Table I.3. Reduction in Performance Period (Service Life) Arising from Swelling Consideration

Initial Pavement Thickness 10.0

Maximum Possible Performance Period (years) 25

Design Serviceability Loss, $\Delta PSI = p_o - p_t =$ $4.5 - 2.5 = 2.0$

(1) Iteration No.	(2) Trial Performance Period (years)	(3) Serviceability Loss Due to Roadbed Swelling ΔPSI_{SW}	(4) Corresponding Serviceability Loss Due to Traffic ΔPSI_{TR}	(5) Allowable Cumulative Traffic (18-kip ESAL)	(6) Corresponding Performance Period (years)
1	20.0	0.25	1.75	4.6×10^6	22.9
2	21.5	0.26	1.74	4.5×10^6	22.8

Step 6. Using Figure I.1, the time corresponding to 4.6×10^6 18-kip ESAL applications is approximately 22.9 years (Column 6).

Step 7. Since the pavement life calculated in Step 6 is not within 1 year of the trial performance period, the iterative process must continue. The trial performance period is now 21.5 years and the process returns to Step 3. The results of the second iteration indicate that regardless of the trial estimate for the performance period, the outcome in Column 6 will always be about 23 years. Thus, no more iterations are required.

For this particular example design, the pavement cross section consists of a 9-inch jointed reinforced concrete slab with 6 inches of granular subbase and a drainage system that removes water in less than 1 day. This structure will reach its terminal serviceability in approximately 23 years. Thus, to complete the design strategy, an overlay must be designed to carry the remaining 18-kip ESAL traffic over the last 12 years of the analysis period.

I.3 REINFORCEMENT DESIGN

The nomograph for estimating the percent of steel reinforcement required in a jointed reinforced concrete pavement is presented in Figure 3.8 in Part II. The inputs to this nomograph for this design example are as follows:

(1) slab length, L = 30 feet
(2) steel working stress, f_s = 45,000 psi
(3) friction factor, F = 1.5

Application of the nomograph for these conditions results in a required longitudinal steel reinforcing percentage of 0.05 percent. Since there are three 12-foot lanes and a 10-foot-wide PCC shoulder (all tied at the longitudinal joints), the transverse steel percentage required is somewhat higher (0.075 percent).

Tie Bar Design

Since the pavement will consist of three 12-foot-wide PCC lanes with a 10-foot-wide (tied) PCC shoulder on the outside lane, the distances to the nearest free edge (as illustrated in Figure I.3) are 12, 22, and 10 feet for longitudinal joints 1, 2, and 3, respectively. Thus, for the 9-inch slab, the maximum recommended tie bar spacing for each joint (as determined from Part II, Figures 3.13 and 3.14) are as follows:

Long. Joint No.	Distance to the Closest Free Edge, x (feet)	Maximum Spacing (inches)	
		1/2-inch Bars	5/8-inch Bars
1	12	36	48
2	22	20	30
3	10	42	48

If 1/2-inch tie bars are used, the minimum overall length should be 25 inches. If 5/8-inch tie bars are used, then the minimum overall length should be 30 inches.

