AASHTO Flexible Pavement Design Method: Fact or Fiction?

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In 1986 AASHTO published the *AASHTO Guide for Design of Pavement Structures*. This new publication incorporates the original development of the Road Test data combined with some extensions applying theoretical and empirical models. A review of this document, the superseded interim guides, technical literature, and the original Road Test reports revealed a number of opportunities for reexamining the Road Test results. These opportunities included an evaluation of the patterns of performance contained in the raw data, an examination of the mathematical formulation of the performance and design equations, and a probabilistic analysis of the Road Test results, treating the layer coefficient as a distributed random variable instead of as a uniquely determined number.

The flexible pavement design method of AASHTO is now well established: the final edition of a series of interim guides was recently (1986) adopted by AASHTO. This document (*1*) adds significant volume and some additional factors to the design process. Specifically, the new AASHTO guide incorporates the original development of the Road Test data with more recent additions relating to subsurface (internal) drainage, materials, reliability, and others.

One interesting observation is that the developments in the new guide appear to accept the original AASHTO formulations as a starting point. Taking this approach ignores the wealth of information contained in the original AASHO Road Test data. New analytical techniques, additional years of experience with pavement performance, and much hard thinking on the results of the Road Test provide an opportunity that was missed in developing the new Guide. In lieu of a fundamental approach, the developments presented in the new Guide that affect the design procedure were evolved by a combination of theoretical and empirical models. The cause and effect of the actual AASHO Road Test performance is not incorporated.

The AASHTO methodology is used by a number of states in some form or another. In many cases, states have modified details of the method to better suit their peculiar circumstances and experience. Other states have made modification only to the various constants in the original formulation. Overall, some of the statistical constants and coefficients originally developed in the analysis of the Road Test results have taken on physical meanings that are not valid.

A recent research project initiated by the Indiana Department of Transportation (INDOT) required the authors to determine the "layer coefficients" for the ten bituminous mixtures currently being specified in Indiana. INDOT uses the original AASHO formulation with their own set of layer coefficients. However, INDOT has recognized that, although the range of mixtures specified represents a vast array of performance characteristics, the assignment of a single-layer coefficient to characterize them is both unrealistic in engineering terms and inefficient in financial benefit.

As part of the preliminary research task, a literature review was undertaken. In the review of the literature, a specific effort was made to establish the definition of layer coefficient and the original method for calculating this parameter. The results of this otherwise simple task initially proved to be highly disturbing. Subsequently, further analysis highlighted some interesting possibilities. This paper is about the findings and conclusions of this preliminary part of the project.

Much of this preliminary research is definitive, although some is still speculative, since the project is ongoing.

LAYER COEFFICIENT

Considerable disagreement is apparent about both the definition and the recommended method of measurement of layer coefficients.

For example, the following statements are from the 1986 AASHTO Guide (*1*):

- "The structural number is an abstract number . . . converted to actual thickness of surfacing, base and subbase, by means of appropriate layer coefficients representing the relative strength of the construction materials."
- "In effect, the layer coefficients are based on the elastic moduli M_R and have been determined based on stress and strain calculations in a multilayered pavement system" (Section 1.2).
- ". . . it is not essential that elastic moduli of these materials are characterized. In general, layer coefficients derived from test roads or satellite sections are preferred" (Section 2.3.3).

At the International Conference on the Structural Design of Asphalt Pavements, Shook and Finn (*2*) stated the following:

"It is believed that the coefficients a_1, a_2, a_3 are functions of the strengths of the various layers involved. At the present time (1962), however, no entirely satisfactory techniques are available for defining or measuring these strength factors."

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Perusal of existing and current literature reveals that two predominant methods have been adopted for estimating the layer coefficients of bituminous materials: (a) a power law relating the layer coefficient to the resilient modulus (M_R) (e.g., see Figure 2.5 in the AASHTO Guide [*1*]) and (b) based on Odemark's equivalent stiffness hypothesis (*3*), an analogous relationship is used, wherein the one-third power of the ratio of the material modulus to that of a reference material (whose layer coefficient is presumed known) gives the ratio of the unknown layer coefficient to that of the reference material.

Assuming a relationship between strength and the layer coefficient is a surprising extrapolation, since no measure of structural strength or adequacy was included in the data used to calibrate the AASHO model. The only variables used in the AASHO model (*4*) are given in Table 1.

It is readily apparent that none of these variables are measures of strength, although it is conceded that the layer thicknesses may be indirect strength indicators. Further, no cognizance was given to the annual cyclic subgrade strength. Instead, the subgrade strength was assumed to be uniform throughout the Road Test, as was climate.

The AASHO statistical flexible pavement design model was set up to integrate the effects of (a) traffic, (b) pavement (materials and layer thicknesses), and (c) serviceability (or level of distress). These effects were measured either directly or indirectly through the factors in Table 1. The development of the AASHO model is given below. A review of this development shows that the layer coefficient is a secondary parameter, whose significance is as a regression coefficient, or a calibration constant. If any physical significance is attributed to the layer coefficient, the significance should be relative to the resistance to distress, rather than to the structural capacity of the layer material.

AASHO MODEL

Background

The basis of the AASHO model is a decay curve, wherein it is assumed that the condition of a pavement will deteriorate, or decay, with accumulated traffic (this implies a certain element of time). To implement this model, the concept of functional pavement serviceability was developed. This concept resulted in the composite measure known as the present serviceability index, (PSI), which results from a regression equation relating the distress measurements given in Table 1 to an aggregated subjective rating of the adequacy of the pavement by a panel of adjudicators. A scale of 0 to 5 was assigned to the panel rating and subsequent qualitative serviceability index. A serviceability of 5 is the ideal, or perfect, pavement. Pavement serviceability has several important characteristics.

TABLE 1 AASHO ROAD TEST MEASURED VARIABLES

Factor	Variable Description	Variable	Unit
Traffic	No. of axle repetitions	W	No.
	Axle weight	L_1	kip
	Axle type	L_2	1 = single 2 = tandem
Pavement	Surfacing thickness	t_1	in.
	Base thickness	t_2	in.
	Subbase thickness	t_3	in.
Distress	Extent of cracking	C	ft²/1,000 ft²
	Extent of patching	P	ft²/1,000 ft²
	Slope variance (roughness)	SV	
	Rut depth	RD	in.

