References

1 Michelow, J., Analysis of Stress and Displacements in an n-Layered Elastic System under a Load Uniformly Distributed on a Circular Area California Research Corporation, Richmond, California, 1963.

2 Lytton, R.L., "Backcalculation of Pavement Layer Properties," Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026, American Society for Testing and Materials, Philadelphia, 1989, pp. 7-38.

3 Rhode, G. T. And Scullion, T., “MODULUS 4.0: Expansion and Validation of the Modulus Backcalculation System,” Research Report 1123-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, November 1990.

4 Hossain, A.S.M., and Zaniewski, J.P., "Detection and Determination of Depth of Rigid Bottom in Backcalculation of Layer Moduli from Falling Weight Deflectometer Data," Transportation Research Record No. 1293, Transportation Research Board, Washington, D.C., 1991.

5 Winters, B.C., "The PACCAR Pavement Test Section — Instrumentation and Validation," Master's thesis, Department of Civil Engineering, University of Washington, Seattle, Washington, March 1993.

6 Lenngren, C.A., "Relating Bearing Capacity to Pavement Condition," Ph.D. Dissertation, Royal Institute of Technology, Department of Highway Engineering, Stockholm, Sweden, 1990.

7 Darter, M.I., Elliott, R.P., and Hall, K.T., "Revision of AASHTO Pavement Overlay Design Procedure," Project 20-7/39, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., September 1991.

8 Newcomb, D. E., “Development and Evaluation of Regression Method to Interpret Dynamic Pavement Deflections,” Ph.D. Dissertation, Department of Civil Engineering, University of Washington, Seattle, Washington, 1986.

9 Bu-Bushait, A. A., “Development of a Flexible Pavement Fatigue Model for Washington State,” Ph.D. Dissertation, Department of Civil Engineering, University of Washington, Seattle, Washington, 1985.

10 The Asphalt Institute, Thickness Design — Asphalt Pavement for Highways and Streets, Manual Series No. 1 (MS-1), College Park, Maryland, September 1981.

11 Shook, J.F., Finn, F.N., Witczak, M.W., and Monismith, C.L., "Thickness Design of Asphalt Pavements — The Asphalt Institute Method," Proceedings, Fifth International Conference on the Structural Design of Asphalt Pavements, The Delft University of Technology, The Netherlands, 1982.

12 Monismith, C.L., and Epps, J.A., "Asphalt Mixture Behavior in Repeated Flexure," Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1969.

13 Finn, F.N., et al., "The Use of Distress Prediction Subsystems for the Design of Pavement Structures," Proceedings, 4th International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1977.

14 Mahoney, J.P., Lee, S.W., Jackson, N.C., and Newcomb, D.E., "Mechanistic Based Overlay Design Procedure or Washington State Flexible Pavements," Research Report WA-RD 170.1, Washington State Department of Transportation, Olympia, Washington, 1989.

15 Southgate, H. F., and Deen, R. C., "Temperature Distributions in Asphalt Concrete Pavements", *Highway Research Record No. 549*, Highway Research Board, Washington, D.C., 1975, pp. 39-46.

16 Horak, E., "The Use of Surface Deflection Basin Measurements in the Mechanistic Analysis of Flexible Pavements," Proceedings, Vol. 1, Sixth International Conference Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Michigan, USA, 1987.

17 The Asphalt Institute, "Asphalt Overlays for Highway and Street Pavement Rehabilitation," Manual Series No. 17, the Asphalt Institute, College Park, Maryland, June 1983.

18 Rutherford, M.S., Mahoney, J.P., Hicks, R.G., and Rwebangira, T., "Guidelines for Spring Highway Use Restrictions," Research Report WA-RD 80.1 (WSDOT) and FHWA-RD-86-501 (FHWA), August 1985.

19 Kono, F., Takahashi, T., Kubo, H. and Hiraoka, H., "Pavement Design in Cold Areas," Proceedings, Symposium on Frost Action on Roads, Norwegian Road Research Laboratory, Oslo, Norway, October 1973.

Appendix A
Nondestructive Testing Interpretation Techniques

Clearly, there are all kinds of NDT data which can be collected on or about pavements but concentration is placed on measured surface deflections.

DEFLECTION BASIN PARAMETERS

Over the years numerous techniques have been developed to analyze deflection data from various kinds of pavement deflection equipment. A fairly complete summary of deflection basin parameters was provided by Horak at the Sixth International Conference Structural Design of Asphalt Pavement [15] and is shown in Table A-1.

Table A-1. Summary of Deflection Basin Parameters [modified from 15]

Parameter	Formula	Measuring device
Maximum deflection	D_0	Benkelman Beam, Lacroux deflectometer, FWD
Radius of curvature	$R = \frac{r^2}{2D_0(D_0/D_r - 1)}$ r = 5"	Curvaturemeter
Spreadability	$S = \left(\frac{[(D_0 + D_1 + D_2 + D_3)/5]100}{D_0}\right)$ D1 … D3 spaced 12" apart	Dynaflect
Area	$A = 6[1 + 2(D_1/D_2) + 2(D_2/D_0) + (D_3/D_0)]$ 0, 1, 2, 3 feet	FWD
Shape factors	$F1 = (D_0 - D_2) / D_1$ $F2 = (D_1 - D_3) / D_2$	FWD
Surface curvature index	$SCI = D_0 - D_r$ where r = 12" or r = 20"	Benkelman Beam Road Rater FWD
Base curvature index	$BCI = D_{24"} - D_{36"}$	Road Rater
Base damage index	$BDI = D_{12"} - D_{24"}$	Road Rater
Deflection ratio	$Q_r = D_r/D_0$ where $D_r = D_0/2$	FWD
Bending index	BI = D/a where a = Deflection basin	Benkelman Beam
Slope of deflection	$SD = \tan^{-1} (D_0 - D_r)/r$ where r = 24 inches	Benkelman Beam

All of these parameters tend to focus on four major areas:

(a) Plate or center load deflection which represents the total defection of the pavement. This was obviously the first deflection parameter which came with the Benkelman

Beam. It has been used for many years as the primary input for several overlay design procedures.

(b) The slope or deflection differences close to the load such as Radius of Curvature (R), Shape Factor (F1), and Surface Curvature Index (SCI). These parameters tend to reflect the relative stiffness of the bound or upper regions of the pavement section.

(c) The slope or deflection differences in the middle of the basin about 11.8 inches to 35.4 inches from the center of the load. These parameters tend to reflect the relative stiffness of the base or lower regions of the pavement section.

(d) The deflections toward the end of the basin. Deflections in this region relate quite well to the stiffness of the subgrade below the pavement surfacing.

The subsequent parameters to be presented were developed to provide a means of obtaining the resilient modulus values of the surfacing layers more easily or quickly than full backcalculation. In general, the success of these regression equations to predict the resilient modulus of the surfacing layers has been limited. There is a clear consensus; however, that the deflections measured beyond the primary effects of the load stress bulb relate quite well to the resilient modulus of the subgrade, (ESG).

AREA PARAMETER

Over the years WSDOT has found that the use of selected indices and algorithms provide a "good picture" of the relative conditions found throughout a project. This picture is very useful in performing backcalculation and may at times be used by themselves on projects with large variations in surfacing layers.

WSDOT is currently using deflections measured at the center of the test load combined with Area values and E_{SG} computed from deflections measured at 24 inches presented in a linear plot to provide a visual picture of the conditions found along the length of any project (as illustrated in Figure A-1).

The Area value represents the normalized area of a slice taken through any deflection basin between the center of the test load and 3 feet. By normalized, it is meant that the area of the slice is divided by the deflection measured at the center of the test load, D_0. Thus the Area value is the length of one side of a rectangle where the other side of the rectangle is D_0. The actual area of the rectangle is equal to the area of the slice of the deflection basin between 0 and 3 feet.

The original Area equation is:

$$A = 6(D_0 + 2D_1 + 2D_2 + D_3)/D_0$$

where D_0 = surface deflection at center of test load,
D_1 = surface deflection at 1 foot,
D2 = surface deflection at 2 feet, and
D3 = surface deflection at 3 feet.

The approximate metric equivalent of this equation is:

$$A = 150(D0 + 2D300 + 2D600 + D900)/D0$$

where D0 = deflection at center of test load,
D300 = deflection at 300 mm,
D600 = deflection at 600 mm, and
D900 = deflection at 900 mm.

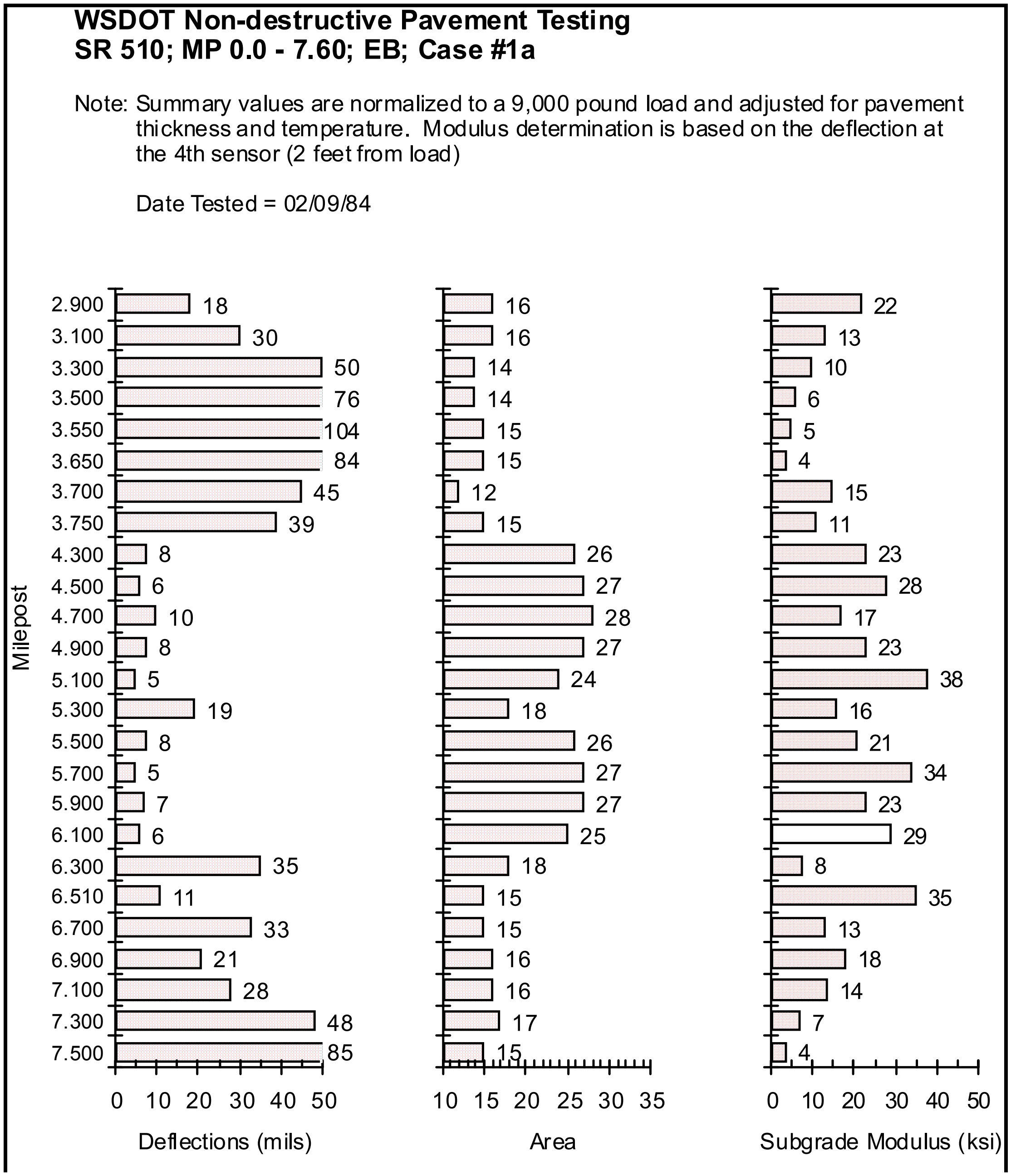


Figure A-1. Illustration of Basic NDT Parameters as used by WSDOT

Figure A-2 shows the development of the normalized area for the Area value using the Trapezoidal Rule to estimate area under a curve.

