3

(All costs are in millions of dollars.)

For this case, the of 45-mm overlay alternative has the highest NPV and IRR. Therefore, it is the best alternative for this section in 40 years.

(2) By Project

By comparing the economic indicators of each alternative with a base alternative, the most cost-effective alternative for the whole project is determined.

Table 45 illustrates the costs and economic indicators in 40 years for all I-405 flexible sections with a discount rate of 4 percent. The base alternative is "Do Nothing." Since 45-mm overlay has the highest NPV and IRR, it is the optimal maintenance alternative for all I-405 flexible sections.

Table 45: Total economic benefits for all I-405 flexible sections

Alternative	Increase in Agency Cost	Decrease in User Cost	Net Present Value (NPV)	Internal Rate of Return (IRR)
Pothole Patching	0.17	4,773.23	4,773.07	--
45mm Overlay	17.00	5169.676	**5,152.68**	**96.7**
45mm Mill & Fill	26.84	5169.676	5,142.84	80.1

(All costs are in millions of dollars.)

4.2: PROGRAM LEVEL ANALYSIS

The program level analysis selects a combination of treatments for sections by optimizing an objective function under budget constraints. It generates the same type of reports as project level analysis, such as traffic reports, pavement distress conditions, works effects, road-user effects, and costs. Furthermore, it compares outputs by different categories under constrained budgets or optimized conditions. The reports generated in program level analysis are (Kerali, 2000a):

- optimum section alternatives for varying levels of budgets
- a pavement surface condition summary by link ID (state route number) or road class (interstate, major collector, minor arterial, or principal arterial)
- average roughness (weighted by section length) by link ID, pavement surface, or road class
- average speed by link ID, pavement surface, or road class
- volume/capacity ratio by link ID, pavement surface, or road class
- work programs optimized or unconstrained by section or by year.

To demonstrate the functions, all I-5 flexible pavements, 141 sections and 872.73 lane miles were analyzed in program level. Table 46 lists the traffic composition and growth rates.

Table 46: Traffic composition and growth rates of I-5

Vehicle Type	**Traffic Composition(%)**	**Annual Growthrate(%)**
Car	90.1	1.48
Single Unit	3.6	1.48
Double Unit	5.9	1.48
Train	0.4	1.48

4.2.1: Multi-Year Forward Program

The multi-year Forward Program method requires one preservation treatment or one treatment after the previous treatment that has been assigned to each road section. The treatments are triggered based on reaching a distress threshold.

4.2.1.1: Maintenance Triggered and Related Costs

Details of the works activity and condition responsive criteria are summarized in Table 47. In this case, a 45-mm overlay is assigned to each I-5 flexible section during an analysis period of five years. No discount rate is applied to the road agency costs.

Thus, in five years, 17 sections out of 141 sections need to be maintained to obtain the optimal road condition, which means that each time a 45-mm overlay is triggered, the section will be overlaid. The total agency financial cost is $8.57 million.

Table 47: Optimized work program for all I-5 flexible sections for five years

Year	Section		Length (km)	AADT	Work Description	Financial Cost	Cumulative Cost
2004	005	MP182.67 - 183.96 (D)	2.08	90906	45 mm Overlay Rutting	0.43	0.43
	005	MP181.51 - 182.67 (D)	1.87	87669	45mm Overlay Cracking	0.39	0.82
	005	MP182.86 - 183.96 (I)	1.77	92292	45 mm Overlay Rutting	0.37	1.19
	005	MP188.70 - 189.30 (I)	0.97	73985	45 mm Overlay Rutting	0.20	1.39
2005	005	MP6.07 - 7.00 (D)	1.50	34656	45 mm Overlay Rutting	0.21	1.60
	005	MP19.83 - 20.08 (D)	0.40	32089	45 mm Overlay Rutting	0.11	1.71
2006	005	MP198.19 - 198.51 (D)	0.51	60772	45 mm Overlay Rutting	0.11	1.82
	005	MP228.25 - 229.33 (D)	1.74	38504	45mm Overlay Cracking	0.24	2.06
2007	005	MP190.21 - 191.60 (I)	2.24	93678	45 mm Overlay Rutting	0.62	2.69
	005	MP181.51 - 182.86 (I)	2.17	90916	45 mm Overlay Rutting	0.45	3.14
	005	MP183.96 - 189.30 (D)	8.59	89293	45mm Overlay Cracking	1.79	4.93
	005	MP135.52 - 139.50 (D)	6.41	88521	45 mm Overlay Rutting	1.78	6.71
2008	005	MP190.12 - 191.60 (D)	2.38	94930	45 mm Overlay Rutting	0.66	7.37
	005	MP276.20 - 276.56 (I)	0.58	8860	45mm Overlay IRI	0.08	7.45
	005	MP180.10 - 180.75 (D)	1.05	94931	45 mm Overlay Rutting	0.22	7.67
	005	MP195.11 - 197.18 (D)	3.33	62584	45 mm Overlay Rutting	0.69	8.36
	005	MP8.10 - 8.70 (I)	0.97	48638	45 mm Overlay Rutting	0.20	8.57

(All costs are in millions of dollars)

4.2.1.2: Average Roughness Distress by Road Class

The annual average roughness, weighted by length for road classes (interstate and non-interstate), of the optimized work program is shown in Figure 17.