- Initial serviceability (p_0) is considered to be the serviceability of the freshly constructed, untrafficked pavement. The ideal pavement has to be rare. In fact, newly constructed flexible pavements at the Road Test reflected an average serviceability index value of 4.2.
- Terminal serviceability (p_t) is considered to be that level of serviceability at which the pavement is deemed to be no longer performing its required function. The lower, limiting value of p_t at the Road Test was 1.5.
- Present serviceability (p) is the measured, or estimated, level of serviceability at any time during the life of the pavement. Under normal circumstances then $p_0 > p > p_t$.

Using these definitions, the AASHO model may be stated:

$$\left(\frac{W}{\rho}\right)^{\beta} = \frac{p_0 - p}{p_0 - p_t} \tag{1}$$

where W is the number of axle (18-kip) repetitions that will reduce the serviceability from p_0 to p, ρ represents the number of axle repetitions at terminal serviceability (p_t), and β is a shape factor. Simply stated, the cumulative traffic at any time as a proportion of the traffic capacity of the pavement is represented as a power function of the proportion of usable serviceability consumed.

By a simple mathematical rearrangement, the more familiar form of the AASHO relationship is obtained:

$$\begin{aligned} \log_{10}(W) &= \log_{10}(\rho) + \frac{\log_{10}\left(\dfrac{p_0 - p}{p_0 - p_t}\right)}{\beta} \\ &= \log_{10}(\rho) + \frac{G}{\beta} \end{aligned} \tag{2}$$

where G represents the logarithm of the serviceability ratio.

Calibration

On each section of the Road Test, the present serviceability (p) and traffic (W) were determined at intervals of 2 weeks throughout the life of the section. The unknown parameters (β and ρ) were obtained by regression analysis. The summarized data used for the original regression analysis is in the form shown in Table 2. In Table 2, the logarithm of traffic is given for serviceabilities of 3.5, 3.0, 2.5, 2.0, and 1.5. These five points then provided the data for the regression used to obtain estimates of β and ρ. It should be noted that on a log-log plot of W versus G, the relationship in Equation 2 is linear.

Having obtained the two parameters (β and ρ) for each section, it was assumed that these parameters were functions of the section design (i.e., thickness) and traffic type. On this basis the following functional relationships were assigned to β and ρ:

$$\rho = A_0 \cdot (D + 1)^{A_1} \cdot (L_1 + L_2)^{A_2} \cdot L_2^{A_3} \tag{3a}$$

$$\beta = 0.4 + B_0 \cdot (D + 1)^{B_1} \cdot (L_1 + L_2)^{B_2} \cdot L_2^{B_3} \tag{3b}$$

In these equations L_1, L_2, and D (where D is the total pavement thickness) were known for each section. The eight unknown constants A_{0-3} and B_{0-3} were obtained by regression analysis. A variant regression was conducted in which the thickness index D was given by $D = a_1 \cdot t_1 + a_2 \cdot t_2 + a_3 \cdot t_3$, such that "these coefficients were permitted to vary so that the three elements of the pavement structure might each enter into the thickness index, (D), with a different weight per unit thickness" (*3*). This linear combination of the layer thicknesses provided a better regression and was retained in the model, with the transformed thickness (thickness index D) becoming better known as the structural number (SN) and the coefficients a_{1-3} as the layer coefficients. The well-known values for the layer coefficients obtained from the Road Test are given in Table 3. As listed, the raw traffic data were referred to as "unweighted," whereas the "weighted" traffic was adjusted in an empirical fashion to attempt to take into account the varying effect of the annual climatic cycle on the subgrade. This technique was the only concession originally given to the effect of climate or variable subgrade support.

Interpretation

The review of the AASHO Road Test analysis showed the layer coefficient to be no more than a regression coefficient with no truly ascribable physical or engineering meaning other than being a form of scaling or normalizing constant. Certainly, no connotation of strength could be assumed since no measurement of strength had been used in its derivation. As a result of this situation, some concern developed about being able to discriminate the strength and performance characteristics of the asphalt mixtures being specified by INDOT. At this stage it was deemed wise to determine the variability (distribution) of the layer coefficients found at the Road Test. The distributions were obtained by using the original equations (*3a* and *3b*), but solving for the layer coefficients section by section rather than globally. Thus the layer coefficients (a_{1-3}) for each section were determined. Because the materials in each layer were designed to be uniform throughout the Road Test, variation in the value of the layer coefficients was expected to be minimal.

The resulting distributions of the section-by-section calculations are shown in Figure 1. The only adjustment made to these distributions was to constrain the layer coefficients to be non-negative. Such a constraint may be explained on the

TABLE 2 AASHO ROAD TEST: SERVICEABILITY DATA (*4*)

FACTORIAL EXPERIMENT—DESIGN 1
FLEXIBLE PAVEMENT, UNWEIGHTED APPLICATIONS
(Continued)