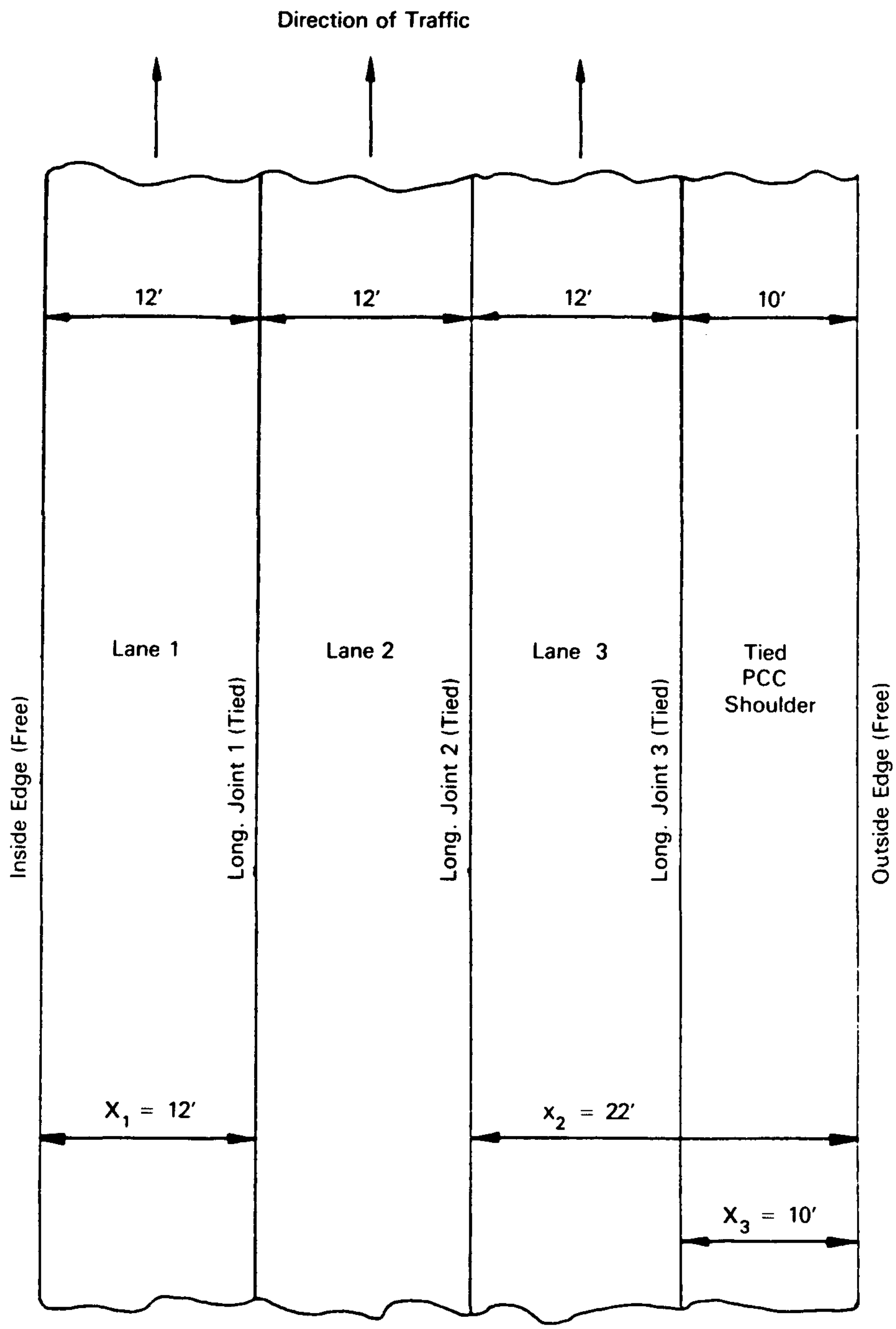

Figure I.3. Plan View of Three-Lane Facility Showing Longitudinal Joint Positions and Corresponding Distances to Nearest Free Edge

Dowel Bar Design

Dowel bar design is described in Section 2.4.4 of Part II. For this design example, the dowel spacing is 12 inches and the dowel length is 18 inches. The dowel diameter is equal to slab thickness (9 inches) multiplied by $^1/_8$, or 1 and $^1/_8$ inches.

APPENDIX J
ANALYSIS UNIT DELINEATION BY CUMULATIVE DIFFERENCES

J.1 APPROACH FUNDAMENTALS

A relatively straightforward and powerful analytical method for delineating statistically homogenous units from pavement response measurements along a highway system is the cumulative difference approach. While the methodology presented is fundamentally easy to visualize, the manual implementation for large data bases becomes very time-consuming and cumbersome. However, the approach is presented because it is readily adaptable to a computerized (microcomputer) solution and graphic analysis. This approach can be used for a wide variety of measured pavement response variables such as deflection, serviceability, skid resistance, pavement distress-severity indices, etc.

