Comparison and Reanalysis of AASHO Road Test Rigid Pavement Data

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Three different computer analyses of the AASHO Road Test for rigid pavements are reviewed, along with their resultant pavement performance equations. A fourth analysis, which is a revision of one of the three, is then briefly presented. A review is provided of the original AASHO least-squares regression analysis of the serviceability data collected during the 2 years of the Road Test. In their book, *Road Work*, Small and Winston propose that the original AASHO analysis overestimates the life of thick rigid pavements and that a right-censored survival regression analysis would be more correct. Most of the thicker rigid test sections of the AASHO road test were incorporated into Interstate 80 and received 12 additional years of heavy-truck traffic. A review is provided of a report by the Illinois Department of Transportation (DOT) in which Little and McKenzie reanalyze the AASHO data, including the additional traffic, using the least-squares method of regression analysis. For comparison, the survival regression analysis proposed by Small and Winston is reanalyzed using the additional data collected by Illinois DOT on the rehabilitated AASHO roadway. It was concluded that the Small/Winston analysis significantly underestimated the life of thick rigid pavements. The original AASHO method overestimated the life of thick rigid pavements, but not as significantly as the Small/Winston analysis underestimated it. A proposed revision to the Small/Winston model results in a performance prediction for thick rigid pavements slightly greater than the Little and McKenzie revision to the original AASHO analysis. Because of the lack of distress for the thicker rigid pavements in the Road Test, the Small/Winston survival analysis for the AASHO Road Test rigid test sections is not valid.

The AASHO Road Test was conducted between November 1958 and November 1960 and applied 1.114 million axle passes of each loaded vehicle type on five of six test loops for a total of 10 lanes (*1*). Most of the thicker rigid sections were not significantly distressed and were later incorporated into the construction of Interstate 80. Additional trafficking of these sections was carefully measured and reported by the Illinois Department of Transportation (DOT), and an analysis of the data was given by Little and McKenzie (*2*).

In their book, *Road Work*, Small and Winston (*3*) state that the original analysis done for the AASHO Road Test was in error. They purport that current techniques of survival analysis show that the fourth power law of equivalent loading should be a third power. Small and Winston believe that this error in the design equation is responsible for rigid Interstate highway pavements lasting, in their estimation, only 13.5 years rather than a typical design life of 20 or 25 years (*4*). On the basis of this assumption, they claim that an $8 billion saving in maintenance costs would be achieved if designers would build the nations' pavements 1 or 2 in. thicker.

The methods and performance equations from the three separate analyses of the data obtained from the AASHO Road Test rigid pavements are compared. The three analyses include (a) the original AASHO analysis, (b) the *Road Work* analysis by Small and Winston (*3*), and (c) the Illinois analysis of additional traffic on AASHO test sections reported by Little and McKenzie (*2*). A fourth analysis is presented using the *Road Work* survival analysis procedure supplemented with the additional traffic data on the rehabilitated AASHO roadway.

AASHO ROAD TEST ANALYSIS

The original analysis of the AASHO Road Test, which led to the *AASHTO Interim Design Guide*, is briefly reviewed in this section. Significant aspects and differences relating to the number of test sections used, type of numerical analysis, and number of traffic and serviceability data sets of each test section are highlighted.

The AASHO Road Test consisted of six test loops of rigid and flexible pavements. Rigid pavement thicknesses of 12.5, 11, 9.5, 8, 6.5, 5, 3.5, and 2.5 in. were tested. Axle loads consisted of 2-, 6-, 12-, 18-, 22.4-, and 30-kip single axles and 24-, 32-, 40-, and 48-kip tandem axles. Figure 1 shows a tabular listing of the rigid test sections. The maximum number of axle repetitions applied was 1,113,800 over a 2-year period. A total of 264 Design 1 rigid pavement test sections were loaded during the test. Variations were made in subbase thickness and type reinforcement. The thinnest rigid pavement test sections that were loaded by 18-kip single axles were 5 in. thick.

The original analysis of the Road Test data was comprehensive and incorporated several different mathematical models. The analysis considered all test sections, including the cases where thinner sections outlasted thicker sections in the same loop and lane. The traffic loading was continued to a terminal serviceability index of 1.5 to ensure that the data would represent the complete serviceability curve. Many of the test sections never reached a present serviceability index (PSI) of 1.5, and several had not reached a PSI of 2.5 at the conclusion of the Road Test. At least five different PSI readings for each test section were included in the numerical analysis, even if that section had not yet reached 2.5 or 1.5 PSI.