			SERVICEABILITY TREND LEVEL					INDEX DAY					STRUCTURE DESIGN			
								11	22	33	44	55				
								APPLICATIONS THROUGH INDEX DAY - THOUSANDS								
								80	233	445	807	1114				
								LOG APPLICATIONS THROUGH INDEX DAY								
			3.5	3.0	2.5	2.0	1.5	4.901	5.368	5.648	5.907	6.047				
LOOP	LANE	SECTION	LOG UNWEIGHTED APP. TO SERVICEABILITY LEVEL*					SERVICEABILITY TREND VALUE ON INDEX DAY**					D1	D2	D3	SECTION
			(x.xxx)					(x.x)					(in.)			
3	1	165		4766	4782	4790	4806						2	0	00	165
3	1	125		3204	3397	3531	3633						2	0	04	125
3	1	143	4846	4850	4854	4858	4862						2	0	08	143
3	1	133	4813	4854	4874	4881	4883						2	0	08	133
3	1	113	4774	4783	4798	4806	4813						2	3	00	113
3	1	135	4842	4846	4850	4858	4862						2	3	04	135
3	1	159		4828	4891	4921	4946	23					2	3	08	159
3	1	127	4756	4850	4862	4874	4887						2	6	00	127
3	1	157	4457	4918	4940	4946	4952	32					2	6	04	157
3	1	111	5715	5760	5793	5820	5858	39	37	37			2	6	08	111
3	1	137	4336	4874	4881	4883	4883						3	0	00	137
3	1	163	4893	4914	4931	4934	4940	34					3	0	04	163
3	1	109	4904	4957	4990	4994	4998	35					3	0	08	109
3	1	147	4457	4828	4846	4854	4858						3	3	00	147
3	1	107	4891	4921	4934	4940	4940	31					3	3	04	107
3	1	115		4854	4899	4921	4940	25					3	3	04	115
3	1	129	5035	5179	5703	5741	5748	39	29	27			3	3	08	129
3	1	117	4874	4911	4934	4940	4940	31					3	6	00	117
3	1	131	5280	5664	5758	5762	5769	38	34	30			3	6	04	131
3	1	155	5538	5756	5804	5862		33	36	34	19	16	3	6	08	155
3	1	119	4747	4874	4883	4887	4889						4	0	00	119
3	1	141	4846	4883	4885	4889	4891						4	0	04	141
3	1	153	4889	4931	4990	5022	5036	34					4	0	08	153
3	1	145	4901	4901	4904	4904	4904	35					4	3	00	145
3	1	151	4828	4921	4990	5030	5036	32					4	3	04	141
3	1	121	5056	5732	5765	5779	5786	36	34	33			4	3	08	121
3	1	161	4887	4990	5076	5159	5250	34					4	6	00	161
3	1	149	4870	4994	5030	5035	5035	33					4	6	00	149

TABLE 3 AASHO ROAD TEST LAYER COEFFICIENTS

Traffic	Coefficient[a] a_1	a_2	a_3
Weighted	0.44	0.14	0.11
Unweighted	0.37	0.14	0.10

[a] a_1, Asphaltic concrete, a_2, crushed limestone base, and a_3, sand-gravel base.

basis that regardless of whether strength or serviceability was to be considered, an increasing layer thickness must lead to an increase in the overall strength or serviceability. Consideration of the layer coefficient distributions in Figure 1 caused considerable concern. The degree of variation, particularly in the surfacing (the most closely controlled material), was surprising. In a specific review of the literature, a measure of confirmation was provided by the values given in Table 10 of an earlier TRB report (*4*) in which it was shown that the value of a_1 varied from 0.33 to 0.83 (weighted) and from 0.33 to 0.78 (unweighted).

Considering the degree of control exercised at the Road Test, further research and analysis were essential to resolve the apparently fatal layer coefficient variability represented in Figure 1. The term fatal is emphasized because it seems futile to discriminate the structural quality of various asphalt mixtures when the single asphalt mixture at the Road Test resulted in such great variability. Consequently, after both the methodology and the computations were found to be substantially correct, a copy of the original Road Test data for the flexible pavement sections was obtained from the TRB. This detailed data base provided qualitative improvement in the data being analyzed.

Remarks

In the remainder of this paper, the raw, or unweighted, traffic data will be used, because the weighting function is somewhat arbitrary and would be difficult to transform for application to sites or climes other than Ottawa, Ill.

For reference, the relationships used by AASHO after the final regressions are given for the standard 18-kip single axle (standard axle) configuration:

Weighted:

$$\log_{10}(W) = 9.61 \cdot \log_{10}(SN + 1) - 0.20 + \frac{\log_{10}\left(\frac{4.2 - p}{2.7}\right)}{0.4 + \frac{1{,}096}{(SN + 1)^{5.19}}} \qquad (4a)$$

Unweighted:

$$\log_{10}(W) = 8.94 \cdot \log_{10}(SN + 1) + 0.35 + \frac{\log_{10}\left(\frac{4.2 - p}{2.7}\right)}{0.4 + \frac{140{,}155}{(SN + 1)^{8.73}}} \qquad (4b)$$

ROAD TEST DATA

The remaining Road Test data held by the TRB is a reduced set of the original data. Many files, folders, and card decks that had not been used have been deleted. The remainder, transferred to computer tape, have been preserved. Of par-

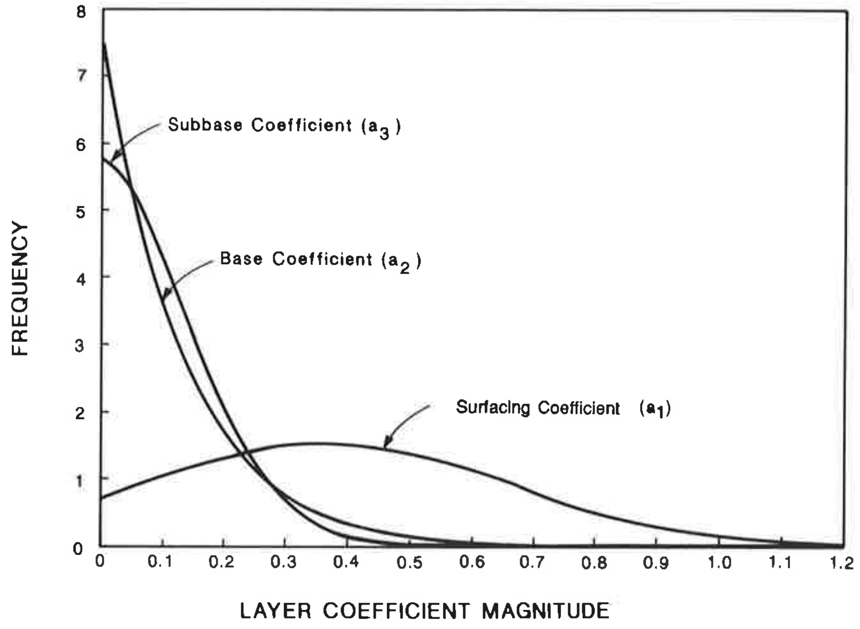


FIGURE 1 AASHO Road Test: layer coefficient distribution.