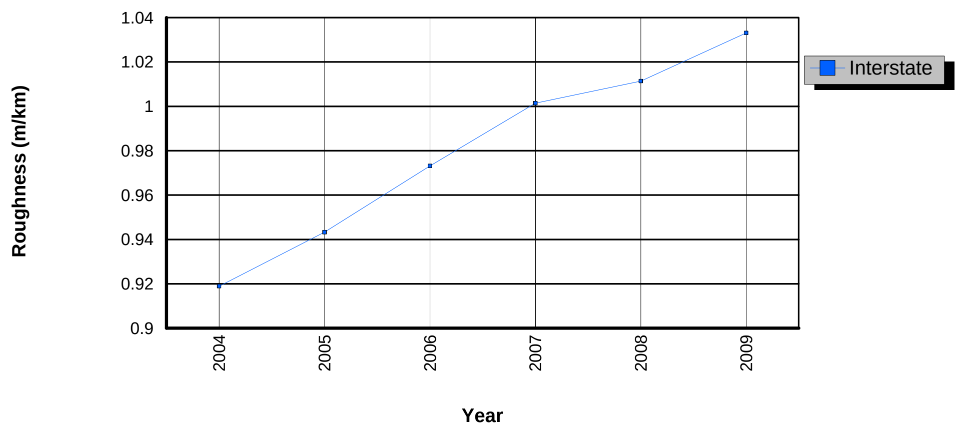

Figure 17: Average roughness of all I-5 flexible pavements for five years (from HDM-4 screen)

4.2.1.3: Volume/Capacity Ratio by Pavement Surface

The annual average volume capacity ratio weighted by length under the optimized work program is shown in Figure 18.

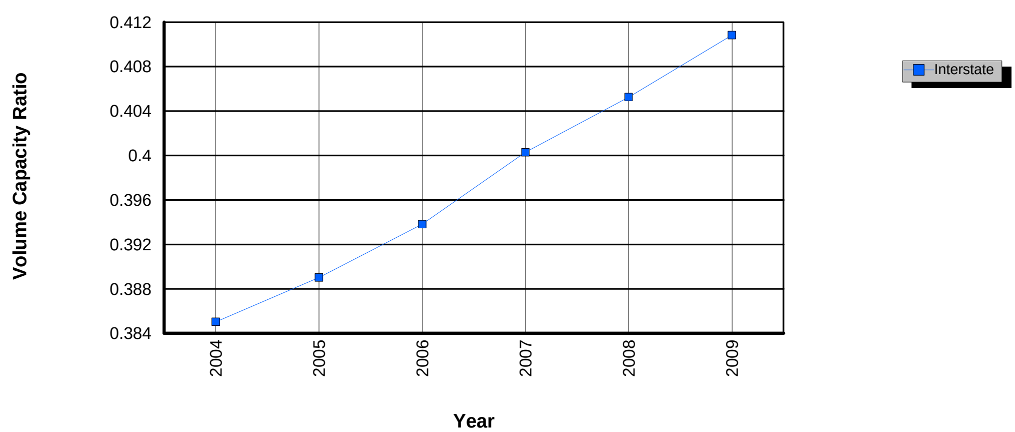

Figure 18: Average volume capacity ratio of all I-5 flexible pavements for five years (HDM-4 screen)

4.2.2: Life-Cycle Analysis

Different than the multi-year program analysis, the life-cycle analysis requires at least two standards for each section to compare the defined works alternatives with the base alternative during the specific analysis period. It selects optimal alternatives for each section that maximize the economic benefits for the whole network while constraining the financial costs to less than the available budget.

4.3: STRATEGIC LEVEL ANALYSIS

For medium to long-term planning, the strategic level analysis groups all road segments with similar characteristics into the road network matrix. As with the program level analysis, it provides a combination of works alternatives, which optimizes objective functions under constrained budgets. The objective functions can be

- maximizing Net Present Value (NPV) for the best benefits
- maximizing the improvement of roughness to obtain the best road condition
- minimizing cost for target roughness.

As explained in Chapter 3, Section 3.3.1, improvement of IRI signifies an improvement in road conditions. Whenever a roadway drops beneath the target roughness, maintenance is triggered. Thus, road distress will never be worse than the targeted level of roughness. The system will select the maintenance scenario that provides the most cost-beneficial schedule for WSDOT highways. This strategic level analysis can benefit WSDOT by:

- determining the required budget levels for specified preservation treatments
- demonstrating the effects of varying budget level on the long-term road performance.
- optimizing the allocation of funds
- presenting economic indicators for varying budget levels (Odoki, 2000).

4.3.1: Road Network Data

Strategic level analysis adopts all 24 typical WSDOT flexible sections prepared in Chapter 3, Section 3.3.7. Appendix D1 describes the definitions of the 18 ACP and 6 BST sections.

These sections represent all WSDOT flexible pavements, so most of the sections are very long. A large amount of funding is needed when any one of these long sections needs repairing. When that time comes, if the given budget is less than required, the sections will not be maintained at that time. The budget cannot be applied to subsequent budget periods. In other words, a budget defined in a specific budget period can only be used during that specific time period; only sections requiring less than the given budget, and with higher economic returns, can be repaired. To entirely spend the allocated budget, the long sections must be divided into shorter sections (keep in mind that all of this is due to HDM-4 software constraints, but this needs to be stated). But how short should they be? If the sections were as small as the project level, there would be 2481 ACP sections and 412 BST sections. Can the strategic analysis handle so many sections?

Although HDM-4 dose not specify any limitations in the number of sections, experiments ascertained that 49 is the maximum number of sections that can be handled by the strategic level analysis. Therefore, the 18 ACPs were divided into 49 sections, and the 6 BSTs were divided into 20 sections. In this configuration, each section is shorter than 300 km. The related road network inputs are listed in appendices D2 and D3 for ACPs and BSTs, respectively.

Because of the limited number of input sections permitted by the system, the strategic level road network cannot simulate the WSDOT highway system as effectively as project level analyses can. For long-term forecasting, the results are reliable, but they can be considered solely as a reference for an analysis detailed in a specific year.

4.3.2: Optimized Road Maintenance and Development Plans

The economic analysis produces a work program that offers alternatives with the minimum costs for a target road distress condition. A target road condition defines the conditions under which the road will be maintained. The road works assigned to each section represents the optimal maintenance standards for each specific section.

The road agency costs in this report exclude overhead, taxes, project engineering, and safety. All costs and funds in this report are financial. For all ACPs, HDM-4 estimates an optimal work program with the total financial cost of $4,224.1 million for 40 years; for all BSTs, the financial cost is $339.9 million. The relative annual costs are $105.6 million and $8.5 million, which represent constant annual purchasing power without considering the discount rate.

4.3.3: WSDOT Funds

WSDOT obtains the pavement maintenance funds every two years. The historical budgets are listed in Table 48.