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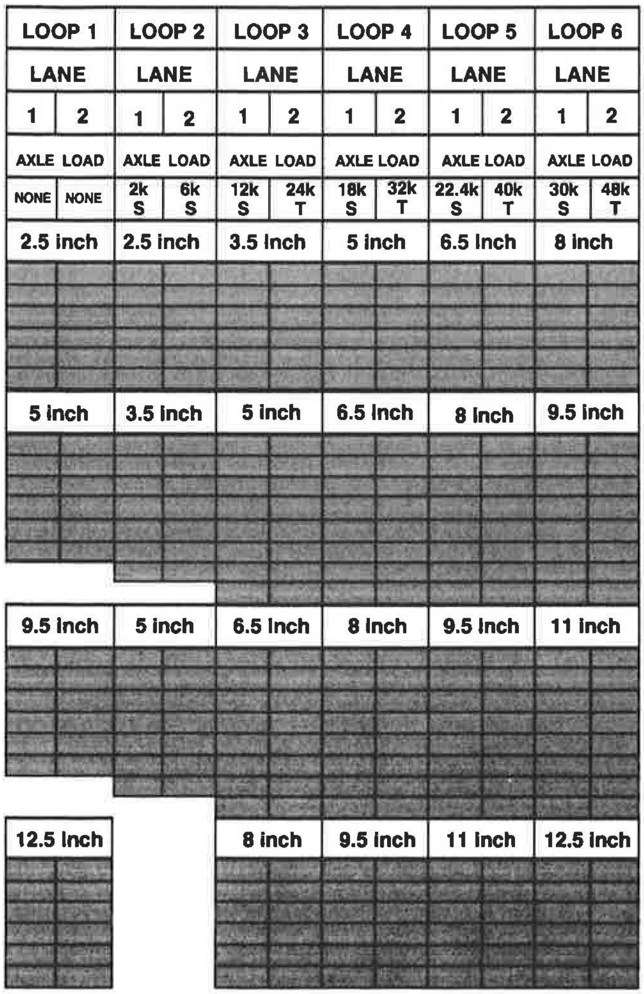

FIGURE 1 AASHO Road Test: Design 1, rigid test sections.

Of the methods tested, the one that yielded the best fit at the Road Test was a regression analysis using least squares.

The general form of the original Road Test performance equation is as follows:

$$\log W = \log \rho + \frac{G}{\beta}$$

where

W = number of load applications,
ρ and β = complex functions of design and load, and
G = serviceability loss term.

For rigid pavements, the expressions for ρ, β, and G are

$$\rho = \frac{10^{5.85}(D_2 + 1)^{7.35}L_2^{3.28}}{(L_1 + L_2)^{4.62}}$$

$$\beta = 1 + \frac{3.63(L_1 + L_2)^{5.20}}{(D_2 + 1)^{8.46}L_2^{3.52}}$$

$$G = \log \frac{4.5 - P_t}{3}$$

where

L_1 = axle load (kips),
L_2 = 1 for single axles and 2 for tandem axles,
D_2 = slab thickness (in.), and
P_t = terminal serviceability index.

For the 18-kip single axle load, when L_1 = 18 and L_2 = 1, the log ρ and β terms reduce to

$$\log \rho = -0.058 + 7.35 \log(D_2 + 1)$$

$$\beta = 1 + [10^{7.209} \times (D + 1)^{-8.46}]$$

ROAD WORK ANALYSIS OF AASHO ROAD TEST

In *Road Work*, Small and Winston (*3*) reanalyzed the original AASHO Road Test data using modern analytical techniques. The model they used to analyze the data was described as the Tobit model—an econometric model developed in the early 1950s by James Tobin (*5*) as a tool for the economic analysis of household expenditures. The Tobit model assumes that some type of left-censoring mechanism is present when estimating an equation from data. The term "left-censored data" refers to a situation in which data may be lost before the event or time occurs. In Tobin's example, the amount of money people spend on luxury items is expected to be zero until some lower limit of income is reached. At this lower limit, which could be different for each household, the amount spent is some function of total income.

The model is functionally the same as a lifetime, or right-censored, survival analysis. The lifetime model is frequently used when the data—for example, laboratory mice—have only two possible options: (a) the mice die at some time during the experiment or (b) they survive the entire length of the experiment. Right-censored data mean that some of the possible events may not have occurred when data collection is terminated.

The major distinction between the lifetime and Tobit analyses is that incomplete observations in pavement studies are considered to be right- rather than left-censored. At the AASHO Road Test, it was not possible to allow every section to receive sufficient loadings to reach a 1.5 PSI. For 196 of the 264 rigid pavement sections, only partial information concerning the actual number of applied loads to failure was available after 2 years. However, that those sections survived a number of given loadings and reached a certain PSI level is useful information that should be efficiently used. In the *Road Work* analysis, any pavement section that had not yet reached a 2.5 serviceability index was considered a survivor and was therefore not included in the analysis in the same manner as other sections. Thus, the serviceability index of that test section was censored.