TABLE 4 RETAINED AASHO ROAD TEST DATA FORMAT

Field #	Description	Field #	Description
1	Loop No.	7,8	Extent of Cracking
2	Lane No.	9,10	Extent of Patching
3	Section No.	11,12	Slope Variance
4	Surfacing Thickness	13,14	Rut Depth
5	Base Thickness	15	PSI
6	Subbase Thickness	16	Accumulated Traffic
		17	AASHO Day

ticular value is that the results from the full factorial experiment have been retained.

The data from the full factorial experiment were reduced to permit easier manipulation, and the data fields given in Table 4 were maintained.

In this file, complete observational data are available for each section for each AASHO day (1 AASHO day = 14 real days). Not only can the PSI (present serviceability index) versus traffic history for each section be reconstructed, but the component parts of the PSI (cracking, patching, slope variance, and rut depth) can be examined. It is not well recognized that the amount of patching at the Road Test was essentially negligible; equally important is that there was no routine maintenance undertaken on the pavement sections such as might be expected on in-service highway pavements.

After the data file was reviewed, all observations were removed for sections after overlay. Data from overlaid sections were not used in the original layer coefficient determination. Subsequently, plots were prepared for PSI versus traffic, PSI versus log (traffic) and PSI versus AASHO day. Examples of these plots are given in Figures 2*a–c*. Examination of these figures reveals that the AASHO model provides a very poor predictive model. In addition, both sets of data (observed and predicted) were submitted to analysis through the SPSS statistical package. The "Runs Test" of this statistical package returned a z-statistic of 16 (typically a value of less than 2.0 might be expected). Thus, although the overall regression might appear reasonable in terms of the r^2 statistic, the model is otherwise inappropriate. (Although the values of the r^2 statistic pertaining to the Road Test are not easily found in the literature, it is believed that the values are 0.23 for unweighted traffic and 0.49 for weighted traffic.)

A review of Figure 2 reveals that the shapes of the curves are not as would have been expected. Instead of being smoothly downcurving, the data appeared to turn sharply downward at either one or two reasonably well-defined events. This was apparent in both the PSI versus traffic (top) and PSI versus $\log_{10}$ (traffic) (middle) plots, although more pronounced in the former. In the PSI versus AASHO day plot (bottom) the locations of these two critical events were particularly noticeable and were found to correspond very closely with the periods of spring thaw.

Not all sections showed this tendency; however, in those that did not, a downward step was noted occurring at the same times. On the PSI versus AASHO day plots the curves appeared to be generally piecewise linear, i.e., the PSI decreased linearly at one rate and then linearly at a much greater rate. In some cases, this decrease in PSI took the form of a step function, with the original slope being reestablished. These observations are shown schematically in Figure 3. Figure 3 outlines three observed performance patterns:

1. P-A-B (rarely observed except on very thick sections or with very light axle weights): exhibits no significant distress. The slope of the line (rate of decay) is clearly independent of traffic volume (axles per day); it is equally independent of climatic (freeze/thaw) events.
2. P-A-C-D-E: a number of sections showed this pattern, in which a distinct and sudden loss of serviceability was noted (ALC) coinciding with the first spring/thaw. Some of these sections cracked, but the majority survived the first year uncracked. Those sections that survived with a crack failed at the onset of the next winter, whereas the uncracked survivors generally failed during the following freeze/thaw event.
3. P-A-F: a large number of sections exhibited this behavior, failing rapidly and catastrophically during the first freeze/thaw event.

The overall linearity of these plots was particularly puzzling because there had been no suggestion that time was a significant factor, which is implied by this result. In fact, axle repetitions (traffic) were considered the primary forcing variable. A check confirmed that the rate of trafficking (axles per AASHO day) over the period of the Road Test was not constant; however, the changes in trafficking rates did not coincide with the changes of slope in the plots. Table 5 shows that the rate of section failure ($p_t < 1.5$) is not well correlated with traffic but is highly correlated with the season of the year. Thus, time, as measured by the number of spring/thaw events, appears to be of greater significance than was previously suspected.

In extending the piecewise linear hypothesis from the trafficked sections to the untrafficked sections of Loop 1, only three particularly thin sections displayed the same pattern. As a result, it was concluded that the interaction of time and traffic might be significant. The relatively sudden serviceability loss observed during the spring/thaw periods was addressed by examining the component parts of the PSI. The examination revealed that this phenomenon was paralleled by the initial observation of Class 2 (alligator) or Class 3 (granulated) cracking, or both (Figure 4). The full set of