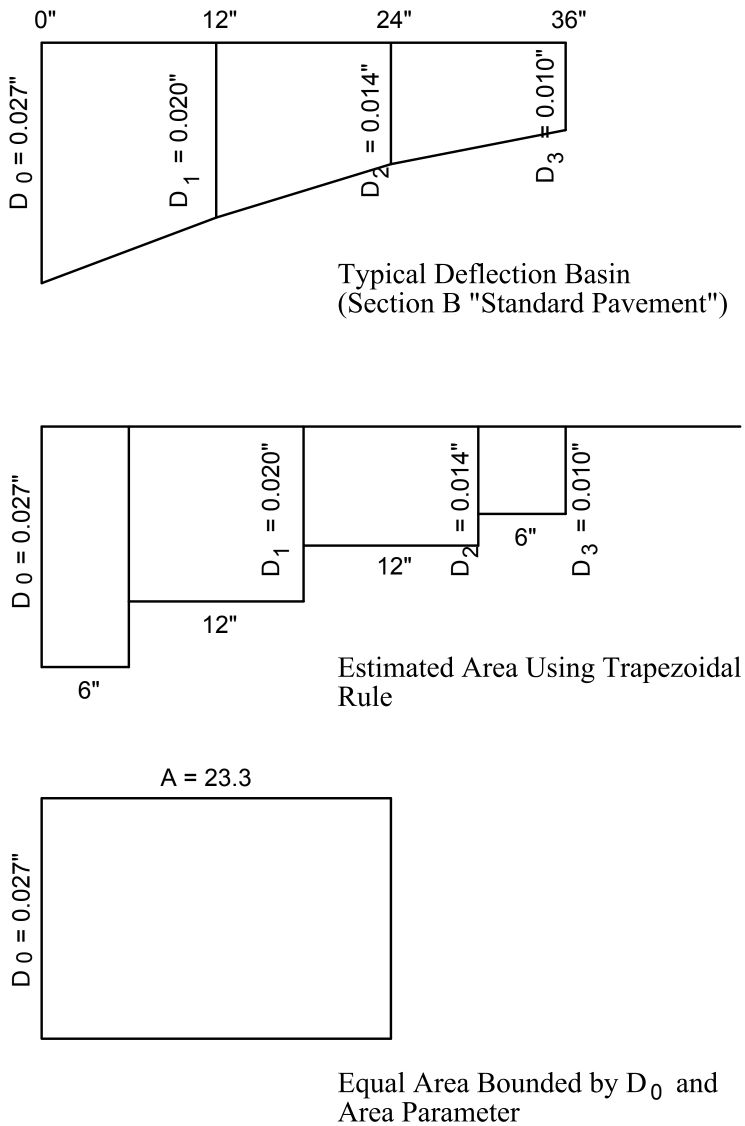


Figure A-2. Computing an Area Parameter

The basic Trapezoidal Rule is:

$$K = h\left(\frac{1}{2}y_0 + y_1 + y_2 + \frac{1}{2}y_3\right)$$

where K = any planar area,
y_0 = initial chord,
y1, y2 = immediate chords,
y3 = last chord, and
h = common distance between chords.

Thus, to estimate the area of a deflected basin using D_0, D_1, D_2, and D_3, and h = 6 inches, then:

K = 6 (D0 + 2D1 + 2D2 + D3)

Further, normalize by dividing by D_0:

$$\text{Area} = \frac{6}{D0}(D0 + 2D1 + 2D2 + D3) \quad \text{or} \quad \text{Area} = 6\left(1 + \frac{2D1}{D0} + \frac{2D2}{D0} + \frac{D3}{D0}\right)$$

Thus, since we normalized by D_0, the Area Parameter's unit of measure is inches (or mm) not in^2 or mm^2 as one might expect.

The maximum value for Area is 36.0 inches and occurs when all four deflection measurements are equal (not likely to actually occur) as follows:

If, $D_0 = D_1 = D_2 = D_3$

Then, Area = 6(1 + 2 + 2 + 1) = 36.0 inches

For all four deflection measurements to be equal (or nearly equal) would indicate an extremely stiff pavement system (like portland cement concrete slabs or thick, full-depth HMA.)

The minimum Area value should be no less than 11.1 inches.

This value can be calculated for a one-layer system which is analogous to testing (or deflecting) the top of the subgrade (i.e., no pavement structure). Using appropriate equations, the ratios of

$$\frac{D_1}{D_0}, \frac{D_2}{D_0}, \frac{D_3}{D_0}$$

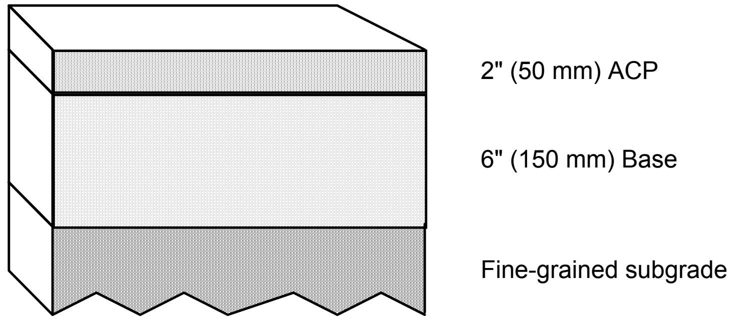
always result in 0.26, 0.125, and 0.083, respectively. Putting these ratios in the Area equation results in

Area = 6(1+ 2(0.26) + 2(0.125) + 0.083) = 11.1 inches

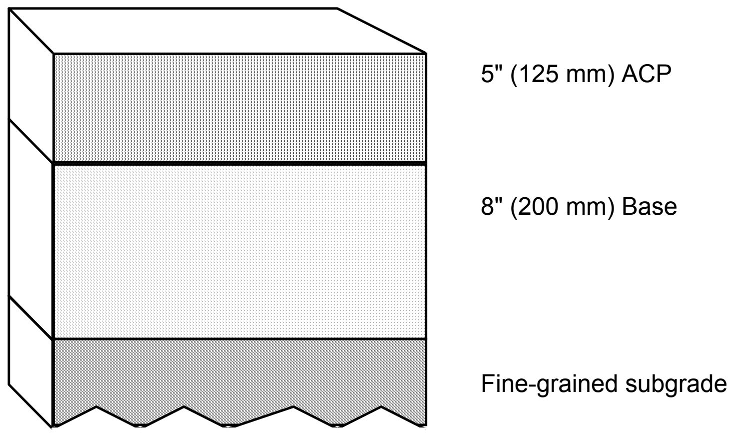
Further, this value of Area suggests that the elastic moduli of any pavement system would all be equal (e.g., $E_1 = E_2 = E_3 = \ldots$). This is highly unlikely for actual, in-service pavement structures. Low area values suggest that the pavement structure is not much different from the underlying subgrade material (this is not always a bad thing if the subgrade is extremely stiff — which doesn't occur very often).

Typical Area values were computed for pavement Sections A, B, and C (refer to Figure A-3) and are shown in Table A-2 (along with the calculated surface deflections (D_0, D_1, D_2, D_3)). The following provides a general guide in the use of Area values obtained from FWD pavement surface deflections.

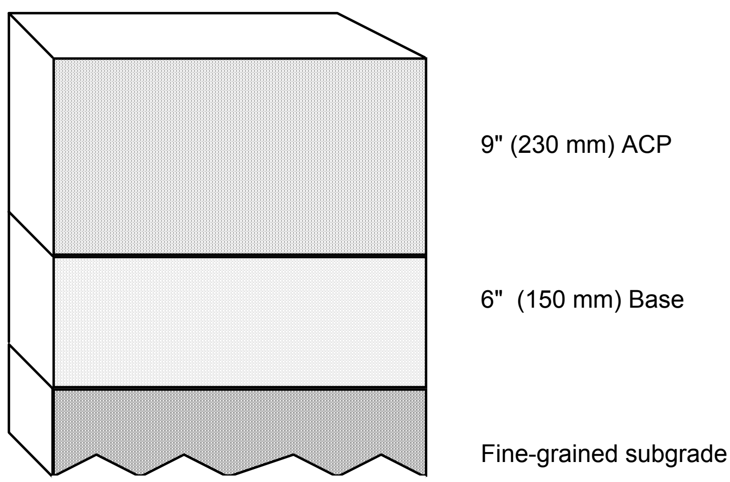
Pavement	**Area (inch)**	**Area (mm)**
PCCP "Sound" PCC*	24-33 29-32	610-840 740-810
Thick HMA (≥ 0.35 feet)	21-30	530-760
Thin HMA (< 0.35 feet)	16-21	410-530
BST flexible pavement (relatively thin structure)	15-17	380-430
Weak BST	12-15	300-380



Section A (Thin Thickness Section)



Section B (Medium Thickness Section)



Section C (Thick Section)

Figure A-3. “Typical” Pavement Sections

Table A-2. Estimates of Area from Pavement Sections — Cases A, B, and C

Pavement Cases	Pavement Surface Deflections, inches				Area	
	D_0	D_1	D_2	D_3	(inch)	(mm)
Standard Pavement						
Section A (thin)	0.048	0.026	0.014	0.009	17.1	(434)
Section B (med)	0.027	0.020	0.014	0.010	23.3	(592)
Section C (thick)	0.018	0.015	0.012	0.009	27.0	(686)
Stabilize Subgrade						
Section A (thin)	0.036	0.020	0.013	0.009	18.5	(470)
Section B (med)	0.023	0.017	0.012	0.009	23.5	(597)
Section C (thick)	0.016	0.013	0.011	0.009	27.4	(696)
Asphalt Treated Base						
Section A (thin)	0.021	0.018	0.013	0.010	26.6	(676)
Section B (med)	0.014	0.012	0.010	0.009	28.7	(729)
Section C (thick)	0.012	0.011	0.009	0.008	30.0	(762)
Moisture Sensitivity						
Section A (thin)	0.053	0.026	0.014	0.009	16.1	(409)
Section B (med)	0.033	0.022	0.014	0.009	20.7	(526)
Section C (thick)	0.024	0.018	0.013	0.010	24.0	(610)

Table A-3. Trends of D0 and Area Values

FWD Based Parameter		Generalized Conclusions*
Area	Maximum Surface Deflection (D_0)	
Low	Low	Weak structure, strong subgrade
Low	High	Weak structure, weak subgrade
High	Low	Strong structure, strong subgrade
High	High	Strong structure, weak subgrade

*Naturally, exceptions can occur

Appendix B
Seasonal Temperature for Washington State

INTRODUCTION

The Everpave© program requires seasonal mean air temperatures (winter, spring, summer, fall). A summary of NOAA temperature data was prepared at the WSDOT Materials Laboratory and is included in this appendix.