The Tobit, or survival, regression analysis is currently available in the commercial software Statistical Analysis System (SAS) as the LIFEREG procedure (*6*). The *Road Work* analysis was also completed using the commercial software SHAZAM (*4*).

The *Road Work* rigid pavement data were obtained from Small in order to rerun his analysis. The data consisted of only 73 uncensored observations out of the 264 test sections of the AASHO road test. Figure 2 is a graphical representation of these 73 observations. Each data point is a recording of the number of axle repetitions when each section reached a 2.5 serviceability index. A close inspection of the 73 observations reveals that only 3 of the 44 test sections of 9.5-in. thickness were included and that none of the 11- or 12.5-in. thick test sections were included because they did not fail. If the PSI is greater than 2.5, whether it be 2.6 or 4.5 PSI (nearly new condition), no PSI value is given to any of these test sections in the *Road Work* analysis. The mean thickness of the observed test sections in the *Road Work* analysis was only 5.8 in. A tabular listing of the subtotal of test sections with respect to thickness is presented in Table 1.

The data provided by Small were checked, and his analysis was duplicated using the LIFEREG procedure. This procedure achieved exactly the same results reported in *Road Work*. The resulting equation is logarithmic, and rough comparisons can be made if the AASHO equation is converted from base 10 logarithms to natural logarithms. In Table 2, a comparison is presented showing the Small/Winston results and this duplication. The most significant difference is the coefficient of the load term (A_1), which is only 3.24 in the Small/Winston

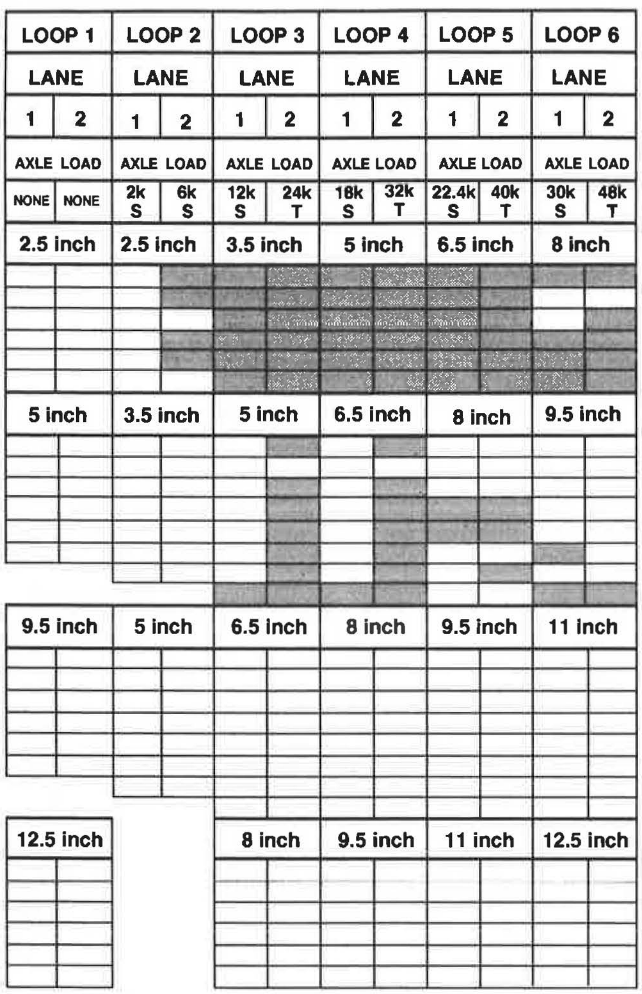

FIGURE 2 AASHO Road Test: rigid test sections with less than 2.5 PSI.

TABLE 1 TEST SECTION DATA USED FOR SMALL/WINSTON MODEL

Pavement Thickness (in.)	Number AASHO Test Sections	Censored	Observed
2.5	12	8	4
3.5	26	14	12
5	42	22	20
6.5	44	24	20
8	56	42	14
9.5	44	41	3
11	28	28	0
12.5	12	12	0
Total	264	191	73

Load coefficient (A_2) = 3.24; standard error = 0.2595; thickness coefficient (A_1) = 5.04; and standard error = 0.3285.

term and 4.62 in the AASHO term. The significance of these equations for a typical 10-in. rigid pavement is a prediction of 9.3 million equivalent single axle loads (ESALs) for the Small/Winston equation and 28.6 million for the AASHO equation.

Because the Small/Winston analysis only used PSI data from the three poorest-performing 9.5-in.-thick test sections and censored all 81 other 9.5-, 11-, and 12.5-in.-thick sections, it would seem that extrapolation into these thicker sections would be less accurate than the least-squares method. From a plot of the comparisons in Figure 3 of predicted ESALs for various thicknesses at 2.5 PSI, it is obvious that the two predictions are far apart for thick sections.