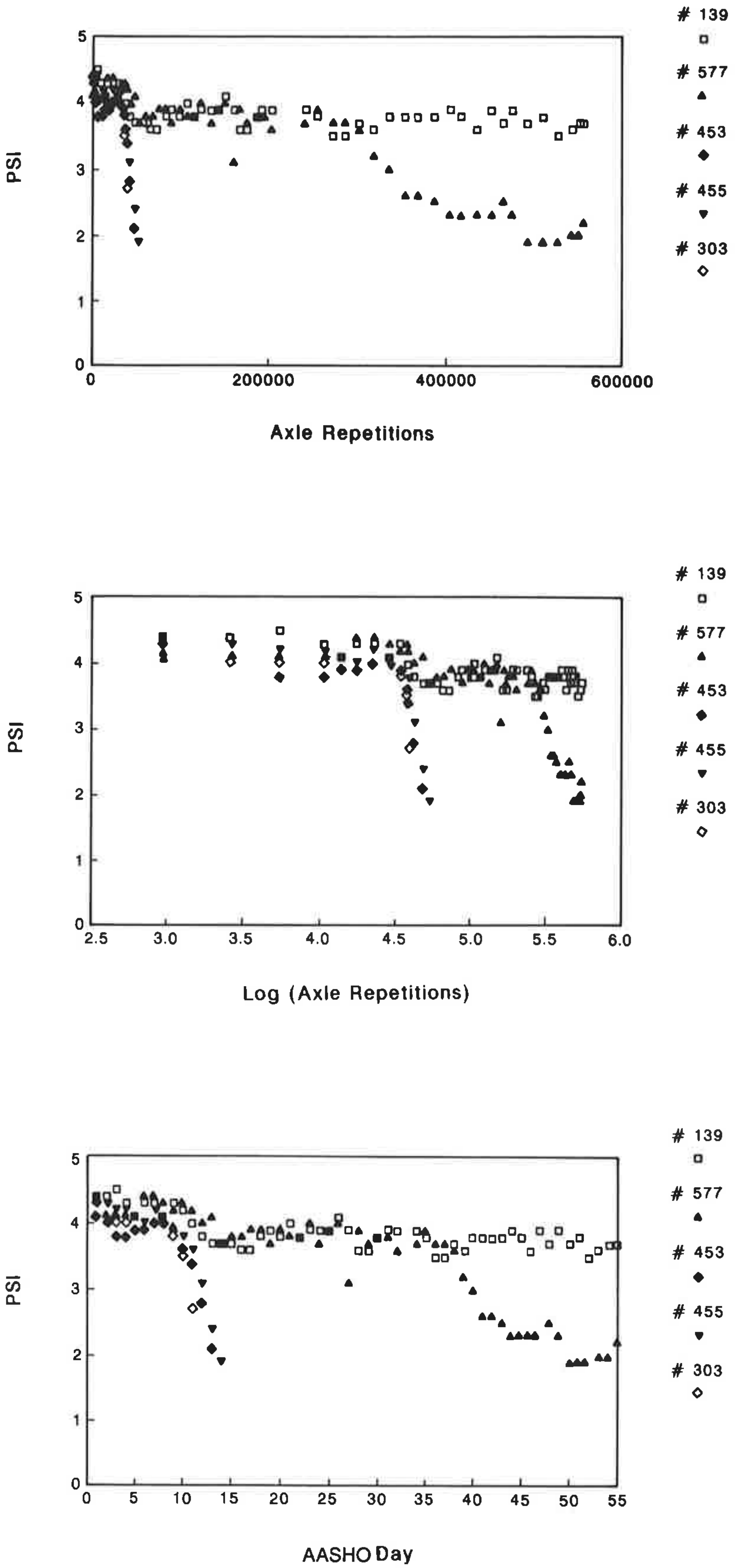


FIGURE 2 AASHO Road Test: serviceability plots: (top) PSI versus traffic; (middle) PSI versus $\log_{10}$ (traffic); and (bottom) AASHO day.

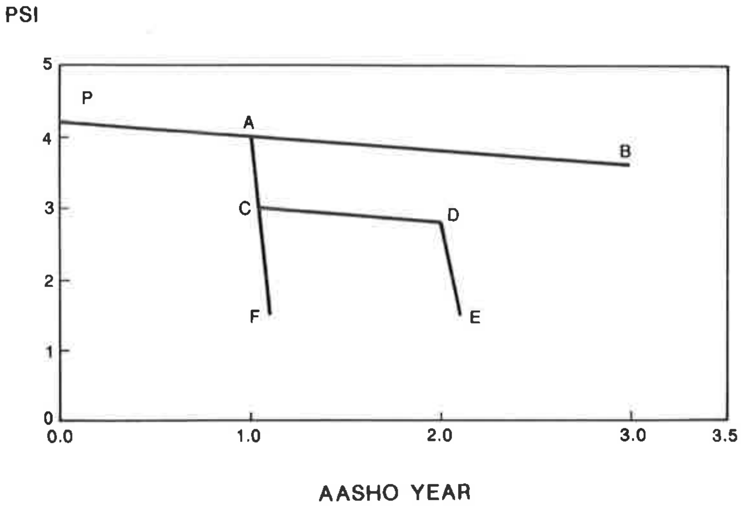


FIGURE 3 **AASHO Road Test: performance schematic.**

TABLE 5 AASHO ROAD TEST: TRAFFIC AND FAILURE RATES

Season	% Traffic	% Failures
Winter	22	28
Spring	24	60
Summer	30	2
Fall	23	10

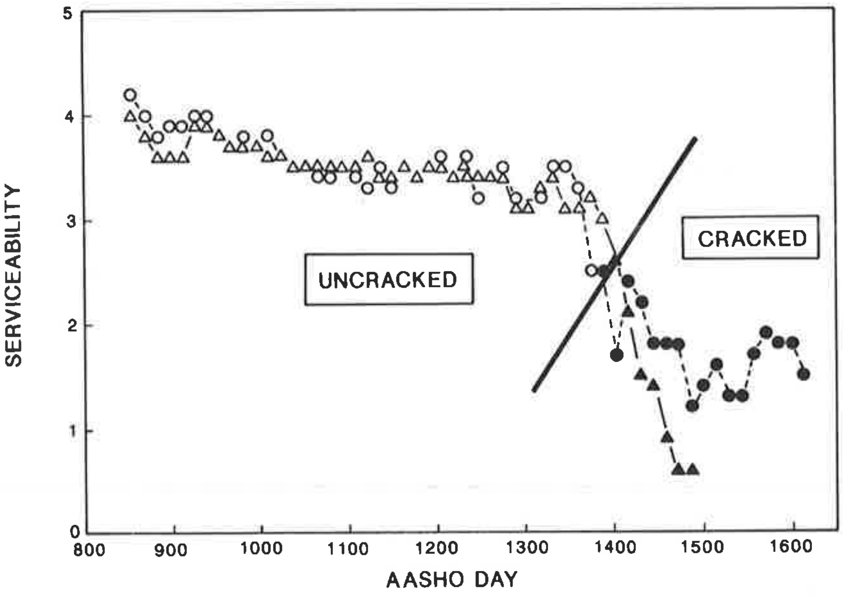


FIGURE 4 **AASHO Road Test: effect of cracking on serviceability.**

observed data from a number of sections was plotted (Figure 5) (instead of only those at $P = 3.5, 3.0, 2.5, 2.0$, and 1.5 as used in the original AASHO Road Test analysis). This full set of data clearly reflects the piecewise linear relationship contrary to the expectation of Equation 2. The points of intersection of the linear portions of the plots closely match the initial observation of Class 2 or Class 3 cracking, or both. In practical terms, two populations of pavement performance have been observed: (a) integral, uncracked and still-sealed pavement and (b) cracked, disintegrating pavements. Because at the Road Test, most Class 2 or Class 3 cracking was initially observed at, or about, a PSI of 3.0 to 3.5, the final AASHO equations (4a and 4b) are calibrated to failed, or failing, pavements.