Table 48: WSDOT historical funds for pavement maintenance

Biennium	**Total Economic Funding per Biennium (and per Year)**	**Financial Funding (Biennium)**		
		AC	**BST**	**PCCP**
1995-1997	$258.3 ($129.2/ year)	$198.5	$13.1	$42.4
1997-1999	$319.1 ($159.6/ year)	$204.9	$16.6	$32.9
1999-2001	$275.6 ($137.8/ year)	$189.0	$20.6	$3.7
2001-2003	$267.4 ($133.7/ year)	$174.1	$13.8	$14.5

(All costs are in millions of dollars) (Refer to Chapter 2, sections 2.4 and 2.5)

The WSDOT FY 2001-2003 preservation funding (again, HDM-4 refers to this with the generic term of "maintenance") is $174.1millon for ACPs and $13.8 million for BSTs. They were used to simulate the current WSDOT's budget scenario for 40 years: $3,482 million for ACPs and $276 million for BSTs, which represent the same constant biennium purchasing power without considering the discount rate.

4.3.4: Road Performance under Varying Levels of Budgets

HDM-4 strategic analysis can calculate minimum costs for a target IRI (smaller than 3.5 m/km) with optimal maintenance. Under varying levels of budgets, it provides an optimal work program.

HDM-4 shows that the minimum cost for target IRI (MCTI) of all ACPs is $4,224 million for 40 years without considering the discount rate. In the following simulation, five budget levels starting in 2004 for 40 years are assumed:

- MCTI ($4224 million)
- WSDOT ($3482 million)
- 75% of MCTI ($3168 million)
- 50% of MCTI ($2112 million)
- 0 (no budget)

For all BSTs, the MCTI is $339.9 million for 40 years without considering the discount rate. Five budget levels starting in 2004 for 40 years are assumed:

- MCTI ($340 M)
- WSDOT($276M)
- 75% of MCTI ($255M)
- 50% of MCTI ($170M)

- 0 (no budget)

Figures 19 and 20 illustrate roughness (weighted by length) performance for all ACPs and BSTs, respectively.

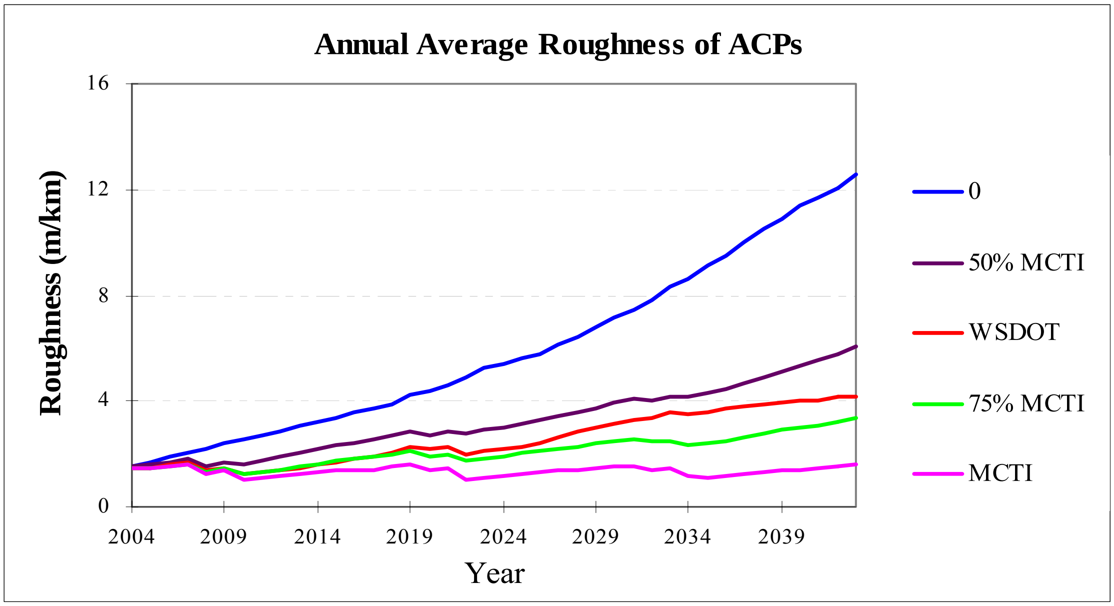

Figure 19: Roughness of all ACPs under varying budgets

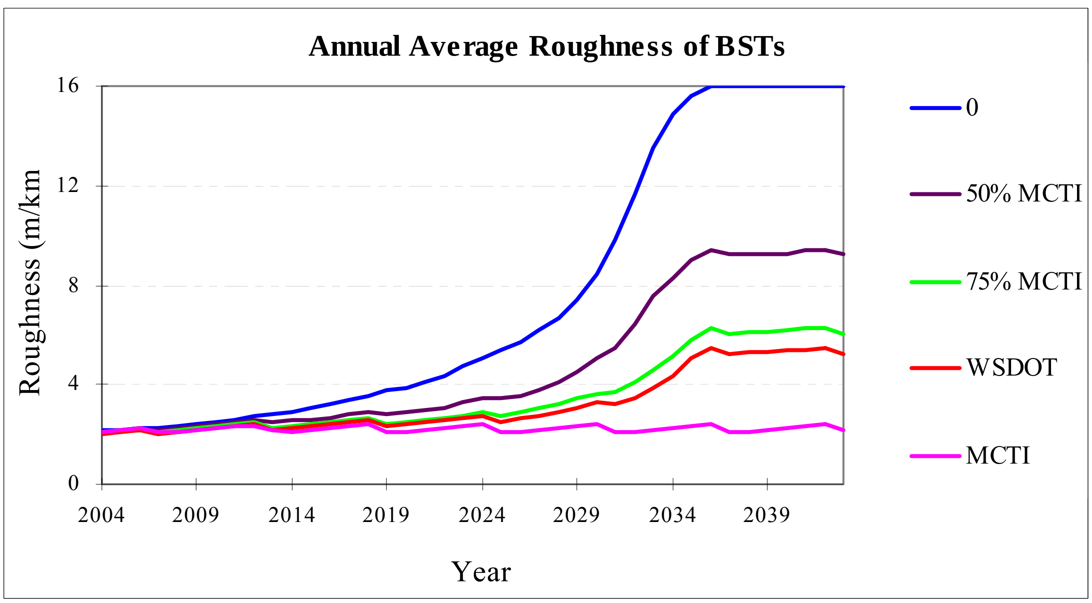

Figure 20: Roughness of all BSTs under varying budgets

Figures 21 and 22 show surface damage conditions. The condition is presented by the total surface damage area (percentage of total carriageway area), which is composed of edge-breaks, potholes, cracking, and raveling areas.