MEAN SEASONAL TEMPERATURES

The NOAA temperature data is summarized in Table B-1 (monthly, yearly means) and Table B-2 (seasonal means) by NOAA designated "divisions." The means are based on monthly means measured from 1957 through 1989.

EXCEPTIONS

The data contained in Tables B1 and B-2 is very general. Specific project locations may have unique temperature conditions due to local microclimate effects, etc. Local temperature effects should be used if known.

NOAA DIVISIONS

"Typical" weather stations used in developing Tables B-1 and B-2 include:

NOAA Division 1:
Western Olympic Peninsula — Coastal Area

- Neah Bay
- Forks
- Clearwater
- Quinault Ranger Station
- Cushman Dam
- Aberdeen
- Montesano
- Westport
- Raymond
- Long Beach

NOAA Division 2:
Northeast Olympia Peninsula — San Juan Islands

- Port Angeles
- Sequim
- Port Townsend
- Anacortes
- Mount Vernon

NOAA Division 3:
Puget Sound Lowlands

- Blaine
- Bellingham
- Sedro Wooley
- Burlington
- Monroe
- Seattle
- Sea-Tac Airport
- Kent
- Tacoma
- Puyallup
- Olympia
- Centralia
- Bremerton

NOAA Division 4:
Eastern Olympic-Western
Cascade Foothills

- Quilcene
- Shelton
- Elma
- Toledo
- Longview
- Vancouver
- Mud Mountain Dam
- Snoqualmie Falls
- Startup
- Arlington
- Concrete

NOAA Division 5:
Western Cascade
Mountains

- Ross Dam
- Marblemount Ranger Station
- Stevens Pass
- Snoqualmie Pass
- Stampede Pass
- Paradise
- Cougar

NOAA Division 6:
East Slope of Cascades

- Mazama
- Winthrop
- Stehekin
- Lake Wenatchee
- Plain
- Leavenworth
- Peshastin
- Easton
- Cle Elum
- Naches
- Mount Adams Ranger Station
- Glenwood
- Status Pass

NOAA Division 7: Okanogan-Big Bend

- Tonasket
- Conconully
- Omak
- Methow
- Nespelem
- Chief Joseph Dam
- Grand Coulee Dam
- Chelan
- Mansfield
- Waterville
- Hartline
- Wilbur
- Davenport
- Odessa

NOAA Division 8: Central Basin

- Wenatchee
- Ephrata
- Quincy
- Moses Lake
- Ritzville
- Othello
- Ellensburg
- Yakima
- Wapato
- Sunnyside
- Dallesport
- Goldendale
- Prosser
- Richland/Kennewick/Pasco
- Connell
- Walla Walla

NOAA Division 9:
Northeastern

- Wauconda
- Republic
- Northport
- Colville
- Chewelah
- Newport
- Spokane

NOAA Division 10:
Palouse-Blue Mountain

- Rosalia
- Tekoa
- St. John
- Colfax
- Pullman
- Pomeroy
- Dayton
- Asotin

Table B-1. Monthly and Yearly Mean Temperatures (Years 1957-1989)

Region (NOAA Division)	Monthly Means (°F)												Yearly Mean (°F)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1 West Olympic-Coastal	39.6	42.5	44.2	47.4	52.5	56.7	59.9	60.5	58.0	51.5	44.7	40.8	49.9
2 Northeast Olympic-San Juans	39.2	42.2	44.6	48.3	53.6	57.9	61.0	61.3	57.7	50.8	44.1	40.6	50.1
3 Puget Sound Lowlands	38.6	42.4	45.0	49.2	55.2	60.2	63.9	64.0	59.4	51.8	44.2	39.9	51.1
4 East Olympic-West Cascades Foothills	—	40.7	43.6	47.8	54.0	59.2	63.3	63.4	58.7	50.8	42.7	38.2	49.9
5 Western Cascade Mountains	29.5	33.2	36.3	41.0	48.2	54.5	60.0	60.2	54.7	46.4	36.4	31.4	44.3
6 East Slope of Cascades	25.6	31.4	37.3	44.2	52.3	59.4	65.0	64.6	56.5	46.2	34.7	27.4	45.4
7 Okanogan-Big Bend	24.7	31.8	39.8	47.7	56.2	63.6	69.6	68.9	59.9	48.1	35.6	27.3	47.8
8 Central Basin	29.9	36.9	44.0	50.6	58.8	66.3	72.2	71.2	62.6	51.5	39.6	31.7	51.3
9 Northeastern	24.1	30.6	37.5	45.3	53.8	60.8	66.7	65.9	56.9	45.6	33.6	26.3	45.6
10 Palouse-Blue Mountains	29.8	36.3	41.5	47.6	55.2	62.4	68.8	68.3	60.0	49.7	38.7	31.9	49.2

Table B-2. Seasonal Mean Temperatures (Years 1957-1989)

Region (NOAA Division)	Seasonal Mean Temperature (°F)			
	Spring • March • April • May	**Summer** • June • July • August	**Fall** • September • October • November	**Winter** • December • January • February
1 West Olympic-Coastal	48.0	59.0	51.4	41.0
2 Northeast Olympic-San Juans	48.8	60.1	50.9	40.7
3 Puget Sound Lowlands	49.8	62.7	51.8	40.3
4 East Olympic-West Cascades Foothills	48.5	62.0	50.7	38.6
5 Western Cascade Mountains	41.8	58.2	45.8	31.4
6 East Slope of Cascades	44.6	63.0	45.8	28.1
7 Okanogan-Big Bend	47.9	67.4	47.9	27.9
8 Central Basin	51.1	69.9	51.2	32.8
9 Northeastern	45.5	64.5	45.4	27.0
10 Palouse-Blue Mountains	48.1	66.5	49.4	32.7

Appendix C
Moduli Seasonal Variation

UNSTABILIZED MODULI

Based on FWD deflections obtained over a three-year period (1985 to 1987), the ratio of the moduli for the different seasons were estimated. These initial estimates are shown in Table C-1.

The data in Table C-1 suggest a greater variation in the base course (seasonally) than the subgrade. Clearly, this phenomenon can be quite site-specific. As such, the ratios are only, at best, "rules of thumb."

For dense graded base materials, numerous sources have suggested that moisture levels exceeding 85 percent of saturation can result in significant moduli reductions.

SEASONAL TEMPERATURES

Seasonal air temperatures are required inputs. These temperatures are used to adjust the AC moduli seasonally. These mean monthly air temperatures (MMAT) are converted to mean monthly pavement temperatures (MMPT) by use of the following equation:

$$MMPT = MMAT \left(1 + \left(\frac{1}{z + 4}\right)\right) - \left(\frac{34}{z + 4}\right) + 6$$

where MMPT = mean monthly pavement temperature (°F),
MMAT = mean monthly air temperature (°F), and
z = depth below pavement surface (inch).

For example, if the MMAT = 65 °F and z = 3 inch, then

$$= (65)\left(1 + \left(\frac{1}{3 + 4}\right)\right) - \left(\frac{34}{3 + 4}\right) + 6$$
$$= 75.4\ °F$$

Table C-1. Design Moduli Ratios for Western and Eastern Washington Base Course and Subgrade Materials[1]

Region		Spring	Summer	Fall	Winter
		Seasonal Period			
Western Washington	Climate:	Cool/Wet	Warm/Dry	Cool/Damp	Cool/Wet
	Months:	March April May	June July August September	October November	December January February
	Base	0.85	1.00	0.90	0.75
	Subgrade	0.85	1.00	0.90	0.85
Eastern Washington	Climate:	Thaw	Hot/Dry	Cool/Dry	Freeze
	Months:	February March April May	June July August September	October November December	January
	Base	0.65	1.00	0.90	1.10
	Subgrade	0.90	1.00	0.90	1.10

[1]Design moduli ratios are appropriate for use if stress sensitive moduli relationships are not used. If stress sensitive moduli relationships are used (e.g., $E = k_1 \theta^{k_2}$), then use of these ratios may overestimate seasonal effects.