CUMULATIVE SUM (CUSUM) PLOTS

If, using the observed data from any section, the cumulative serviceability loss is plotted against AASHO day, a piecewise linear graph will be observed (Figure 6). (In Figure 6 the serviceability loss is given as $(5.0 - p(i))$, and the Cusum as

$$\sum_{i=1}^{t} (5.0 - p(i))$$

where t is the number of AASHO days from the start of trafficking to the point in time considered). In the following analysis, serviceability loss is defined as $(p_0 - p(i))$. Close inspection indicates that the relation rapidly approaches linearity on each leg, i.e., that the data exhibit linearity asymptotically.

If the expected serviceability loss at any time t is represented by a rearrangement of Equation 1, then

$$\begin{aligned} p_0 - p(i) &= \text{Serviceability loss} \\ &= (p_0 - p_t) \cdot \left(\frac{W(i)}{\rho}\right)^{\beta} \qquad (5) \end{aligned}$$

Then, recreating the Cusum plot mathematically:

AASHO Day	*Incremental Loss*	*Accumulated Loss*
1	$(p_0 - p_t) \cdot \left(\frac{W(1)}{\rho}\right)^{\beta}$	$(p_0 - p_t) \cdot \left(\frac{W(1)}{\rho}\right)^{\beta}$
2	$(p_0 - p_t) \cdot \left(\frac{W(2)}{\rho}\right)^{\beta}$	$(p_0 - p_t) \cdot \left(\frac{W(1) + W(2)}{\rho}\right)^{\beta}$
. . .	. . .	. . .
n	$(p_0 - p_t) \cdot \left(\frac{W(n)}{\rho}\right)^{\beta}$	$(p_0 - p_t) \cdot \left(\frac{W(1) + W(2) + \ldots + W(n)}{\rho}\right)^{\beta}$

To approach linearity, Cusum$(n + 1)$ − Cusum(n) must approach a constant value in the limit as n increases. Assuming for simplicity that the traffic rate is constant at w axles per AASHO day (i.e., that $W(n) = n \cdot w$), then

$$\begin{aligned} &\text{Cusum}(n + 1) - \text{Cusum}(n) \\ &\quad = (p_0 - p_t) \cdot \left(\frac{w}{\rho}\right)^{\beta} \cdot n^{\beta} \qquad (6) \end{aligned}$$

If this expression is to be constant, then it may be simplified thus:

$$n^{\beta} = \text{constant} \qquad (7)$$

This expression is true only in the limit for all n, as n approaches infinity if β is vanishingly small. For a range of structural number (SN) of 1 to 6, the corresponding range of β in Equation 4b is found to be $0.4 < \beta < 300$. Thus, the piecewise linear relationship observed in Figure 6 cannot be supported by the AASHO model.

The implication of this analysis is that on linear portions ($\beta \approx 0$) of the Cusum plot, traffic (axle weight and repetitions) has no effect, and it is only during those periods when the Cusum is in transition from one linear portion to another ($\beta \neq 0$) that traffic has a significant effect on serviceability.

The mathematics of the Cusum transformation have not been developed sufficiently to permit the derivation of the relationship that gives rise to the observed asymptotically linear Cusum function.

The smoothing effect of the Cusum transformation can clearly be seen in Figure 6 and was used to help identify the critical points (changes of slope) in the behavior of each section.

Figure 7 superimposes the Cusum plots for a number of different sections on the same graph; the axle weight was the same for all of these sections. Although not overly evident, it can be seen that (a) until cracking (a change of slope) separates a section from the main plot, the behavior of all of the sections is essentially the same, (b) in general, the thicker (total pavement thickness) pavements survive the longest before cracking, and (c) within pavements of the same or similar total thickness, those with thicker surfacing t_1 survive longer.

SURVIVAL PROBABILITY

A probabilistic analysis was made in an attempt to quantify, or model, the step function reported above, which was identified as being triggered, or initiated, by a spring/thaw event. On any given lane of the Road Test (constant axle weight and type) pavements of various composition either failed or survived the first full seasonal cycle of spring/thaw. By trying to relate the elements of structure to the probability of failure

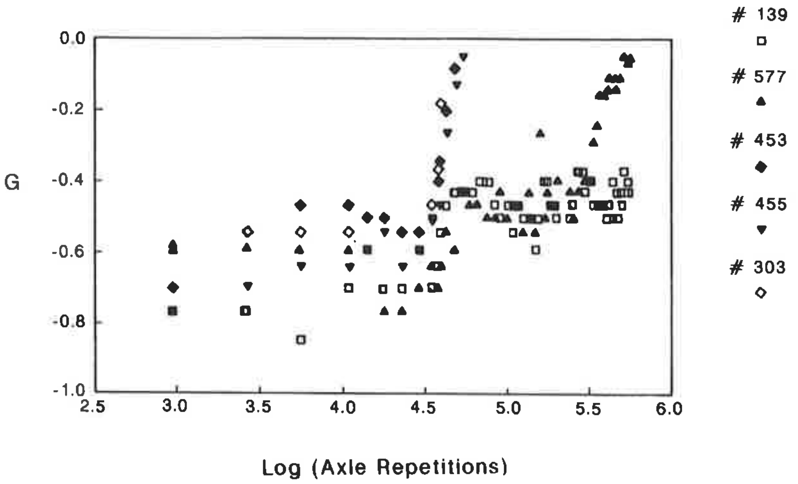


FIGURE 5 AASHO Road Test: section serviceability histories.