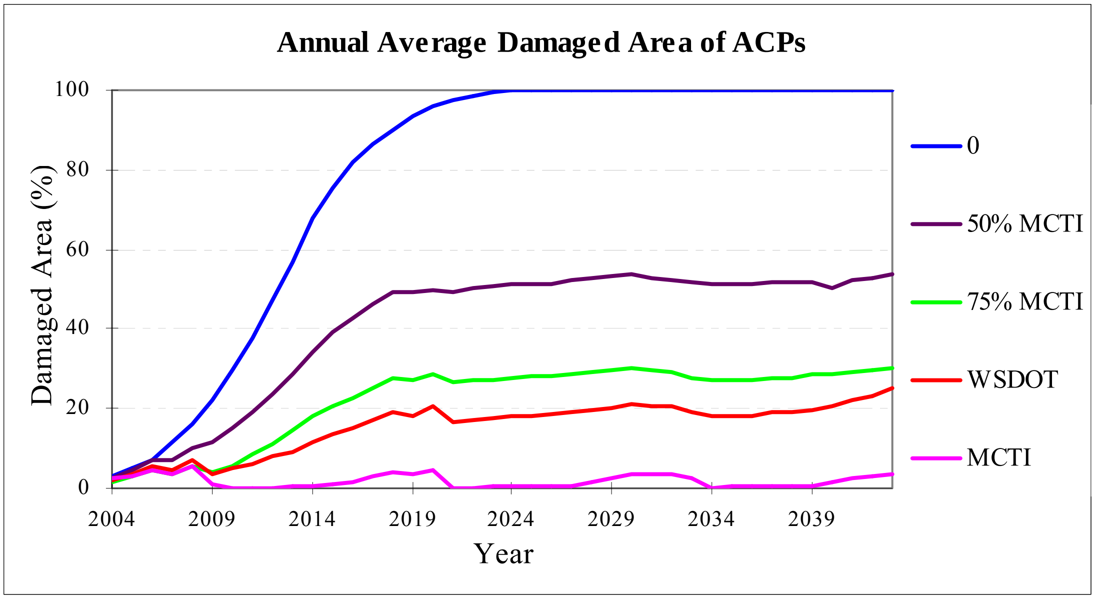

Figure 21: Surface damage of all ACPs under varying budgets

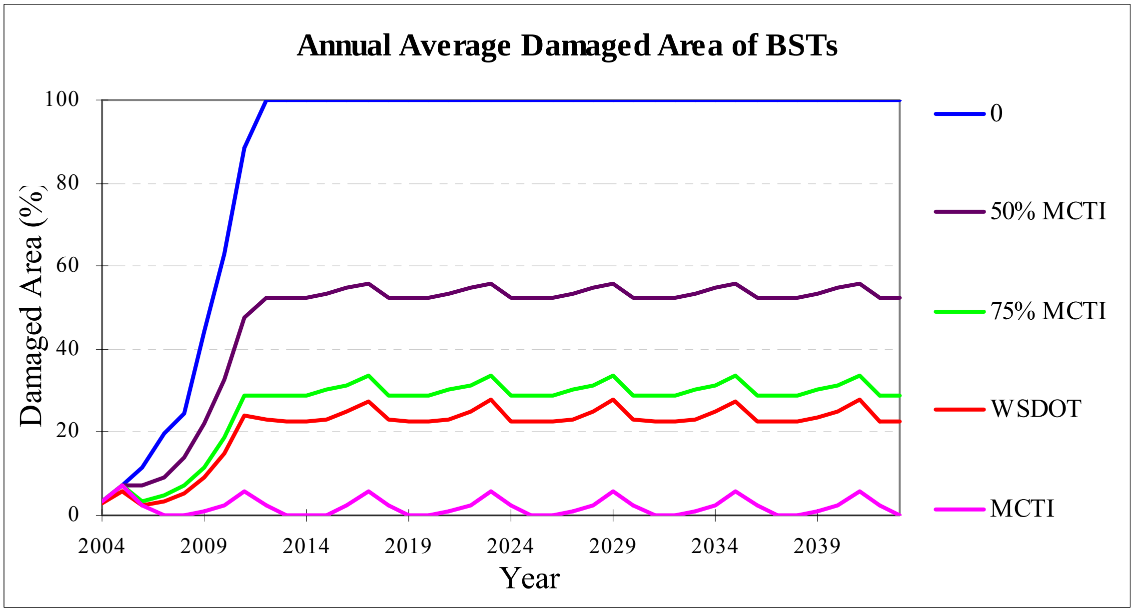

Figure 22: Surface damage of all BSTs under varying budgets

The five budget levels for ACPs can be expressed by the constant annual purchasing power for 40 years beginning in 2004, without considering the discount rate. The amounts are as follows:

- MCTI ($105.6 million)
- WSDOT ($87 million)
- 75% of MCTI ($79.2 million)
- 50% of MCTI ($52.8 million)
- 0 (no budget)

In FY 2004-2005, if $30 million is cut from the current WSDOT budget for ACPs, and the funding will revert back to the current level in subsequent bienniums, what is the impact of this cut? What is the added user cost due to this cut in 40 years? How much will it cost over the next 10 years to bring the network back to the same condition had there been no cut? To answer these questions, all related funding scenarios are listed in the Table 49.