Appendix D
Case Study Photographs

Photo 1. MP 207.90, NB lane, area of longitudinal and alligator cracking

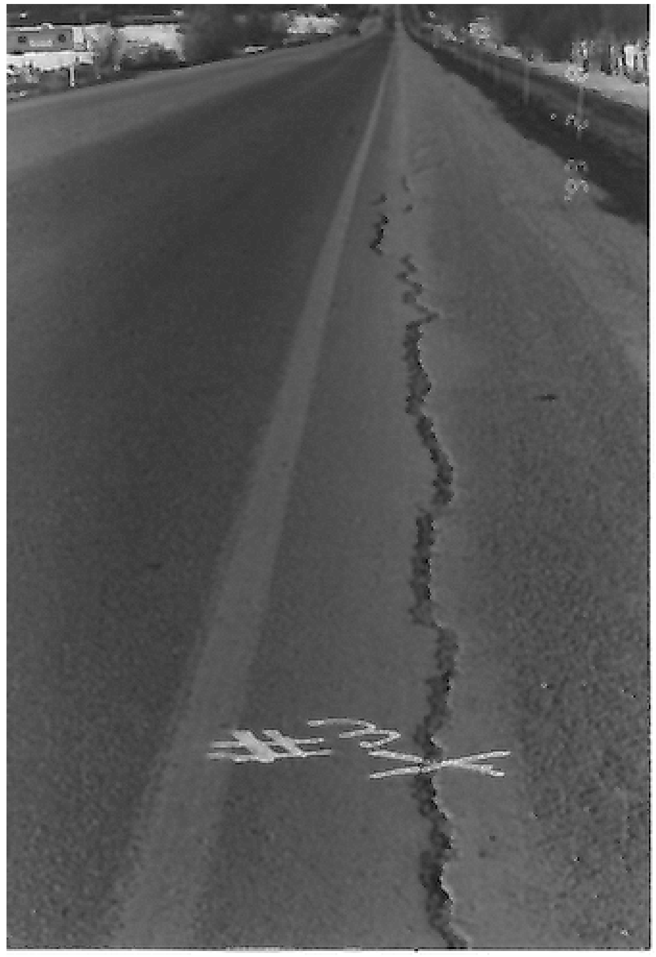


Photo 2. MP 208.00, NB shoulder cracking, occurring from MP 207.82 to MP 208.29

Photo 3. MP 208.07, cracking within the NB shoulder

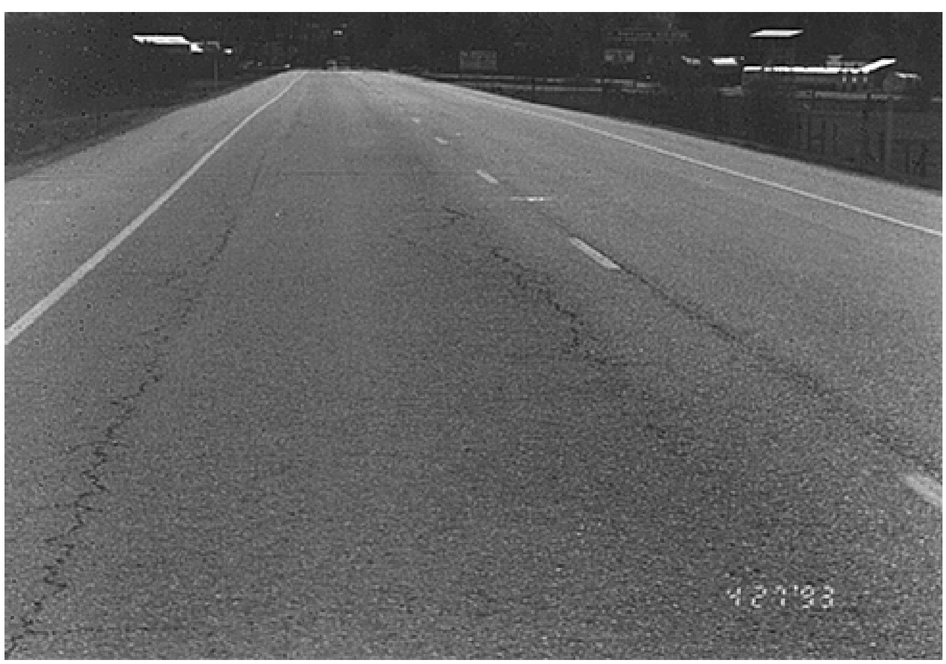


Photo 4. MP 208.18, NB lane, longitudinal cracking progressing to alligator cracks

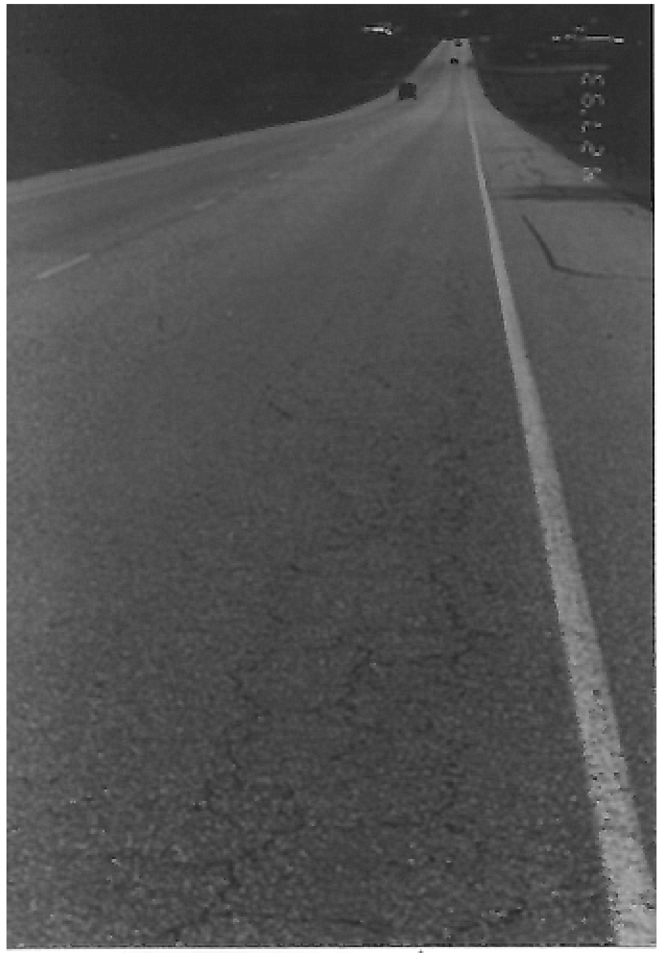


Photo 5. MP 208.56, NB lane, typical alligator cracking within the wheel paths

Photo 6. MP 208.56, SB shoulder (typical from MP 208.52 to MP 208.56)

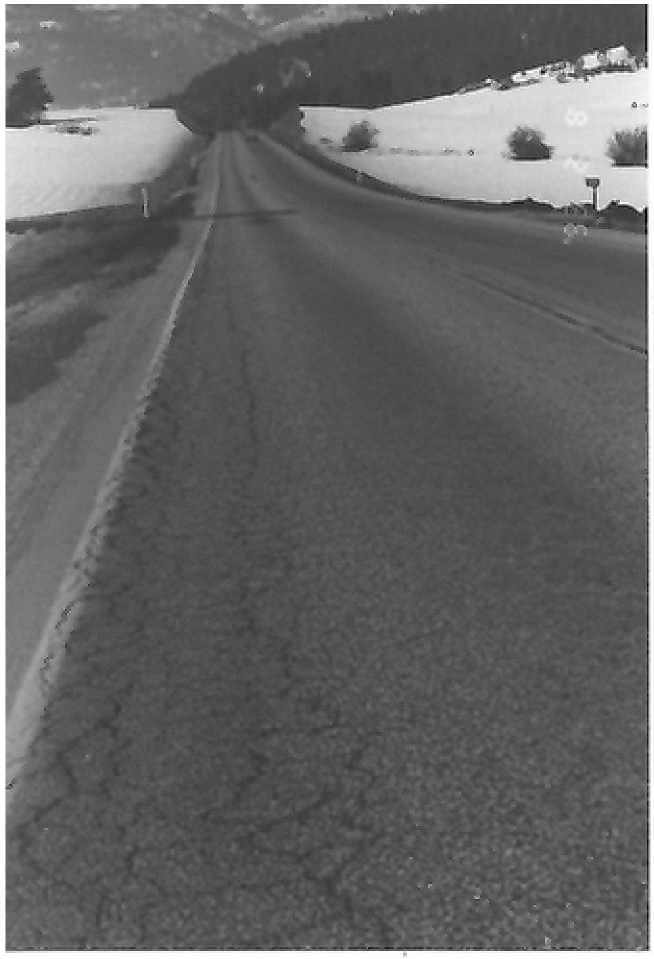


Photo 7. MP 209.00, SB lane, looking north, alligator cracking within outside wheel path

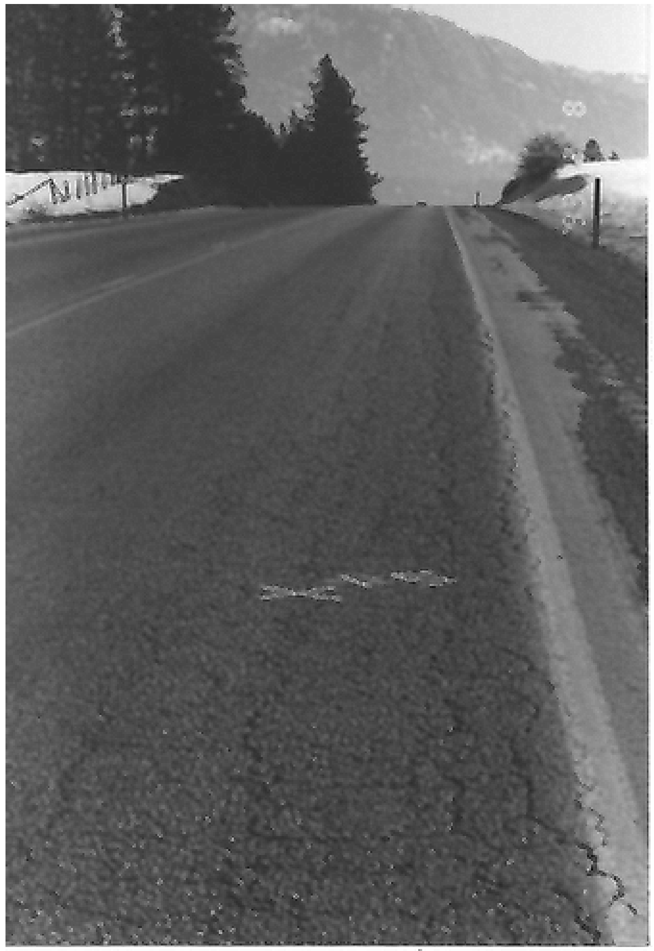


Photo 8. MP 209.00, SB lane, looking south, alligator cracking within outside wheel path

Photo 9. MP 209.05, SB lane, frost heave causing 150 to 200 mm of differential movement

Photo 10. MP 209.40, NB lane, alligator cracking, which occurs in both wheel paths