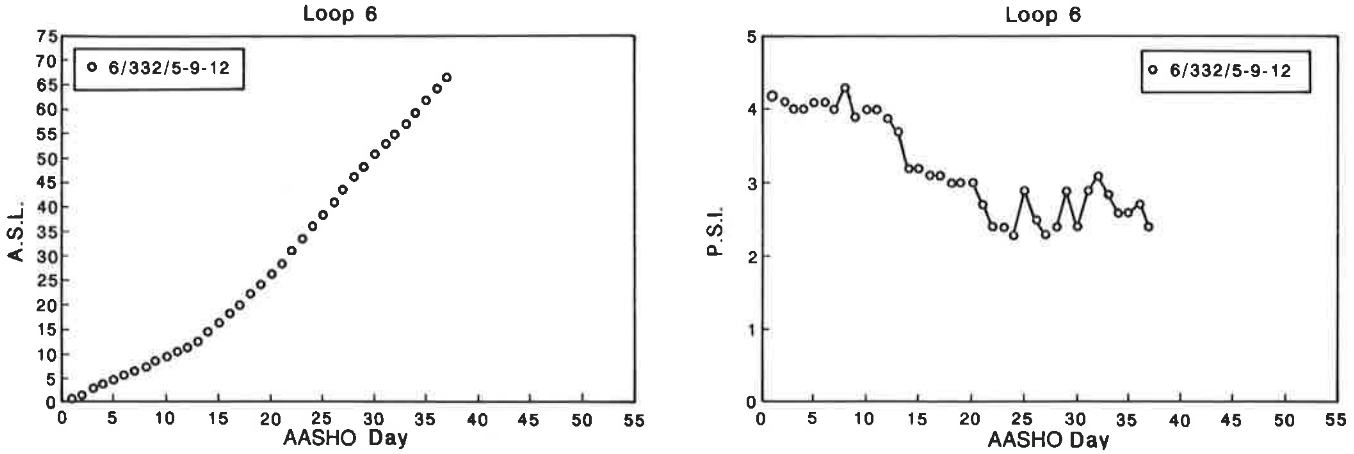


FIGURE 6 AASHO Road Test: accumulated serviceability loss case.

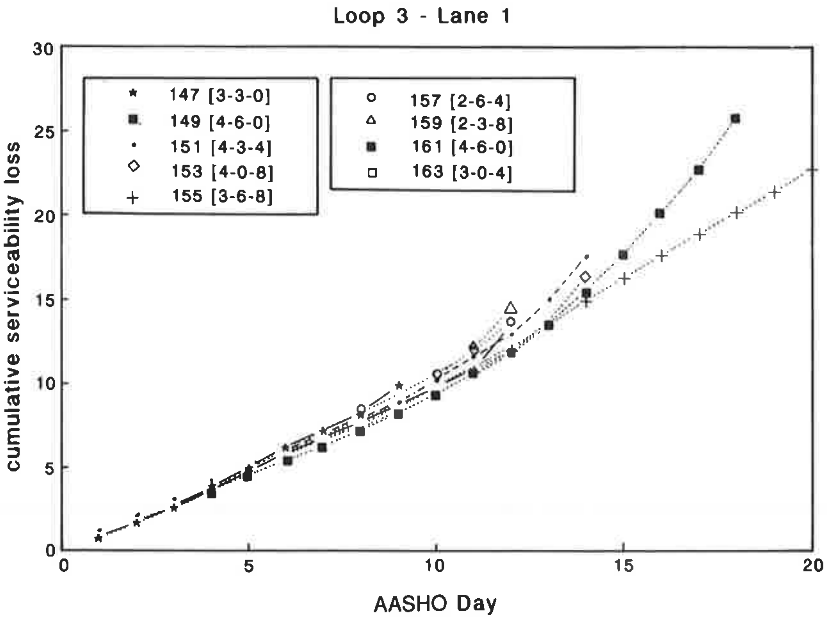
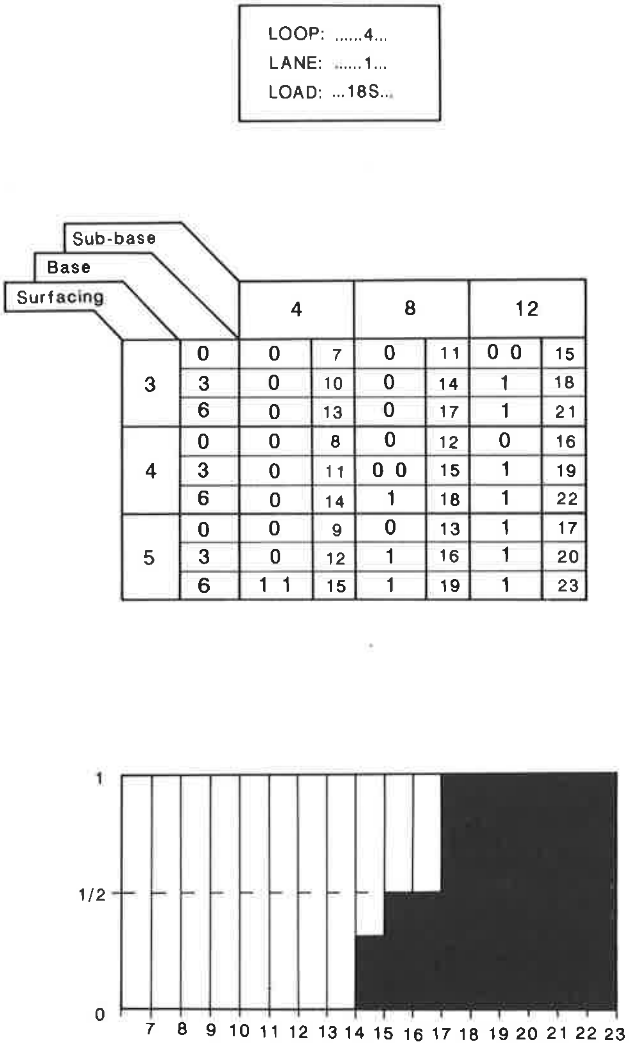


FIGURE 7 AASHO Road Test: ASL plots.

(or survival), certain conclusions could be drawn, i.e., whereas the thicknesses of each individual layer provided a small measure of correlation with the probability of survival, no factor was found to be as significant as the effect of the total physical thickness (surfacing + base + subbase), regardless of the layer thickness combinations.

Although total pavement thickness was particularly significant in this analysis, it is evident that for pavements of the same total thickness, those with thicker surfacing have an enhanced probability of survival. This has been demonstrated by plotting, but the mathematical and statistical analyses are not yet complete.

An example of the first-year survival matrix is given in Figure 8 for Lane 1 of Loop 4 (18-kip single axle), where 1 = survival and 0 = failure (did not survive) (the righthand column under each subbase thickness gives the full pavement thickness for each section). The composite survival regression curves are given in Figure 9 for all the axle weights and types used in the main factorial experiment.