Figure J.1 illustrates the overall approach concept using the initial assumptions of a continuous and constant response value (r_i) within various intervals (0 to x_1; x_1 to x_2; x_2 to x_3) along a project length. From this figure, it is obvious that *three* unique units having different response magnitudes (r_1, r_2, and r_3) exist along the project. Figure J.1(a) illustrates such a response-distance result. If one were to determine the trend of the cumulative area under the response-distance plot, Figure J.1(b) would result. The solid line indicates the results of the actual response curves. Because the functions are continuous and constant within a unit, the cumulative area, at any x, is simply the integral or

$$A = \int_0^{x_1} r_1\,dx + \int_{x_1}^{x} r_2\,dx \qquad (J.1)$$

with each integral being continuous within the respective intervals:

$$(0 \le x \le x_1) \text{ and } (x_1 \le x \le x_2)$$

In Figure J.1(b), the dashed line represents the cumulative area caused by the overall *average* project response. It should be recognized that the slopes (derivatives) of the cumulative area curves are simply the response value for each unit (r_1, r_2, and r_3) while the slope of the dashed line is the overall average response value of the entire project length considered. At the distance, x, the cumulative area of the average project response is:

$$A_x = \int_0^{x} r\,dx \qquad (J.2)$$

with

$$\bar{r} = \frac{\int_0^{x_1} r_1\,dx + \int_{x_1}^{x_2} r_2\,dx + \int_{x_2}^{x_3} r_3\,dx}{L_p} = \frac{A_T}{L_p}$$

and therefore

$$\bar{A}_x = L_p \times A_T$$

Knowing both A_x and A_x allows for the determination of the cumulative difference variable Z_x from:

$$Z_x = A_x - \bar{A}_x$$

As noted in Figure J.1(b), Z_x is simply the difference in cumulative area values, at a given x, between the actual and project average lines. If the Z_x value is, in turn, plotted against distance, x, Figure J.1(c) results. An examination of this plot illustrates that the location of unit boundaries always coincides with the location (along x) where the slope of the Z_x function changes algebraic signs (i.e., from negative to positive or vice versa). This fundamental concept is the ultimate basis used to analytically determine the boundary location for the analysis units.