Table 49: WSDOT funding scenarios

Scenario	Description	Budget Distribution		
		2004-2005	2006-2015	2016-2043
A	Cut $30M from the current WSDOT budget for ACPs in FY 2004-2005, then apply the MCTI budget for the remaining 38 years	$144.1 ($72/year)*	$4012.8 ($105.6/year)*	
B	Cut $30M from the current WSDOT budget for ACPs in FY 2004-2005, then back to the current WSDOT budget level for the remaining 38 years	$144.1 ($72/year)*	$870.5 ($87/year)*	$2437.5 ($87/year)*
C	Cut $30M from the current WSDOT budget for ACPs in FY 2004-2005, then bring the network back to the same condition as the scenario D in 10 years	$144.1 ($72 /year)*	$1050 ($105/year)*	$2437.5 ($87/year)*
D	The WSDOT current level of budget for ACPs	$3482 ($87/year)*		

(All costs are in millions of dollars)
(* the constant annual purchasing power in the defined FYs)

Figure 23 illustrates roughness performance curves for all ACPs under the four funding scenarios above. Figure 24 shows surface damage conditions. The differences between the road performance curves of scenarios B and D indicate the effects of the budget cut. The total road user cost of Scenario B in 40 years is $200.2 billion. Comparing that with Scenario D, $37.5 billion is added in 40 years. Moreover, to bring the road condition back in 10 years to the same condition it would have been without the budget cut would cost an additional $ 179.5 million.

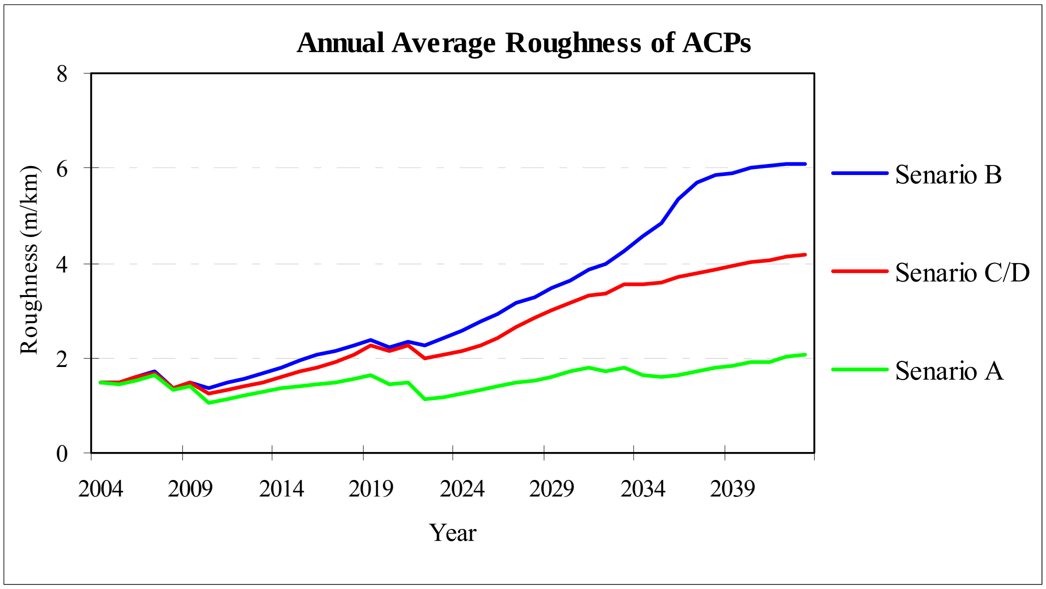

Figure 23: Roughness of all ACPs under WSDOT scenarios

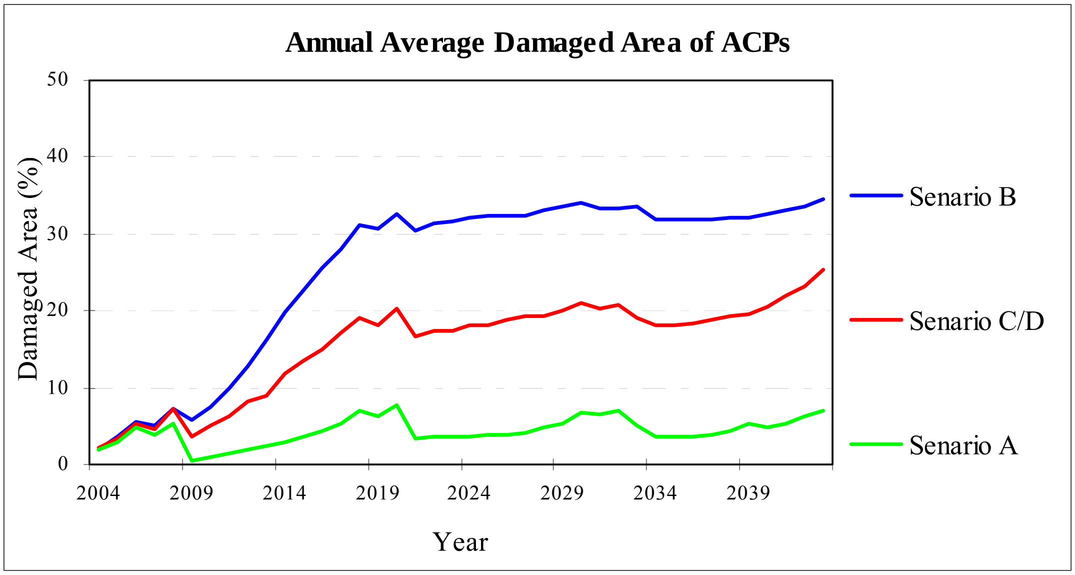

Figure 24: Damaged area of all ACPs under WSDOT scenarios

4.3.5: Economic Indicators Under Varying Levels of Budgets

Reports produced by Optimum Section Alternatives provide an economic analysis using a defined budget level. Table 50 collects costs and maximum benefits using different budget levels. In this table, the discount rate is 4 percent.