Photo 11. MP 209.60, NB lane, alligator and longitudinal cracking

Photo 12. MP 209.82, NB lane, frost heave that affects the NB lane and shoulder

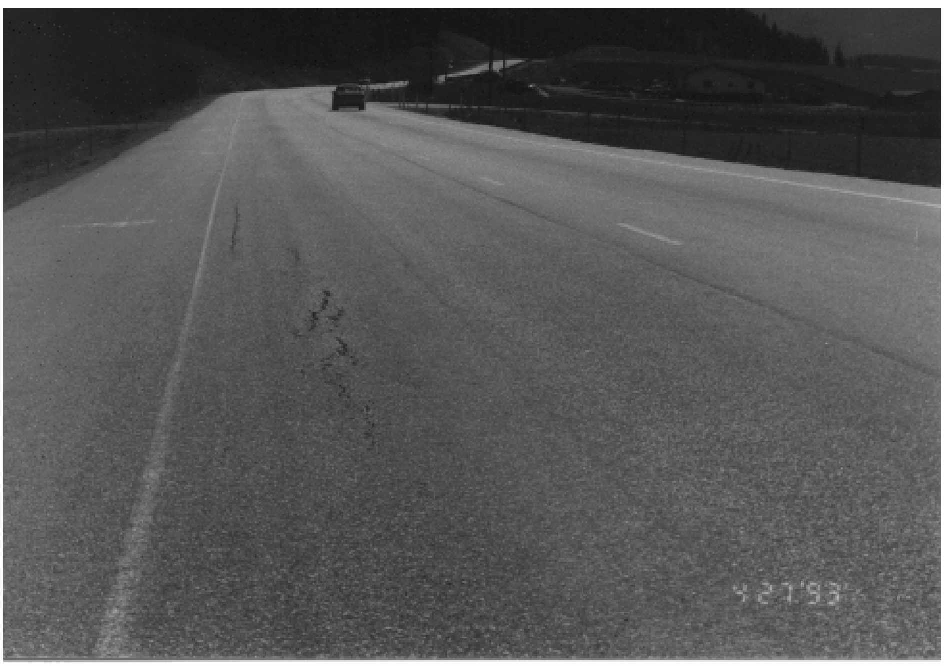


Photo 13. MP 211.91, NB lane, isolated distress occurring from MP 210.55 to MP 212.67

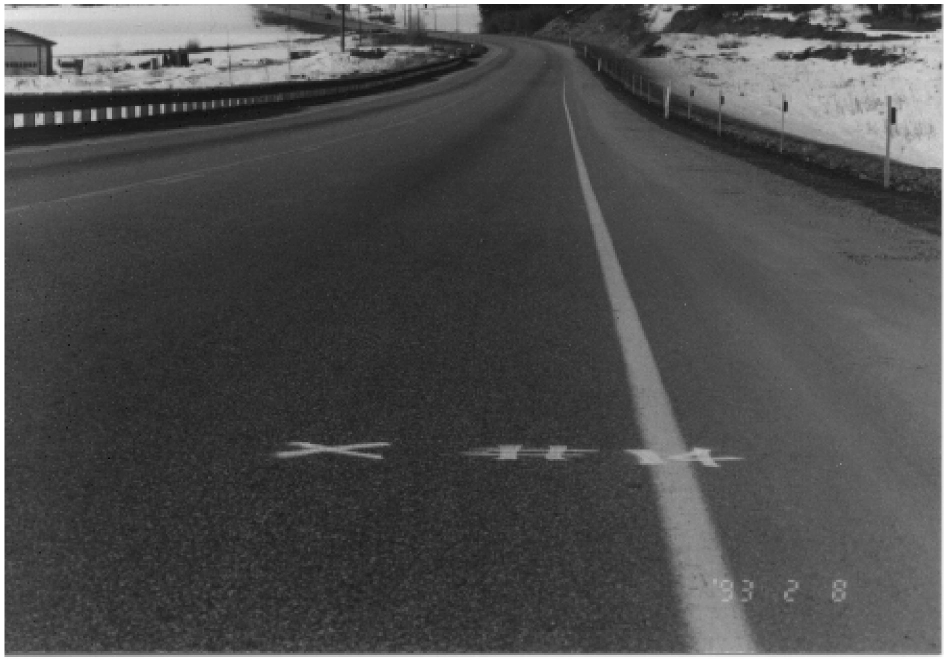


Photo 14. MP 211.50, NB lane, pavement is generally in good condition

Appendix E
Asphalt institute Component Analysis (MS-1)

This component analysis design approach (termed "effective thickness" by the Asphalt Institute) uses relationships between subgrade strength, pavement structure, and traffic [17]. The existing structural integrity of the pavement is converted to an equivalent thickness of HMA, which is then compared to that required for a new design. The structural evaluation procedure developed by the Asphalt Institute allows for determining the required thickness of HMA overlay or to estimate the length of time until an overlay is required.

The essential parts of this overlay design procedure will be briefly described:

(a) Subgrade analysis,
(b) Pavement structure thickness analysis, and
(c) Traffic analysis

Subgrade Analysis

Testing of the subgrade materials is encouraged even if original design records are available. The resilient modulus (M_R), soaked CBR or R-value tests appear to be the easiest to use with this procedure. For actual design, the design strength of the subgrade must be characterized in terms of resilient modulus. Associated correlations for CBR and R-value are:

M_R (psi) = 1500 (CBR)

= 1155 + 555 (R-value)

If test data in terms of M_R, CBR, or R-value are not available, subgrades can be placed into one of three classes for design purposes as follows:

(a) Poor soils. Soft and plastic when wet, generally composed of silts or clays. Typical properties: M_R = 4,500 psi, CBR = 3, R-value = 6.

(b) Medium soils. Include soils such as loams, silty sands, and sand-gravels which contain moderate amounts of clay and silt. These soils can be expected to lose only a moderate amount of strength when wet. Typical properties: M_R = 12,000 psi, CBR = 8, R-value = 20.

(c) Good soils. These soils can be expected to retain a substantial amount of their strength when wet and include clean sands and sand-gravels. Typical properties: M_R = 25,000 psi, CBR = 17, R-value = 43.

Assuming that at least six to eight individual subgrade tests are available, a conservative value is chosen as a function of the design traffic (ESALs). To do this a plot is prepared of the percent equal to or greater than (y axis) versus resilient modulus test results (x axis). Basically, one must create a cumulative frequency plot. Following this, the design subgrade resilient modulus is selected from the plot as follows:

Design ESALs	Design Subgrade Percentile Value (%)
10,000 or less	60
10,000 to 1,000,000	75
greater than 1,000,000	87.5

For more information, refer to The Asphalt Institute's MS-1 (September 1981 Edition).

Pavement Structure Thickness Analysis

The goal of this portion of the design method is to determine the "Effective Thickness (Te)" of the existing pavement structure. The Asphalt Institute has two approaches that can be used; only one will be illustrated here. First, the significant pavement layers are identified and their condition determined. Second, "Conversion Factors" are selected for each layer (judgment by the designer is very important at this point). Third, the Effective Thickness for each layer is determined by multiplying the actual layer thickness by the appropriate Conversion Factor. The Effective Thickness of the complete pavement structure is the sum of the individual Effective Thicknesses. Typical layer thickness Conversion Factors are shown in Table E-1Table .

Traffic Analysis

The Asphalt Institute treatment of traffic includes consideration of volume composition, and axle weights, with the goal being to develop the equivalent number of 18,000 lb equivalent single axle loads (ESALs).

Table E-1. Example of Asphalt Institute Conversion Factors for Estimating Thickness of Existing Pavement Components to Effective Thickness [17]

Description of Layer Material	Conversion Factor*
1. Native subgrade	0.0
2. a. Improved subgrade - predominantly granular materials b. Lime modified subgrade of high PI soils	0.0
3. a. Granular subbase or base - CBR not less than 20 b. Cement modified subbases and bases constructed from low PI soils	0.1 - 0.3
4. a. Cement or lime-fly ash bases with pattern cracking b. Emulsified or cutback asphalt surfaces and bases with extensive cracking, rutting, etc. c. PCC pavement broken into small pieces	0.3 - 0.5
5. a. Hot mix asphalt surface and base that exhibit extensive cracking	0.5 - 0.7
6. a. Hot mix asphalt - generally uncracked b. PCC pavement - stable, undersealed and generally uncracked pavement	0.9 - 1.0
7. Other categories of pavement layers listed in Reference 17	

*Equivalent thickness of new HMA

To estimate the ESALs for the overlay design period, at least two approaches can be used, depending on availability of site-specific traffic information. One approach provides broad traffic classifications and the associated 18,000 lb (80 kN) ESAL amounts, as illustrated in Table E-2. The second approach includes the use of "truck factors" along with the number and type of trucks that are expected to use the facility. This approach can accommodate a wide variety of truck information ranging from only an estimate of the percent of the Average Daily Traffic (ADT) that constitutes trucks to estimates of trucks broken into the categories of single and multi-units (as illustrated by "vehicle type" in Table E-2).

The term "truck factor" represents the average 18 KESAL per truck. Truck factors are shown in Table E-3 for a variety of vehicle types, with the average being 0.4 ESAL per truck averaged over all highway and truck types. Thus, if a given "average" highway is expected to have 1,000,000 trucks during the design period, the resulting ESALs would be 400,000.

Table E-2. Asphalt Institute Traffic Classifications [17]

Type of Street or Highway	Estimated 18,000 lb (80 kN) ESALs
▪ Parking lots ▪ Light traffic residential streets and farm roads	5,000
▪ Residential streets ▪ Rural farm and residential roads	10,000
▪ Urban and rural minor collectors	100,000
▪ Urban minor arterial and light industrial streets ▪ Rural major collector and minor arterial highways	1,000,000
▪ Urban freeways and other principal arterial highways ▪ Rural interstate and other principal arterial highways	3,000,000
▪ Some interstate highways ▪ Some industrial roads	10,000,000

Table E-3. Average Truck Factors Compiled from FHWA Data [17]

	Truck Factors				
Vehicle Types	Rural Highways			Urban Highways	Combined
	Interstate	Other	All	All	All
1. Single-units					
(a) 2-axle, 4-tire	0.02	0.02	0.03	0.03	0.02
(b) 2-axle, 6-tire	0.19	0.21	0.20	0.26	0.21
(c) 3-axles or more	0.56	0.73	0.67	1.03	0.73
(d) All single-units	0.07	0.07	0.07	0.09	0.07
2. Tractor semi-trailers					
(a) 3-axle	0.51	0.47	0.48	0.47	0.48
(b) 4-axle	0.62	0.83	0.70	0.89	0.73
(c) 5-axles or more	0.94	0.98	0.95	1.02	0.95
(d) All multiple units	0.93	0.97	0.94	1.00	0.95
3. All trucks	0.49	0.31	0.42	0.30	0.40

Appendix F
case study photographs

Photo 1. MP 0.23 SB, full depth longitudinal crack at the core location

Photo 2. MP 0.29 NB, beginning of curbed section through the town of Morton

Photo 3. MP 0.44 SB, transverse cracking at the core location (marked with an "X")

Photo 4. MP 0.99 NB, core taken at full depth longitudinal crack. This section has numerous Maintenance patches

Photo 5. MP 2.83 SB, pavement in relatively good condition, pavement rutting is present

Photo 6. MP 3.68 NB, core taken at localized pavement distress

Photo 7. MP 6.48 NB, highly distressed pavement

Photo 8. MP 7.18 SB, pavement has several maintenance patches and rutting

Photo 9. MP 9.96 SB, location of freeze/thaw damage, which is typical of this section for several km. Damage could be caused by snowplows and heavy truck traffic

Photo 10. MP 9.98 NB, location of wide longitudinal cracking. Damage may be caused by snowplows

Photo 11. MP 15.08 NB, Maintenance has placed several HMA or BST patches

Appendix G
Washington State Climate Data

Figure G-1 and Table G-1 provide an overview of Washington State mean FI data (summarized for 1951 to 1980). Figure G-2 is a contour map of Washington for design FI data. The FI contours for both Figure G-1 and Figure G-2 are only approximate. FI's should be obtained at specific sites (projects) if possible.