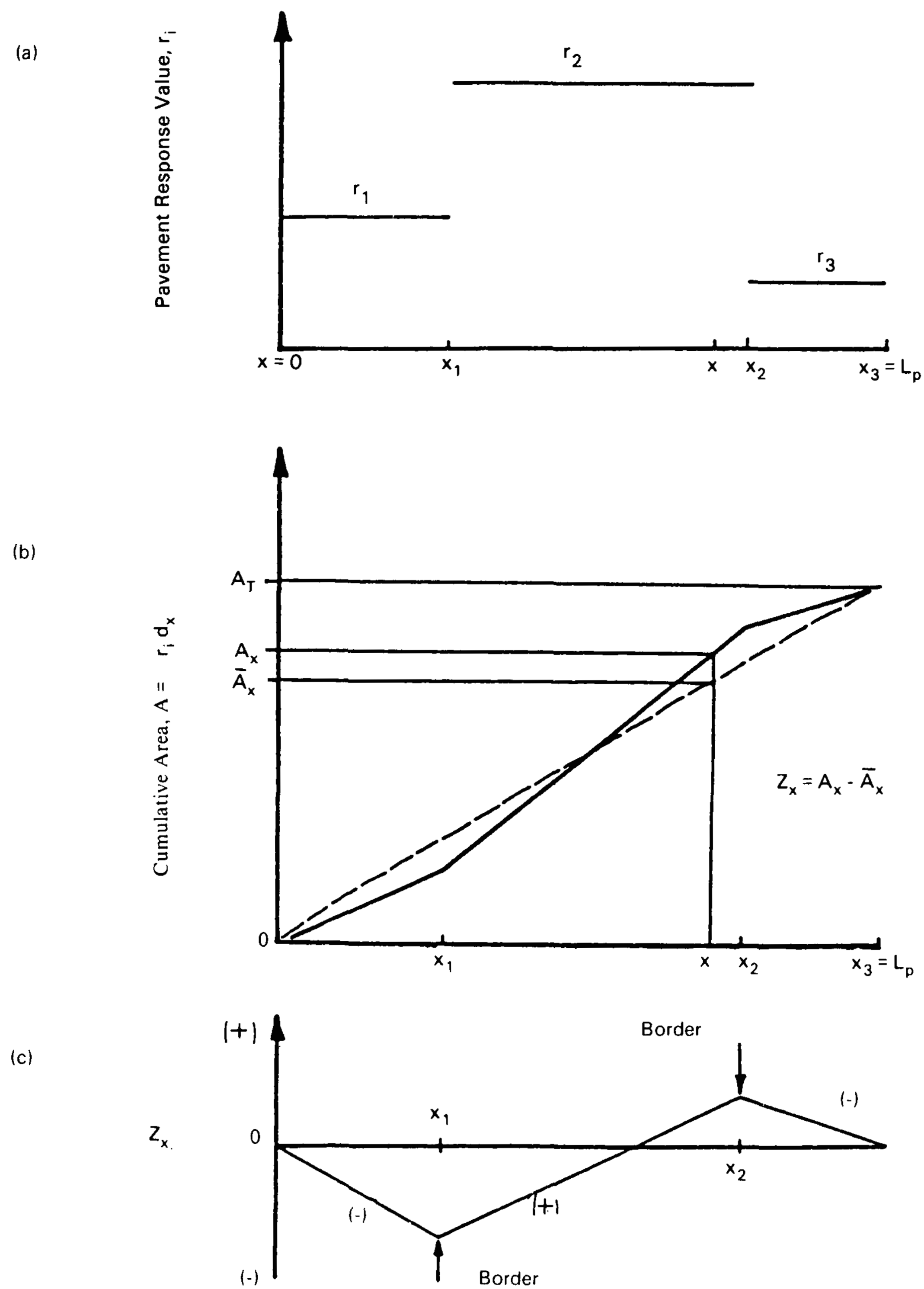

Figure J.1. Concepts of Cumulative Difference Approach to Analysis Unit Delineation

J.2 APPLICATION TO DISCONTINUOUS VARIABLES

The schematic figures shown in Figure J.1 are obviously highly idealized. In practice, measurements are normally discontinuous (point measurements), frequently obtained at unequal intervals and never constant, even within a unit. In order to apply the foregoing principles into a solution methodology capable of dealing with these conditions, a numerical difference approach must be used. The form of the Z_x function is:

$$Z_X = \sum_{i=1}^{n} a_i - \frac{\sum_{i=1}^{n} a_i}{L_p} \sum_{i=1}^{n} x_i$$

with

$$a_i = \frac{(r_{i-1} + r_i) \times x_i}{2} = \bar{r}_i \times x_i \qquad \text{(J.6)}$$

(NOTE: let $r_o = r_1$ for first interval)

where

n = the nth pavement response measurement,
n_t = total number of pavement response measurements taken in project,
r_i = pavement response value of the ith measurement,
r_i = average of the pavement response values between the $(i - 1)$ and ith tests, and
L_p = total project length.

If equal pavement testing intervals are used:

$$Z_x = \sum_{i=1}^{n} a_i - \frac{n}{n_t} \sum_{i=1}^{n_t} a_i$$

J.3 TABULAR SOLUTION SEQUENCE

Table J.1 is a table illustrating how the solution sequence progresses and the necessary computational steps required for an unequal interval analysis. The table and entries should be self-explanatory.

J.4 EXAMPLE ANALYSIS

In Part III, Chapter 3, actual results were shown for an analysis unit delineation based upon a field Skid Number test survey: SN(40). Table J.2 is a partial summary of the analysis, indicating only the initial and final portions of the analysis for brevity. This tabular data and solution forms the basis of the information shown in Part III, Figures 3.3 and 3.4.