Table 50: Economic indicators under varying levels of budgets for all ACPs

Scenario	Annual Budget	Length Repaired (Lane-km)	40-year Agency Cost		Average Roughness (m/km)	NPV
			Undiscounted	Discounted		
50% MCTI	52.8	8,642	2,112	1,193	4.63	146,619
75% MCTI	79.2	13,094	3,168	1,785	2.93	159,682
WSDOT	87	14,294	3,482	1,951	2.55	162,461
MCTI	105.6	17,420	4,224	2,372	1.33	198,052

(All costs are in millions of dollars)

4.3.6: Optimized Allocation of Defined Budgets

An optimal work program is produced for a defined budget. The program has a total cost that falls within the specified budget. Table 51 lists optimal works, time to apply, and road agency costs under the current WSDOT budget for ACPs in 40 years. The actual total cost is $ 3,449 million.

Table 51: Optimized work program under the current WSDOT budget for ACPs

Year	Section	Length (km)	Work Description	Financial Cost	Cumulative Cost
2004	Interstate Flexible Pavement High Traffic Poor Condition	14	45mm Mill & Fill Rutting	3	3
	Other Flexible Pavement Medium Traffic Poor Condition1	164	45 mm Overlay Rutting	25	28
	Other Flexible Pavement High Traffic Poor Condition	23	45mm Mill & Fill Rutting	9	37
	Other Flexible Pavement Low Traffic Poor Condition1	213	45 mm Overlay Rutting	32	70
	Other Flexible Pavement Low Traffic Poor Condition2	200	45 mm Overlay Rutting	30	100
	Interstate Flexible Pavement Low Traffic Poor Condition	3	45mm Mill & Fill Rutting	1	101
2007	Interstate Flexible Pavement High Traffic Fair Condition	119	45mm Overlay Cracking	18	119
	Interstate Flexible Pavement Medium Traffic Fair Condition	205	45mm Overlay Cracking	31	150
	Other Flexible Pavement Medium Traffic Fair Condition1	130	45mm Overlay Cracking	20	170
	Other Flexible Pavement Medium Traffic Fair Condition2	200	45mm Overlay Cracking	30	200
	Other Flexible Pavement Medium Traffic Fair Condition3	200	45mm Overlay Cracking	30	231
	Other Flexible Pavement Medium Traffic Fair Condition4	200	45mm Overlay Cracking	30	261
	Other Flexible Pavement Medium Traffic Fair Condition5	200	45mm Overlay Cracking	30	291
	Other Flexible Pavement Medium Traffic Fair Condition6	200	45mm Overlay Cracking	30	322
	Other Flexible Pavement Medium Traffic Fair Condition7	200	45mm Overlay Cracking	30	352
	Other Flexible Pavement High Traffic Fair Condition	64	45mm Mill & Fill Cracking	25	377
	Other Flexible Pavement Low Traffic Fair Condition1	213	45mm Overlay Cracking	32	409
	Other Flexible Pavement Low Traffic Fair Condition2	200	45mm Overlay Cracking	30	440
	Other Flexible Pavement Low Traffic Fair Condition3	200	45mm Overlay Cracking	30	470
	Other Flexible Pavement Low Traffic Fair Condition4	200	45mm Overlay Cracking	30	501
	Interstate Flexible Pavement Low Traffic Fair Condition	7	45mm Mill & Fill Cracking	2	502
2009	Interstate Flexible Pavement Medium Traffic Good Condition1	180	45mm Overlay Cracking	27	530
	Interstate Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	560
	Interstate Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	591
	Other Flexible Pavement Medium Traffic Good Condition10	200	45mm Overlay Cracking	30	621
	Other Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	651
	Other Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	682
	Other Flexible Pavement Medium Traffic Good Condition4	200	45mm Overlay Cracking	30	712
	Other Flexible Pavement Medium Traffic Good Condition5	200	45mm Overlay Cracking	30	743
	Other Flexible Pavement Medium Traffic Good Condition6	200	45mm Overlay Cracking	30	773
	Other Flexible Pavement Medium Traffic Good Condition7	200	45mm Overlay Cracking	30	803
	Other Flexible Pavement Low Traffic Good Condition10	200	45mm Overlay Cracking	30	834
	Other Flexible Pavement Low Traffic Good Condition11	200	45mm Overlay Cracking	30	864
	Other Flexible Pavement Low Traffic Good Condition2	200	45mm Overlay Cracking	30	895
	Other Flexible Pavement Low Traffic Good Condition3	200	45mm Overlay Cracking	30	925
	Other Flexible Pavement Low Traffic Good Condition4	200	45mm Overlay Cracking	30	955
	Other Flexible Pavement Low Traffic Good Condition5	200	45mm Overlay Cracking	30	986
	Other Flexible Pavement Low Traffic Good Condition6	200	45mm Overlay Cracking	30	1,016
	Other Flexible Pavement Low Traffic Good Condition7	200	45mm Overlay Cracking	30	1,047
	Other Flexible Pavement Low Traffic Good Condition8	200	45mm Overlay Cracking	30	1,077
	Other Flexible Pavement Low Traffic Good Condition9	200	45mm Overlay Cracking	30	1,107
	Interstate Flexible Pavement Low Traffic Good Condition	12	45mm Mill & Fill Cracking	3	1,110
2015	Interstate Flexible Pavement High Traffic Poor Condition	14	45mm Mill & Fill Cracking	3	1,114
	Other Flexible Pavement Medium Traffic Poor Condition1	164	45mm Overlay Cracking	25	1,139
	Other Flexible Pavement High Traffic Poor Condition	23	45mm Mill & Fill Cracking	9	1,147
2016	Other Flexible Pavement Low Traffic Poor Condition1	213	45mm Overlay Cracking	32	1,180
	Other Flexible Pavement Low Traffic Poor Condition2	200	45mm Overlay Cracking	30	1,210

Table 51 (Continued)