DEPTH OF FREEZE — IMPLICATIONS FOR PAVEMENT DESIGN

One of the implications of the preceding calculations, FI contour maps, etc., is that the total depth of the pavement structure should be influenced in some way by such results. For example, several SHAs use the rule-of-thumb that the pavement structure should equal at least one-half of the expected depth of freeze. To this end, Figure G-7 and Figure G-4 were prepared. These contour maps show the expected depths of freeze corresponding to the design FI (refer to Figure G-2) for fine-grain soil (Figure G-7) and coarse-grain soil (Figure G-4). The fine-grain soil calculations assumed a γ_d = 100 lb/ft^3 (1600 kg/m^3) and water content = 20 percent. The coarse-grain soil calculations assumed a γ_d = 130 lb/ft^3) (2080 kg/m^3) and water content = 5 percent.

Figure G-5 shows contours of measured depths of freeze as determined during the extremely cold winters of 1949 and 1950 (letter correspondence from B. Tremper, State Materials and Research Engineer to W.A. Bugge, Director of Highways, dated, October 17, 1951). The freeze depths were measured in dug holes often along the edge of the main lanes. The freeze depths were measured during February 1949 and January and February 1950 (a total of 401 holes). Figure G-5 is, in general, similar to Figure G-7 (calculated freeze depths based on Design Freezing Indices and fine-grained soil) with the exception of the Olympic Peninsula which is closer to those results shown in Figure G-4 (coarse-grained soil). Some observations made by Highway Department personnel during the winters of 1949 and 1950:

- Greatest freeze depths were observed in sandy or gravelly soils
- Snow or ice cover substantially reduced the depth of the freeze
- Frost heaving
  - Most heaving observed in coastal areas (higher availability of water)
  - Heaving somewhat infrequent in Eastern Washington but more severe when it did occur (again, likely related to the availability of water (or lack of))
  - Maximum differential heave of 9 inch (225 mm) noted in North Central Region
  - Silty sands showed the largest amount of ice lenses
- Specific Region Comments
  - Northwest Region: Maximum frost depth was measured between Issaquah and North Bend 30 inches (0.8 m). On Camano Island, a 20 inches (0.5 m) frost depth was measured. Maximum differential heave was 4 inches (100 mm) (several district locations).
  - North Central Region: Maximum depth of freeze was 36 inches (0.9 m) measured in 1949 (Wauconda Summit) and 51 inches (1.3 m) in 1950 (between Brewster and Okanogan).
- Olympic Region: Maximum depth of freeze in 1949 was 24 inches (0.6 m) and 17 inches (0.4 m) in 1950.
- Southwest Region: Maximum frost depth was 20 inches (0.5 m) in 1950.

- South Central Region: Maximum frost depth was 30 inches (0.8 m) measured in 1950 with a district-wide average of 24 inches (0.6 m) Differential heave of 6 inches (150 mm) was noted.
- Eastern Region: The maximum depth of freeze was 43 inches (1.1 m) with a district average of 35 inches (0.9 m) measured in 1949. In 1950, the maximum was 48 inches (1.2 m) with a district average of 28 inches (0.7 m)

The statement about SHA frost design needs a bit of explanation. A survey conducted during 1985 [18] revealed the following from several "northern" states:

Agency	Use of Frost Protection in Thickness Design
• Alaska DOT	• More than 50 percent but not full
• Maine DOT	• More than 50 percent but not full
• Montana DOT	• Frost protection not included in design
• North Dakota DOT	• Frost protection not included in design
• Oregon DOT	• More than 50 percent but not full
• Washington DOT	• Depth $>$ 50 percent of maximum frost depth expected

Thus, states such as Alaska, Maine, Oregon, and Washington use knowledge about expected frost depths in the design process. Presumably, limiting the depth of frost into the subgrade soils limits, adequately, the potential for frost heave and thaw weakening for most projects/locations.

The above percentages (pavement structural section as a percentage of expected frost depth) are further reinforced by Japanese practice. Kono et al. [19] reported in 1973 that on the island of Hokkaido the pavement structure is set at 70 percent of the expected frost penetration (the pavement materials are non-frost susceptible).