LOOP: ......4...
LANE: ......1...
LOAD: ...18S...

Base	Sub-base	Surfacing 4		8		12	
3	0	0	7	0	11	0 0	15
	3	0	10	0	14	1	18
	6	0	13	0	17	1	21
4	0	0	8	0	12	0	16
	3	0	11	0 0	15	1	19
	6	0	14	1	18	1	22
5	0	0	9	0	13	1	17
	3	0	12	1	16	1	20
	6	1 1	15	1	19	1	23

FIGURE 8 AASHO Road Test: one-year survival matrix.

These observations serve to validate the concept of the U.S. Army Corps of Engineers method for frost design, wherein the pavement is first designed from purely structural considerations, and subsequently the total pavement thickness is checked against the anticipated depth of frost penetration.

From the limited data available (two seasonal cycles), the data tend to support the possibility that, among survivors, the probability of survival is Markovian; thus if a pavement has a 0.95 probability of first-year survival, then its 2-year survival probability is 0.95^2, and its n-year survival probability is 0.95^n.

These curves (Figure 9) are of course only applicable to the climatic and subgrade conditions of the Road Test. If the subgrade were free draining, not frost susceptible, or if there were no frost, then it might be reasonable to expect that these curves would translate significantly to the left.

SUMMARY AND CONCLUSIONS

AASHO Model

It has been shown that the AASHO model does not represent the observed behavior of the pavements trafficked at the Road Test. The AASHO model (Equation 1) is biased to more closely represent the behavior of cracked pavement. Within the AASHO model, the layer coefficients are shown to be *secondary regression coefficients* with no direct physical significance. To attribute to them a significance as indicators of strength is spurious. Instead, the layer coefficients are indicators of resistance to serviceability loss.

In the original development of the AASHO model, no cognizance was given to the effect of climate (including its effect on the subgrade support characteristics), i.e., the effect of climate was assumed to be constant from section to section. A tacit assumption was made at the Road Test that all deterioration in pavement serviceability was because of the composite effects of traffic (axle weight and frequency) and pavement structure (materials and layer thicknesses).

However, the present analysis suggests that at Ottawa, Ill., the effect of climate was in fact decisive. The initiating event of all significant deterioration in pavement serviceability was inevitably linked to spring/thaw. The subsequent performance of the trial sections was found to be critically dependent on the observation of Class 2 or Class 3 cracking.

The effect of traffic (frequency) is most difficult to define. However, results of the current analysis indicate that the frequency of loading is critical only during the spring/thaw periods. At other times of the year, the effect of traffic (axle weight) is explicitly clear in the AASHO model (Equation 3a and b); however, the effect of the axle weight is seen to be negligible except in relation to the survival probability, which is significantly affected by the spring/thaw events.

Alternative Analyses

Cusum Analysis

The Cusum analysis outlined in this paper provides a clear method from which the performance of Road Test pavements

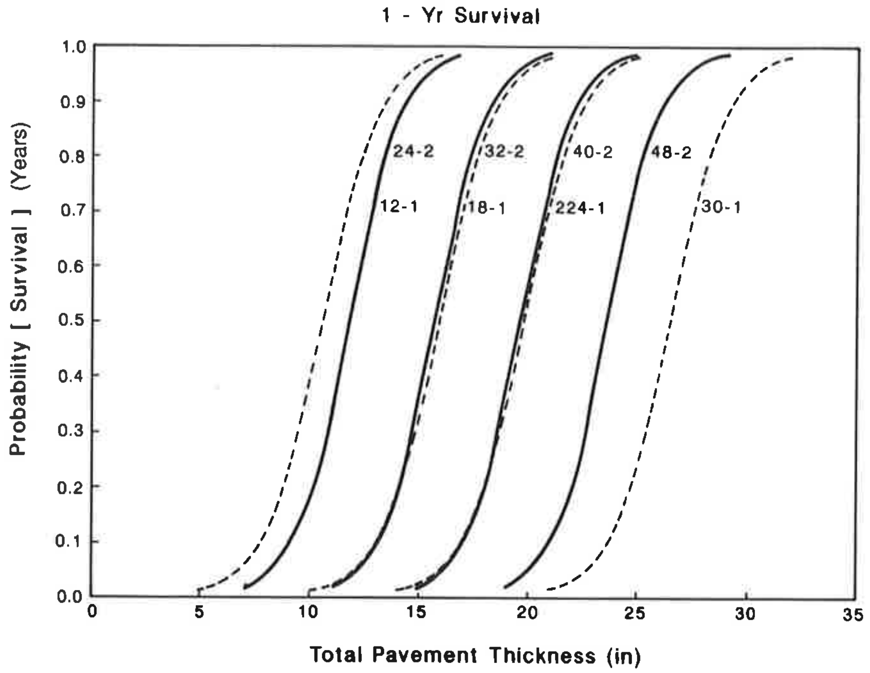


FIGURE 9 AASHO Road Test: survival probability plots.

may be analyzed. The surprising smoothing effect and piecewise linearity lend themselves to the identification of changes in performance. It is anticipated that the study of the Cusum plots and their mathematical basis will provide a more defensible foundation from which to build an alternative pavement performance model.

Probabilistic Analysis

The variability in the factors and parameters associated with pavement design and performance, however well controlled, lends itself readily to a probabilistic analysis. The first analysis presented here clearly demonstrates the power of such an approach.

The new AASHTO Guide (1986) (*1*) advocates the use of reliability concepts. The application of the principles of reliability to empirically derived deterministic formulae (the AASHO model) is fraught with problems during implementation and interpretation. The application of probabilistic methods to pavement design would be better served by a total reanalysis of the Road Test data (and other data bases) from a probabilistic basis; in this fashion the full model (and its submodels) would be internally consistent and far more transportable.

Conclusion

The preliminary results from a study that has highlighted shortcomings in the AASHO model and the interpretation of the Road Test data have been presented. As far as is possible, both observational and mathematical justification for each point raised has been provided.

It is strongly recommended that the AASHO Road Test data be closely scrutinized and reanalyzed in the light of 25 years of hindsight, newer pavement technology tools, and the more recent concepts of probabilistic analysis and reliability. In this way new (and better) models and submodels of pavement behavior and performance may be developed.

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