Year	Section	Length (km)	Work Description	Financial Cost	Cumulative Cost
2016	Interstate Flexible Pavement Low Traffic Poor Condition	3	45mm Mill & Fill Cracking	1	1,211
2018	Interstate Flexible Pavement High Traffic Fair Condition	119	45mm Overlay Cracking	18	1,229
2019	Interstate Flexible Pavement Medium Traffic Fair Condition	205	45mm Overlay Cracking	31	1,260
	Other Flexible Pavement Medium Traffic Fair Condition1	130	45mm Overlay Cracking	20	1,280
	Other Flexible Pavement Medium Traffic Fair Condition2	200	45mm Overlay Cracking	30	1,310
	Other Flexible Pavement Medium Traffic Fair Condition3	200	45mm Overlay Cracking	30	1,341
	Other Flexible Pavement Medium Traffic Fair Condition4	200	45mm Overlay Cracking	30	1,371
	Other Flexible Pavement Medium Traffic Fair Condition5	200	45mm Overlay Cracking	30	1,402
	Other Flexible Pavement Medium Traffic Fair Condition6	200	45mm Overlay Cracking	30	1,432
	Other Flexible Pavement Medium Traffic Fair Condition7	200	45mm Overlay Cracking	30	1,462
	Other Flexible Pavement High Traffic Fair Condition	64	45mm Mill & Fill Cracking	25	1,487
	Other Flexible Pavement Low Traffic Fair Condition1	213	45mm Overlay Cracking	32	1,520
	Other Flexible Pavement Low Traffic Fair Condition2	200	45mm Overlay Cracking	30	1,550
	Other Flexible Pavement Low Traffic Fair Condition3	200	45mm Overlay Cracking	30	1,581
	Other Flexible Pavement Low Traffic Fair Condition4	200	45mm Overlay Cracking	30	1,611
2020	Interstate Flexible Pavement Low Traffic Fair Condition	7	45mm Mill & Fill Cracking	2	1,613
2021	Interstate Flexible Pavement Medium Traffic Good Condition1	180	45mm Overlay Cracking	27	1,640
	Interstate Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	1,670
	Interstate Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	1,701
	Other Flexible Pavement Medium Traffic Good Condition10	200	45mm Overlay Cracking	30	1,731
	Other Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	1,762
	Other Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	1,792
	Other Flexible Pavement Medium Traffic Good Condition4	200	45mm Overlay Cracking	30	1,822
	Other Flexible Pavement Medium Traffic Good Condition5	200	45mm Overlay Cracking	30	1,853
	Other Flexible Pavement Medium Traffic Good Condition6	200	45mm Overlay Cracking	30	1,883
	Other Flexible Pavement Medium Traffic Good Condition7	200	45mm Overlay Cracking	30	1,914
	Other Flexible Pavement Low Traffic Good Condition10	200	45mm Overlay Cracking	30	1,944
	Other Flexible Pavement Low Traffic Good Condition11	200	45mm Overlay Cracking	30	1,974
	Other Flexible Pavement Low Traffic Good Condition2	200	45mm Overlay Cracking	30	2,005
	Other Flexible Pavement Low Traffic Good Condition3	200	45mm Overlay Cracking	30	2,035
	Other Flexible Pavement Low Traffic Good Condition4	200	45mm Overlay Cracking	30	2,066
	Other Flexible Pavement Low Traffic Good Condition5	200	45mm Overlay Cracking	30	2,096
	Other Flexible Pavement Low Traffic Good Condition6	200	45mm Overlay Cracking	30	2,126
	Other Flexible Pavement Low Traffic Good Condition7	200	45mm Overlay Cracking	30	2,157
	Other Flexible Pavement Low Traffic Good Condition8	200	45mm Overlay Cracking	30	2,187
	Other Flexible Pavement Low Traffic Good Condition9	200	45mm Overlay Cracking	30	2,218
2022	Interstate Flexible Pavement Low Traffic Good Condition	12	45mm Mill & Fill Cracking	3	2,220
2027	Interstate Flexible Pavement High Traffic Poor Condition	14	45mm Mill & Fill Cracking	3	2,224
	Other Flexible Pavement Medium Traffic Poor Condition1	164	45mm Overlay Cracking	25	2,249
2028	Other Flexible Pavement High Traffic Poor Condition	23	45mm Mill & Fill Cracking	9	2,258
2029	Other Flexible Pavement Low Traffic Poor Condition1	213	45mm Overlay Cracking	32	2,290
	Other Flexible Pavement Low Traffic Poor Condition2	200	45mm Overlay Cracking	30	2,320
2030	Interstate Flexible Pavement High Traffic Fair Condition	119	45mm Overlay Cracking	18	2,339
	Interstate Flexible Pavement Low Traffic Poor Condition	3	45mm Mill & Fill Cracking	1	2,339
2031	Interstate Flexible Pavement Medium Traffic Fair Condition	205	45mm Overlay Cracking	31	2,370
	Other Flexible Pavement Medium Traffic Fair Condition1	130	45mm Overlay Cracking	20	2,390

Table 51 (Continued)