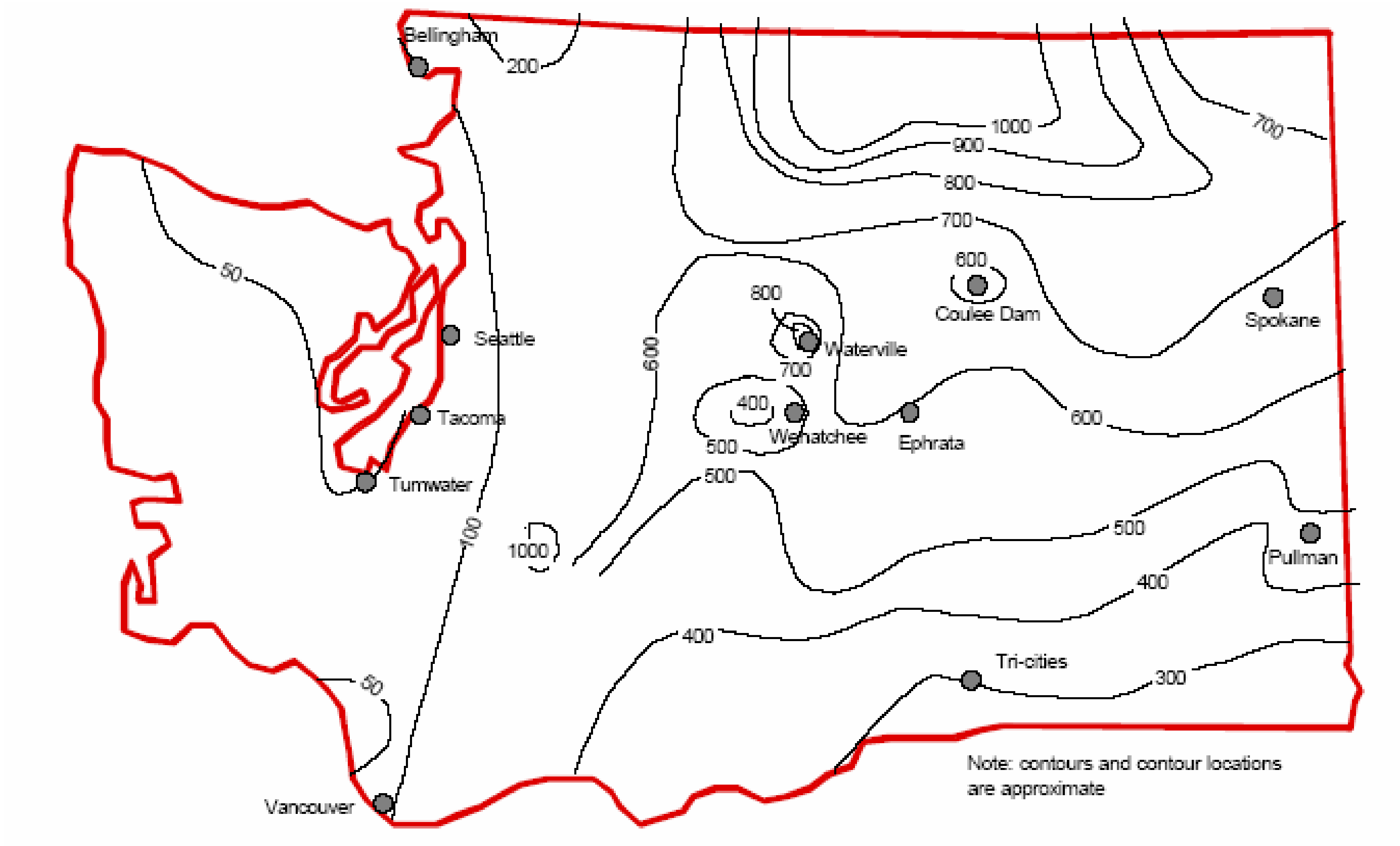


Figure G-1. Mean Annual Freezing Index Contour Map

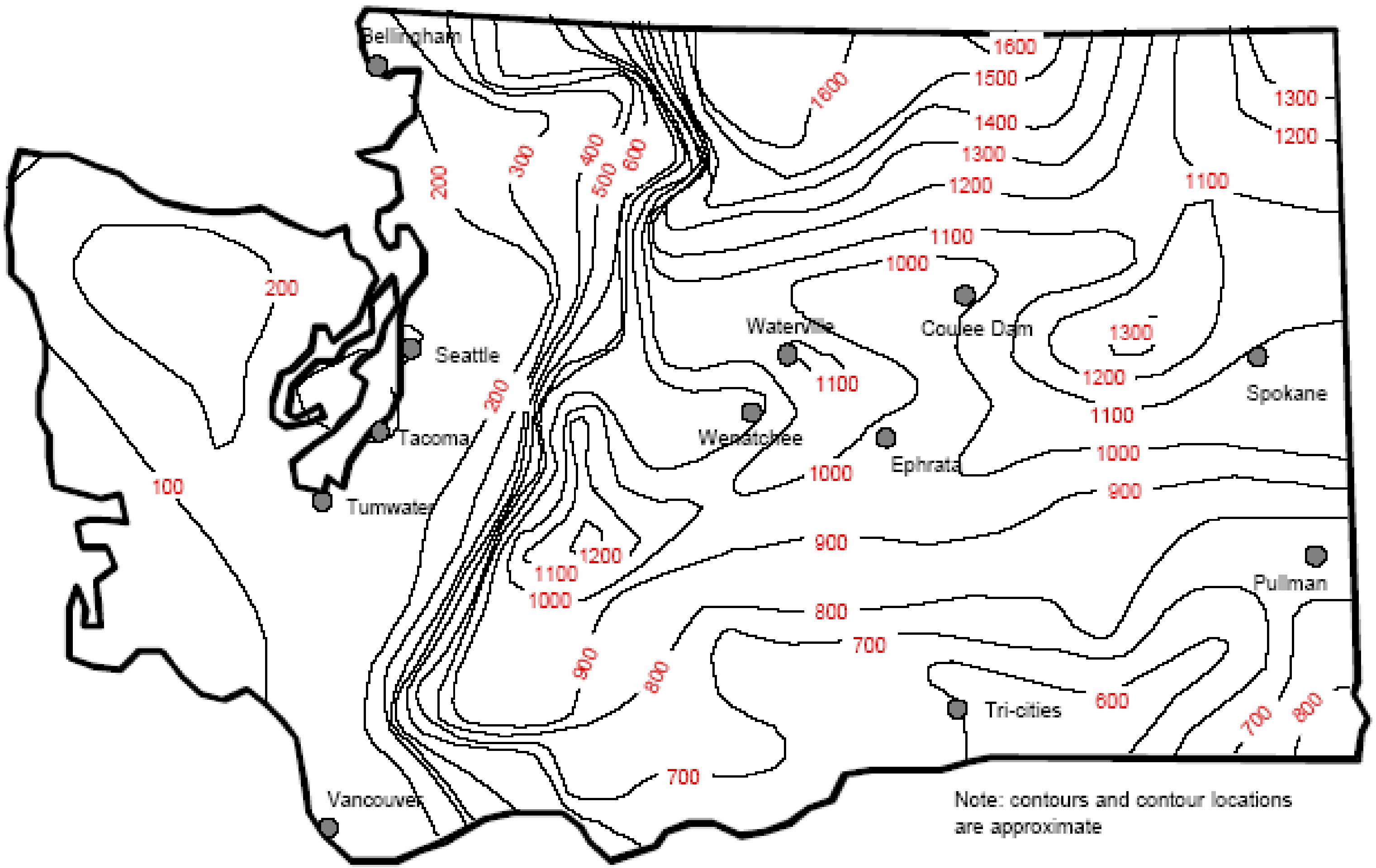


Figure G-2. Design Annual Freezing Index Contour Map

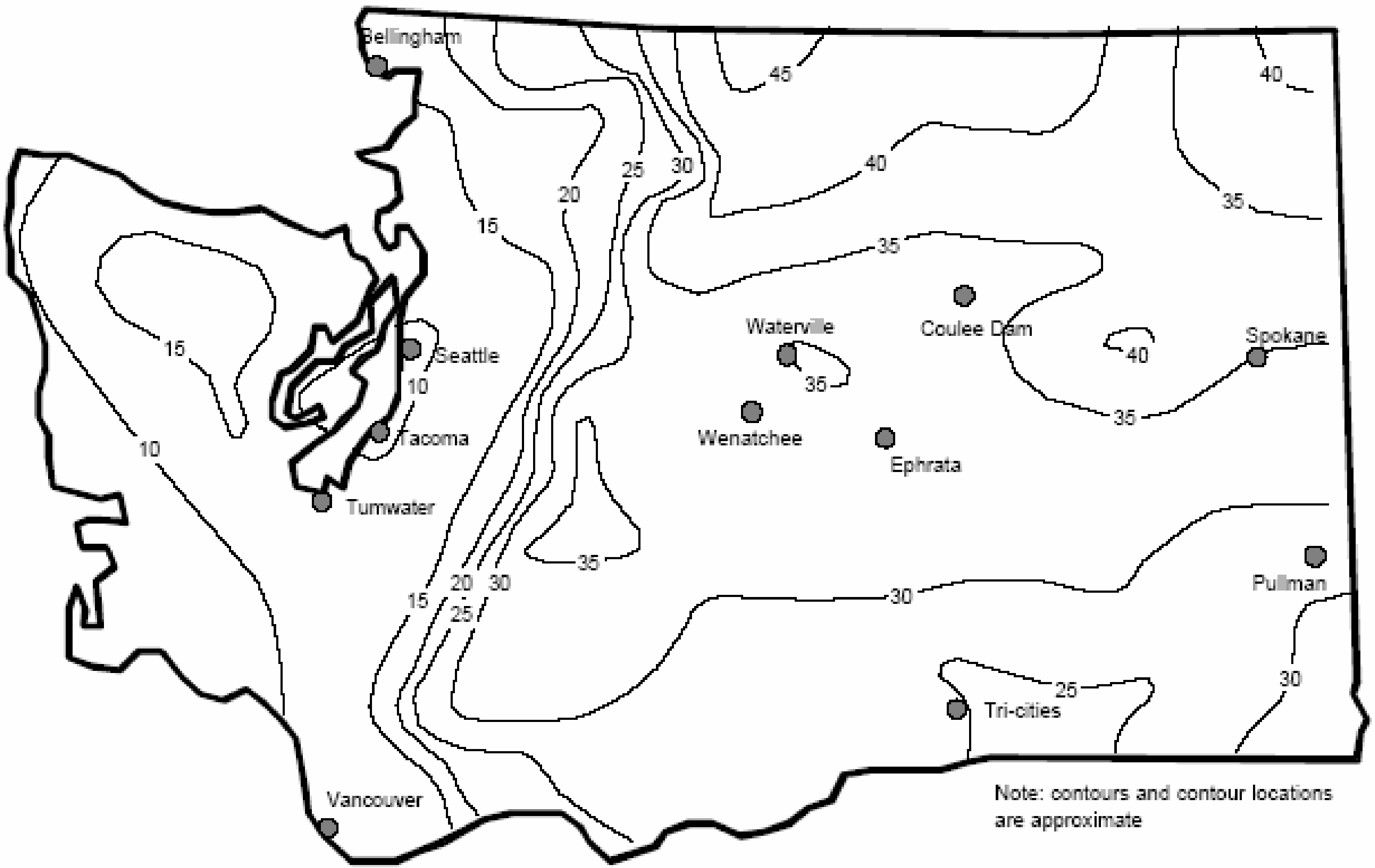


Figure G-3. Frost Depth Contour Map (inches) for Fine Grained Soil (dry density = 100 pcf, wc = 20%)

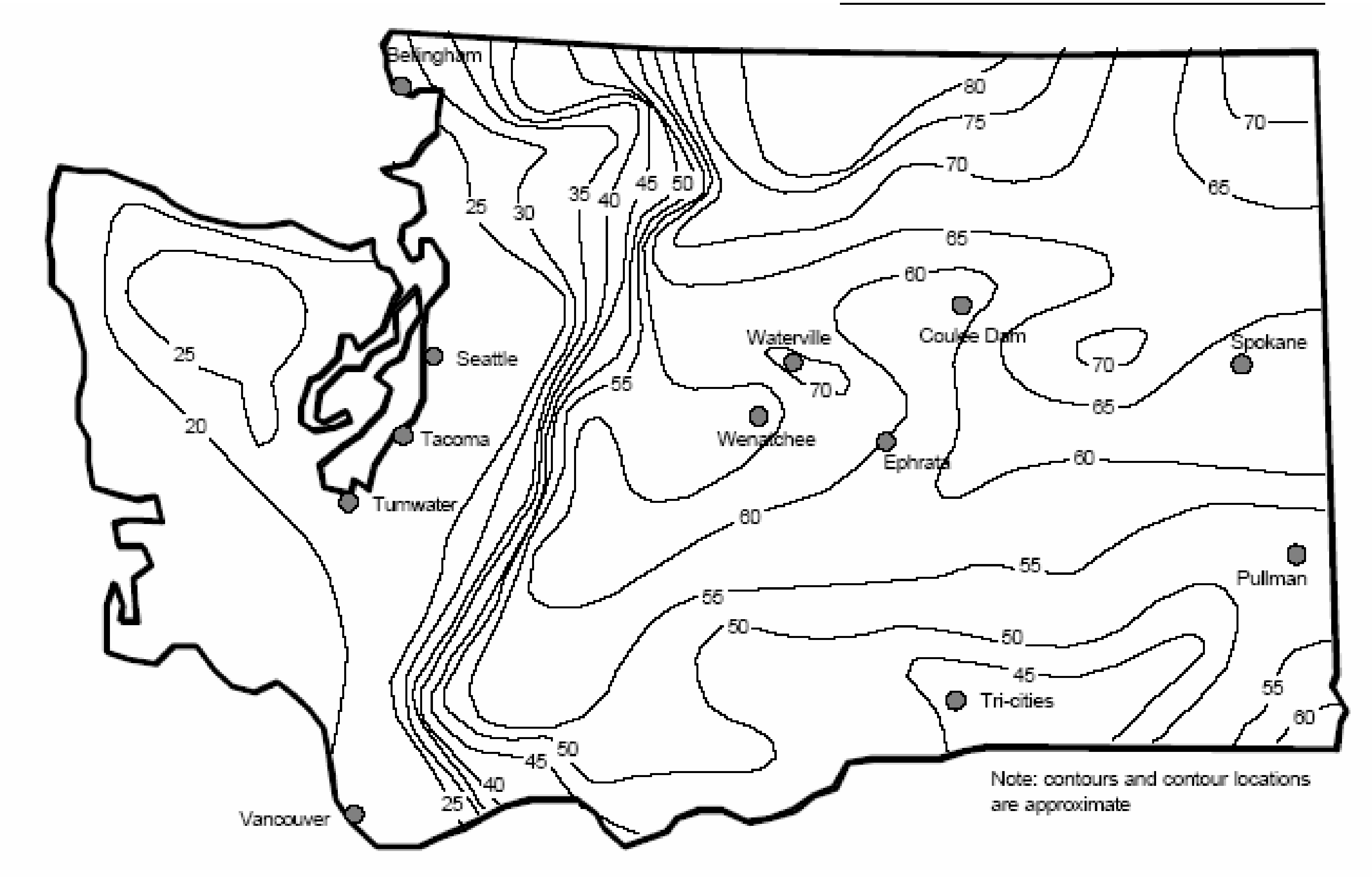


Figure G-4. Frost Depth Contour Map (inches) for Coarse Grained Soil (dry density = 130 pcf, wc = 5%)