Table J.1. Tabular Solution Sequence—Cumulative Difference Approach

Col. (1) Station (Distance)	Col. (2) Pavement Response Value (r_i)	Col. (3) Interval Number (n)	Col. (4) Interval Distance (Δx_i)	Col. (5) Cumulative Interval Distance $(\Sigma \Delta x_i)$	Col. (6) Average Interval Response $(\bar{r}_i)$	Col. (7) Actual Interval Area (a_i)	Col. (8) Cumulative Area Σa_i	Col. (9) Z_x Value $Z_x =$ Col. (8) − F* Col. (5)
		1	Δx_1	Δx_1	$\bar{r}_1 = r_1$	$a_1 = \bar{r}_1 \Delta x_1$	a_1	$Z_{x_1} = a_1 - F^* \Delta x_1$
1	r_1							
		2	Δx_2	$(\Delta x_1 + \Delta x_2)$	$\bar{r}_2 = \frac{(r_1 + r_2)}{2}$	$a_2 = \bar{r}_2 \Delta x_2$	a	$Z_{x_2} = (a_1 + a_2) - F^*(\Delta x_1 + \Delta x_2)$
2	r_2							
		3	Δx_3	$(\Delta x_1 + \Delta x_2 + \Delta x_3)$	$\bar{r}_3 = \frac{(r_2 + r_3)}{2}$	$a_3 = \bar{r}_3 \Delta x_3$	$a_1 + a_2 + a_3$	
3	r_3							
		N_t	Δx_{nt}	$(\Delta x_1 + \cdots + \Delta x_{nt})$	$\bar{r}_{nt} = \frac{(r_{n-1} + r_n)}{2}$	$a_{nt} = \bar{r}_{nt} \Delta x_{nt}$	$a_1 + \cdots + a_{2t}$	$Z_{xnt} = (a_1 + \cdots + a_{nt}) - F^*(\Delta x_1 + \cdots + \Delta x_{nt})$
L_p	r_n							
							$A_t = \sum_{i=1}^{h_t} a_i$	
							$F^* = \frac{A_t}{L_p}$	

Table J.2. Cumulative Difference Example Problem (SN – 40)

Col. (1) Station (Distance)	Col. (2) SN (40) Value	Col. (3) Interval Number	Col. (4) Interval Distance	Col. (5) Cumulative Distance	Col. (6) Avg. Interval SN (40)	Col. (7) Actual Interval Area	Col. (8) Cumulative Area	Col. (9) Z_x Value
0.5 mi	23	1	0.5	0.5	23	11.50	11.50	11.50 – 31.49(0.5) = –4.25
1.0	26	2	0.5	1.0	24.5	12.25	23.75	23.75 – 31.49(1.0) = –7.74
1.5	23	3	0.5	1.5	24.5	12.25	36.00	36.00 – 31.49(1.5) = –11.24
2.0	24	4	0.5	2.0	23.5	11.75	47.75	47.75 – 31.49(2.0) = –15.23
2.5	26	5	0.5	2.5	25.0	12.50	60.25	60.25 – 31.49(2.5) = –18.48
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
74.0	27	148	0.5	74.0	29.5	14.75	2340.00	2340 – 31.49(74) = +9.74
74.5	25	149	0.5	74.5	26.0	13.00	2353.00	2353.00 – 31.49(74.5) = +7.00
75.0	28	150	0.5	75.0	26.5	13.25	2366.25	2366.25 – 31.49(75.0) = +4.50
75.5	26	151	0.5	75.5	27.0	13.50	2379.75	2379.75 – 31.49(75.5) = +2.26
76.0	28	152	0.5	76.0	27.0	13.50	2393.25	2393.25 – 31.49(76.0) = +0.00
							A_t = 2393.25	
							L_p = 76.0	
							F^* = 31.49	

APPENDIX K
TYPICAL PAVEMENT DISTRESS TYPE-SEVERITY DESCRIPTIONS

TYPICAL PAVEMENT DISTRESS TYPE-SEVERITY DESCRIPTIONS

This appendix contains general descriptions of the major types of distress that may be encountered in both flexible (asphalt concrete) and rigid pavements. Also noted is a typical description of three distress severity levels associated with each distress. This information has been obtained from FHWA/RD-81/080 study "A Pavement Moisture Accelerated Distress Identification System." These descriptions are provided as a guide to user agencies only and should not be viewed as a standard method for distress type-severity identification. This information, along with an estimate of the amount of each distress-severity combination, represents an example of the minimum information needs required for a thorough condition (distress) survey.

NOTE: In presenting the distress types and severity descriptions, the following letters refer to different levels of severity:

L—Low M—Medium H—High

K.1 DISTRESS TYPES (ASPHALT SURFACED PAVEMENTS)

Name of Distress: Alligator or Fatigue Cracking

Description:

Alligator or fatigue cracking is a series of interconnecting cracks caused by fatigue failure of the asphalt concrete surface (or stabilized base) under repeated traffic loading. The cracking initiates at the bottom of the asphalt surface (or stabilized base) where tensile stress and strain is highest under a wheel load. The cracks propagate to the surface initially as one or more longitudinal parallel cracks. After repeated traffic loading, the cracks connect, forming many-sided, sharp-angled pieces that develop a pattern resembling chicken wire or the skin of an alligator. The pieces are usually less than 1 foot on the longest side. Alligator cracking occurs only in areas that are subjected to repeated traffic loadings. Therefore, it would not occur over an entire area unless the entire area was subjected to traffic loading. Alligator cracking does not occur in asphalt overlays over concrete slabs. Pattern-type cracking which occurs over an entire area that is *not* subjected to loading is rated as block cracking which is not a load-associated distress. Alligator cracking is considered a major structural distress.