Year	Section	Length (km)	Work Description	Financial Cost	Cumulative Cost
2031	Other Flexible Pavement Medium Traffic Fair Condition2	200	45mm Overlay Cracking	30	2,421
	Other Flexible Pavement Medium Traffic Fair Condition3	200	45mm Overlay Cracking	30	2,451
	Other Flexible Pavement Medium Traffic Fair Condition4	200	45mm Overlay Cracking	30	2,481
	Other Flexible Pavement Medium Traffic Fair Condition5	200	45mm Overlay Cracking	30	2,512
	Other Flexible Pavement Medium Traffic Fair Condition6	200	45mm Overlay Cracking	30	2,542
	Other Flexible Pavement Medium Traffic Fair Condition7	200	45mm Overlay Cracking	30	2,573
2032	Other Flexible Pavement High Traffic Fair Condition	64	45mm Mill & Fill Cracking	25	2,598
	Other Flexible Pavement Low Traffic Fair Condition1	213	45mm Overlay Cracking	32	2,630
	Other Flexible Pavement Low Traffic Fair Condition2	200	45mm Overlay Cracking	30	2,660
	Other Flexible Pavement Low Traffic Fair Condition3	200	45mm Overlay Cracking	30	2,691
	Other Flexible Pavement Low Traffic Fair Condition4	200	45mm Overlay Cracking	30	2,721
2033	Interstate Flexible Pavement Medium Traffic Good Condition1	180	45mm Overlay Cracking	27	2,748
	Interstate Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	2,779
	Interstate Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	2,809
	Other Flexible Pavement Medium Traffic Good Condition10	200	45mm Overlay Cracking	30	2,840
	Other Flexible Pavement Medium Traffic Good Condition2	200	45mm Overlay Cracking	30	2,870
	Other Flexible Pavement Medium Traffic Good Condition3	200	45mm Overlay Cracking	30	2,900
	Other Flexible Pavement Medium Traffic Good Condition4	200	45mm Overlay Cracking	30	2,931
	Other Flexible Pavement Medium Traffic Good Condition5	200	45mm Overlay Cracking	30	2,961
	Other Flexible Pavement Medium Traffic Good Condition6	200	45mm Overlay Cracking	30	2,992
	Other Flexible Pavement Medium Traffic Good Condition7	200	45mm Overlay Cracking	30	3,022
2034	Other Flexible Pavement Low Traffic Good Condition10	200	45mm Overlay Cracking	30	3,052
	Other Flexible Pavement Low Traffic Good Condition11	200	45mm Overlay Cracking	30	3,083
	Other Flexible Pavement Low Traffic Good Condition2	200	45mm Overlay Cracking	30	3,113
	Other Flexible Pavement Low Traffic Good Condition3	200	45mm Overlay Cracking	30	3,144
	Other Flexible Pavement Low Traffic Good Condition4	200	45mm Overlay Cracking	30	3,174
	Other Flexible Pavement Low Traffic Good Condition5	200	45mm Overlay Cracking	30	3,204
	Other Flexible Pavement Low Traffic Good Condition6	200	45mm Overlay Cracking	30	3,235
	Other Flexible Pavement Low Traffic Good Condition7	200	45mm Overlay Cracking	30	3,265
	Other Flexible Pavement Low Traffic Good Condition8	200	45mm Overlay Cracking	30	3,296
	Other Flexible Pavement Low Traffic Good Condition9	200	45mm Overlay Cracking	30	3,326
	Interstate Flexible Pavement Low Traffic Fair Condition	7	45mm Mill & Fill Cracking	2	3,328
2036	Interstate Flexible Pavement Low Traffic Good Condition	12	45mm Mill & Fill Cracking	3	3,331
2039	Interstate Flexible Pavement High Traffic Poor Condition	14	45mm Mill & Fill Cracking	3	3,334
2040	Other Flexible Pavement Medium Traffic Poor Condition1	164	45mm Overlay Cracking	25	3,359
2042	Interstate Flexible Pavement High Traffic Fair Condition	119	45mm Overlay Cracking	18	3,377
	Other Flexible Pavement High Traffic Poor Condition	23	45mm Mill & Fill Cracking	9	3,386
2043	Other Flexible Pavement Low Traffic Poor Condition1	213	45mm Overlay Cracking	32	3,418
	Other Flexible Pavement Low Traffic Poor Condition2	200	45mm Overlay Cracking	30	3,449

(All costs are in millions of dollars)

5: CONCLUSIONS AND SUMMARY

5.1 CONCLUSIONS

This study collected pavement related data, calibrated the HDM-4 models for flexible pavements, and applied them to the WSDOT road network. The calibration factors were shown to be reliable. Significant findings are:

1. HDM-4 can be used for the WSDOT road network.
2. Road deterioration models can be calibrated for flexible pavements. For the WSDOT network, it is impossible to apply one set of calibration factors to the entire network. The WSDOT road network requires calibration factors significantly different than default HDM-4 values.
3. The current version of HDM-4 (version 1.3) does not provide meaningful analysis output for WSDOT concrete pavements. Therefore, HDM-4 cannot be used to analyze concrete pavements.
4. WSPMS data are essential to this research. The annually updated data make the calibration procedure possible.
5. Current research mainly focuses on road deterioration models and road works effects models. Further studies on traffic and environmental effects would benefit WSDOT.

5.2 SUMMARY

The research has contributed the following:

1. HDM-4 input data were collected and processed from existing WSPMS data and other available sources. The data included traffic, climate and environment,

vehicle mechanical characteristics, and costs and benefits of road works.

2. An integrated method of deriving and formatting pavement condition data from WSPMS to HDM-4 was created and applied.

3. Most pavement deterioration models were systematically simplified, except in several models where factors had negligible impacts on road performance.

4. A method of calibrating concrete pavement deterioration models is proposed. Although HDM-4 cannot currently execute those models, the method can be used for future applications.

5. An econometric software-LIMDEP was successfully applied to estimate calibration factors based on local condition data and HDM-4 models.

6. All calibration factors of flexible pavement deterioration models (based on HDM-4 models) were proved to be reliable by the validation process. The estimated performance of road conditions matched the actual local conditions reasonably well and proved that these factors can be used for WSDOT's future applications.

7. Four major functions were derived on the basis of the three levels of analysis:

    - Predict the required budget based on selected target road conditions.
    - Produce strategies for selecting and timing of road works under varying budget levels.
    - Assist WSDOT and policy makers in determining the long-term effects of different funding scenarios, including the effects of near-term funding cuts on (1) long-term pavement condition, (2) long-term user costs and (3) future funding required to restore the network.

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LIST OF APPENDICES

Because many of these appendices would be too large and unwieldy to print, they are available electronically.

Appendix A: Climate Data of Washington State

Appendix B1: Road Network Definitions for Project Analysis

Appendix B2: Road Network Input Table for Project Analysis—High ESAL ACPs

Appendix B3: Road Network Input Table for Project Analysis—Medium ESAL ACPs

Appendix B4: Road Network Input Table for Project Analysis—Low ESAL ACPs

Appendix B5: Road Network Input Table for Project Analysis—BSTs

Appendix B6: Road Network Input Table for Project Analysis—PCCPs

Appendix C1: Vehicle Fleet Definitions for Cars

Appendix C2: Vehicle Fleet Definitions for Single Units

Appendix C3: Vehicle Fleet Definitions for Double Units

Appendix C4: Vehicle Fleet Definitions for Trains

Appendix C5: Data Sources of Vehicle Fleet Input

Appendix C6: Vehicle Fleet Input Table

Appendix D1: Road Network Definitions for Strategic Analysis

Appendix D2: Road Network Input Table for Strategic Analysis—ACPs

Appendix D3: Road Network Input Table for Strategic Analysis—BSTs