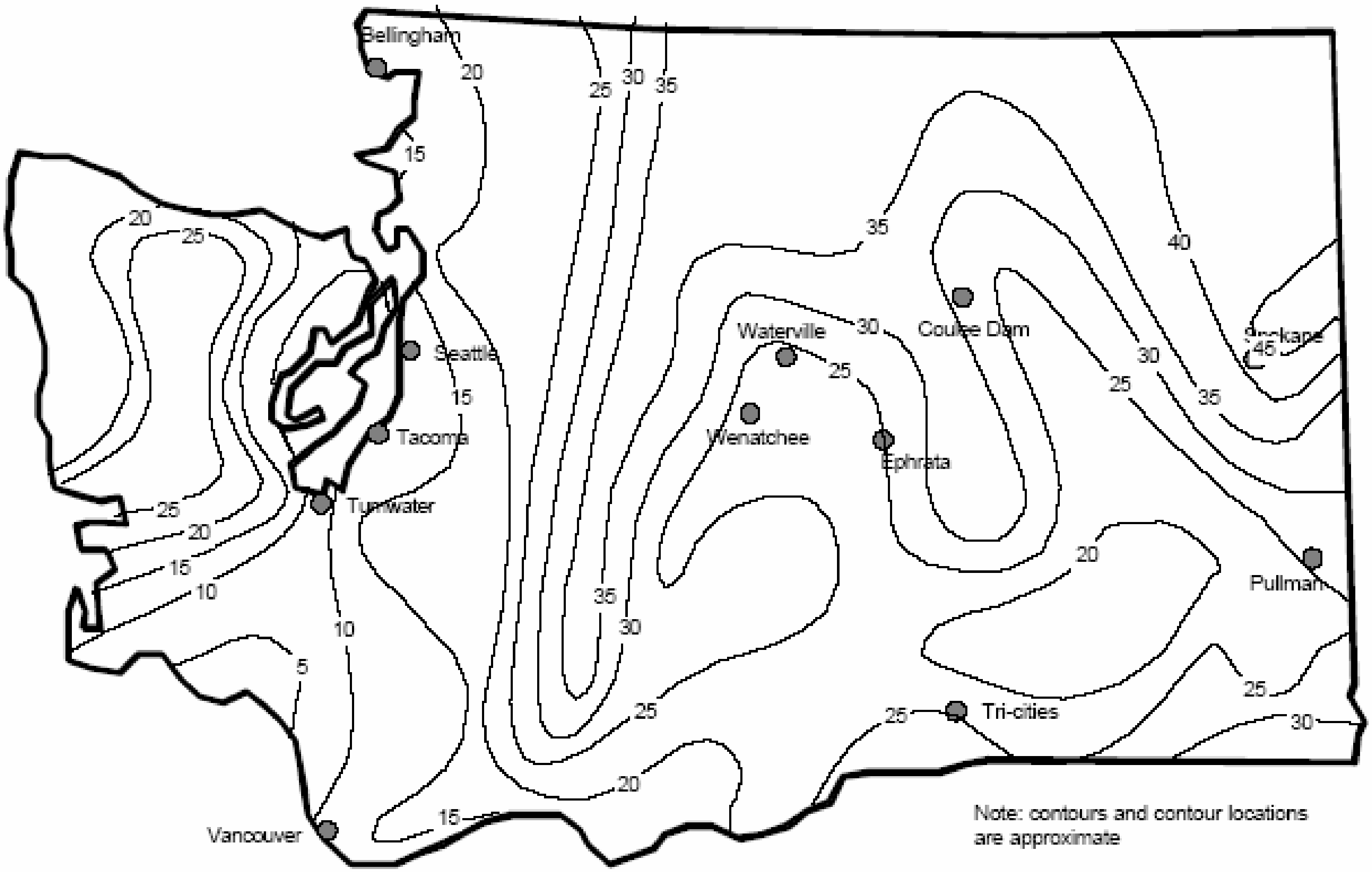


Figure G-5. Frost Depth Contour Map (inches) Based on Field Measurements – Winters of 1949 and 1950

Table G-1. Mean Freezing Indices for Washington State (based on temperature data from 1951 through 1980)

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Aberdeen	18	0	0	0	0	0	0	0	0	0	0	6	24
Anacortes	30	0	0	0	0	0	0	0	0	0	0	7	37
Battle Ground	45	0	0	0	0	0	0	0	0	0	0	8	53
Bellingham	59	6	0	0	0	0	0	0	0	0	0	18	83
Bellingham Airport	67	7	0	0	0	0	0	0	0	0	0	23	97
Bickleton	231	68	18	7	0	0	0	0	0	0	0	42	120
Blaine	68	7	0	0	0	0	0	0	0	0	0	25	100
Bremerton	20	0	0	0	0	0	0	0	0	0	0	8	28
Buckly	40	8	0	0	0	0	0	0	0	0	0	17	65
Cedar Lake	85	26	10	0	0	0	0	0	0	0	9	140	70
Centralia	29	0	0	0	0	0	0	0	0	0	0	8	37
Chelan	262	110	10	0	0	0	0	0	0	0	29	149	560
Chewelah	339	150	35	0	0	0	0	0	0	0	62	216	802
Chief Joseph Dam	293	136	17	0	0	0	0	0	0	0	34	175	655
Clearbrook	103	13	0	0	0	0	0	0	0	0	6	39	161
Clearwater	22	0	0	0	0	0	0	0	0	0	0	6	28
Cle Elum	268	94	22	0	0	0	0	0	0	0	48	151	583
Colfax	226	45	9	0	0	0	0	0	0	0	29	99	408
Colville	321	119	29	0	0	0	0	0	0	0	75	221	765
Concrete	57	9	0	0	0	0	0	0	0	0	0	18	84
Coulee Dam	284	107	14	0	0	0	0	0	0	0	35	155	595
Coupeville	28	0	0	0	0	0	0	0	0	0	0	11	39
Dallesport Airport	179	14	0	0	0	0	0	0	0	0	8	52	253
Davenport	315	133	25	0	0	0	0	0	0	0	66	198	737
Dayton	206	30	0	0	0	0	0	0	0	0	18	61	315
Diablo Dam	126	23	9	0	0	0	0	0	0	0	10	54	222
Electron Headworks	78	20	8	0	0	0	0	0	0	0	8	40	154
Elma	22	0	0	0	0	0	0	0	0	0	0	7	29
Elwha Rngr Station	47	6	0	0	0	0	0	0	0	0	0	14	67
Ephrata Airport	285	98	5	0	0	0	0	0	0	0	41	167	596
Everett	35	0	0	0	0	0	0	0	0	0	0	11	46
Forks	22	5	0	0	0	0	0	0	0	0	0	10	37
Glenoma	47	9	0	0	0	0	0	0	0	0	0	17	73
Grapeview	17	0	0	0	0	0	0	0	0	0	0	7	24
Hatton	266	54	0	0	0	0	0	0	0	0	43	124	487
Hoquiam	15	0	0	0	0	0	0	0	0	0	0	9	24
Kennewick	202	26	0	0	0	0	0	0	0	0	18	54	300
Kent	28	0	0	0	0	0	0	0	0	0	0	8	36
Kid Valley	43	8	0	0	0	0	0	0	0	0	0	16	67

Table G-1. Freezing Indices for Washington State, continued

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Lacrosse	248	42	0	0	0	0	0	0	0	0	30	103	423
Landsburg	48	8	0	0	0	0	0	0	0	0	0	15	71
Laurier	350	121	35	0	0	0	0	0	0	0	82	238	826
Lind	266	62	0	0	0	0	0	0	0	0	43	126	497
Longview	36	0	0	0	0	0	0	0	0	0	0	6	42
Millin Reservoir	42	6	0	0	0	0	0	0	0	0	0	13	61
Monroe	38	0	0	0	0	0	0	0	0	0	0	14	52
Moses Lake	292	92	0	0	0	0	0	0	0	0	50	153	587
Mt. Adams Rngr Sta.	197	48	22	0	0	0	0	0	0	0	31	90	388
Moxee City	263	63	0	0	0	0	0	0	0	0	31	134	491
Mud Mtn. Dam	56	15	5	0	0	0	0	0	0	0	0	21	97
Newhalem	88	18	6	0	0	0	0	0	0	0	7	39	158
Newport	306	112	49	0	0	0	0	0	0	0	73	199	739
Northport	275	94	19	0	0	0	0	0	0	0	46	174	608
Oakville	35	0	0	0	0	0	0	0	0	0	0	10	45
Odessa	273	82	9	0	0	0	0	0	0	0	41	144	549
Olga	29	0	0	0	0	0	0	0	0	0	0	11	40
Olympia	31	5	0	0	0	0	0	0	0	0	0	15	51
Omak	344	175	28	0	0	0	0	0	0	0	67	234	848
Othello	276	64	0	0	0	0	0	0	0	0	35	125	500
Palmer	58	14	5	0	0	0	0	0	0	0	0	25	102
Pomeroy	201	32	7	0	0	0	0	0	0	0	22	66	328
Port Angeles	14	0	0	0	0	0	0	0	0	0	0	6	20
Prosser	240	46	0	0	0	0	0	0	0	0	22	84	392
Pullman	243	77	0	0	0	0	0	0	0	0	38	118	476
Puyallup	30	0	0	0	0	0	0	0	0	0	0	11	41
Quilcene	39	5	0	0	0	0	0	0	0	0	0	14	58
Quillayute	22	5	0	0	0	0	0	0	0	0	0	9	36
Quincy	303	106	9	0	0	0	0	0	0	0	51	189	658
Paradise	254	161	161	85	27	9	0	0	9	19	103	219	1047
Republic	408	170	73	0	0	0	0	0	0	0	117	304	1072
Richland	199	28	0	0	0	0	0	0	0	0	13	54	294
Ritzville	281	94	10	0	0	0	0	0	0	0	42	143	570
Rosalia	269	94	22	0	0	0	0	0	0	0	49	142	576
Seattle	11	0	0	0	0	0	0	0	0	0	0	6	17
Sea-Tac	24	6	0	0	0	0	0	0	0	0	0	9	39
Sea U.W.	14	0	0	0	0	0	0	0	0	0	0	6	20
Sedro Wooley	46	6	0	0	0	0	0	0	0	0	0	15	67
Sequim	20	0	0	0	0	0	0	0	0	0	0	8	28
Shelton	21	0	0	0	0	0	0	0	0	0	0	8	29
Snqlm. Falls	44	10	0	0	0	0	0	0	0	0	0	16	70
Spokane	299	108	24	0	0	0	0	0	0	0	58	178	667
Sprague	287	94	14	0	0	0	0	0	0	0	48	148	591

Table G-1. Mean Freezing Indices for Washington State, continued

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Stampede Pass	283	150	116	48	13	0	0	0	0	9	105	213	937
Startup	38	7	0	0	0	0	0	0	0	0	0	13	58
Stehekin	195	70	12	0	0	0	0	0	0	0	44	127	448
Sunnyside	216	35	0	0	0	0	0	0	0	0	16	73	340
Tacoma City Hall	17	0	0	0	0	0	0	0	0	0	0	7	24
Vancouver	57	0	0	0	0	0	0	0	0	0	0	8	65
Walla-Walla Airport	192	24	0	0	0	0	0	0	0	0	18	59	293
Walla-Walla	188	20	0	0	0	0	0	0	0	0	14	50	272
Wapato	214	36	0	0	0	0	0	0	0	0	18	80	348
Waterville	349	152	51	0	0	0	0	0	0	0	84	246	882
Wenatchee	233	83	0	0	0	0	0	0	0	0	22	128	466
Wilbur	306	126	20	0	0	0	0	0	0	0	53	189	694
Willapa Harbor	12	0	0	0	0	0	0	0	0	0	0	0	12
Wilson Creek	276	79	6	0	0	0	0	0	0	0	42	163	566
Winthrop	451	206	65	0	0	0	0	0	0	0	108	342	1172
Yakima	258	63	0	0	0	0	0	0	0	0	31	123	475

Source: U.S. Department of Commerce, "Degree Days to Selected Bases," National Climatic Center, Federal Building, Asheville, N.C., December 1982.