Severity Levels:

L—Longitudinal disconnected hairline cracks running parallel to each other. The cracks are not spalled. Initially there may only be a single crack in the wheel path (defined as Class 1 cracking at AASHO Road Test).

M—Further development of low-severity alligator cracking into a pattern of pieces formed by cracks that may be lightly surface-spalled. Cracks may be sealed (defined as Class 2 cracking at AASHO Road Test).

H—Medium alligator cracking has progressed so that pieces are more severely spalled at the edges and loosened until the cells rock under traffic. Pumping may exist (defined as Class 3 cracking at AASHO Road Test).

How to Measure:

Alligator cracking is measured in square feet or square meters of surface area. The major difficulty in measuring this type of distress is that many times, two or three levels of severity exist within one distressed area. If these portions can be easily distinguished from each other, they should be measured and recorded separately. However, if the different levels

Table K.1. Identification of Distress Types

Asphalt Surfaced Pavements	Jointed Reinforced Concrete Pavements
1. Alligator or Fatigue Cracking	1. Blow-Up
2. Bleeding	2. Corner Break
3. Block Cracking	3. Depression
4. Corrugation	4. Durability ("D") Cracking
5. Depression	5. Faulting-Transverse Joints/Cracks
6. Joint Reflection Cracking from PCC Slab	6. Joint Load Transfer System Deterioration
7. Lane/Shoulder Dropoff or Heave	7. Seal Damage-Transverse Joints
8. Lane/Shoulder Joint Separation	8. Lane/Shoulder Dropoff or Heave
9. Longitudinal and Transverse Cracking (Non-PCC Slab Joint Reflective)	9. Lane/Shoulder Joint Separation
	10. Longitudinal Cracks
10. Patch Deterioration	11. Longitudinal Joint Faulting
11. Polished Aggregate	12. Patch Deterioration
12. Potholes	13. Patch Adjacent Slab Deterioration
13. Pumping and Water Bleeding	14. Popouts
14. Raveling and Weathering	15. Pumping and Water Bleeding
15. Rutting	16. Reactive Aggregate Distress
16. Slippage Cracking	17. Scaling and Map Cracking
17. Swell	18. Spalling (Transverse and Longitudinal Joint/Crack)
	19. Spalling (Corner)
	20. Swell
	21. Transverse and Diagonal Cracks

of severity cannot be easily divided, the entire area should be rated at the highest severity level present.

Name of Distress: Bleeding

Description:

Bleeding is a film of bituminous material on the pavement surface which creates a shiny, glass-like, reflecting surface that usually becomes quite sticky. Bleeding is caused by excessive amounts of asphalt cement in the mix and/or low air void contents. It occurs when asphalt fills the voids of the mix during hot weather and then expands out onto the surface of the pavement. Since the bleeding process is not reversible during cold weather, asphalt will accumulate on the surface.

Severity Levels:

No degrees of severity are defined. Bleeding should be noted when it is extensive enough to cause a reduction in skid resistance.

How to Measure:

Bleeding is measured in square feet or square meters of surface area.

Name of Distress: Block Cracking

Description:

Block cracks divide the asphalt surface into approximately *rectangular* pieces. The blocks range in size from approximately 1 ft^2 to 100 ft^2. Cracking into larger blocks are generally rated as longitudinal and transverse cracking. Block cracking is caused mainly by shrinkage of the asphalt concrete and daily temperature cycling (which results in daily stress/strain cycling). *It is not load-associated*, although load can increase the severity of individual cracks from low to medium to high. The occurrence of block cracking usually indicates that the asphalt has hardened significantly. Block cracking normally occurs over a large proportion of pavement area, but sometimes will occur only in nontraffic areas. This type of distress dif-