ILLINOIS DOT ANALYSIS OF REHABILITATED TEST SECTIONS

After the AASHO Road Test, many thicker rigid test sections remained in excellent condition. The other sections were rehabilitated as new 10-in.-thick rigid test sections constructed to duplicate the original AASHO construction practices. This rehabilitated roadway was incorporated into I-80 to continue the research on this historic road test. For inclusion into the new study of the rehabilitated roadway, the rigid test sections had to be at least 8 in. thick and structurally sound, with no visible signs of deterioration. A few 8-in. sections, most of the 9.5-in. sections, and all of the 11- and 12.5-in. sections were retained as original test sections. The rehabilitated test facility included 84 original Design 1 rigid test sections, 10 original Design 3 rigid test sections, and 74 new 10-in.-thick rigid test sections. All of these were in the eastbound roadway, but only half of each were in the outside lane.

The facility was opened to traffic in November 1962 and initially received an average daily traffic (ADT) of 3,500 veh/day. The traffic consisted of 71 percent passenger cars, 6 percent single-unit trucks, and 23 percent multiple-unit trucks. More than 96 percent of the heavy trucks used the outer lane; therefore, only the outer lane was evaluated. In 1973 the ADT was 15,700. In 1974 the ADT dropped to 14,000 due to the fuel shortage but began to rise when the fuel shortage eased. The annual growth rate of ADT during the first 10 years was a very high 22 percent.

TABLE 2 COMPARISON OF PERFORMANCE EQUATIONS

	A_0	(Std Error)	A_1	(Std Error)	A_2	(Std Error)	A_3	(Std Error)	ESALs Predicted
AASHO	13.53		7.08		4.53		3.17		28.6
Small/Winston	13.505	(0.307)	5.041	(0.329)	3.241	(0.260)	2.270	(0.242)	9.3

$\ln N = A_0 + A_1 \ln (D + 1) - A_2 \ln (L_1 + L_2) + A_3 \ln (L_2)$
where
D = thickness;
L_1 = load in Kips;
L_2 = number of axles.

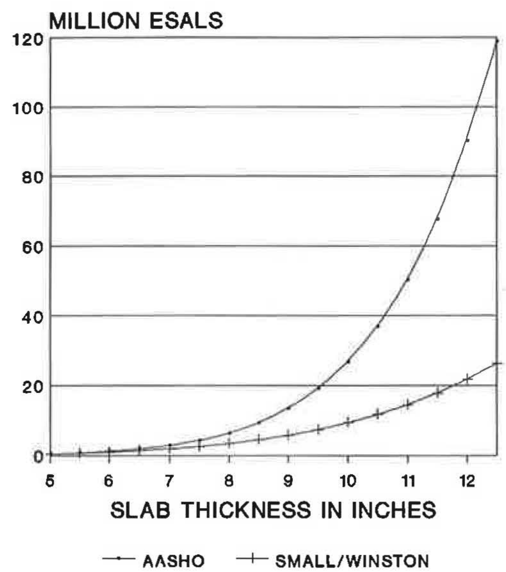

FIGURE 3 Comparison of predicted ESALs.

All of the 9.5-, 11-, and 12.5-in. test sections of AASHO Loop 6, Lane 2 (48-kip tandem loading), were retained as original test sections and received 10 million ESALs of additional mixed loading, except for two 9.5-in. test sections (372 and 340). All of the 9.5- and 11-in. test sections of AASHO Loop 5, Lane 2 (40-kip tandem loading), were retained and received 10 million ESALs of additional mixed loading, except two 9.5-in. test sections (526 and 536). All of the 9.5-in. sections of AASHO Loop 4, Lane 2 (32-kip tandem loading), were continued for additional traffic in the outer lane for 12 years. All of the sections retained as original in Loops 4, 5, and 6 that were in Lane 1 (18-, 22.4-, and 30-kip single-axle loading) received additional traffic in the experiment but were incorporated into I-80 as the inside lane, and therefore received much less heavy traffic. Figure 4 shows a listing of the AASHO test sections that received traffic in the Illinois study.

The results of the additional trafficking of these original test sections were published by Illinois DOT (*2*). Analysis of the data by Little and McKenzie concluded that the Road Test performance equation failed to predict the serviceability trend for the 11- and 12.5-in. rigid pavement sections with the same precision that was achieved for the 8- and 9.5-in. pavements. They concluded that the Road Test performance equation fit the 9.5-in. rigid pavement data well. Because the 11- and 12.5-in. rigid pavements showed so little change in serviceability index during the AASHO Road Test, Little and

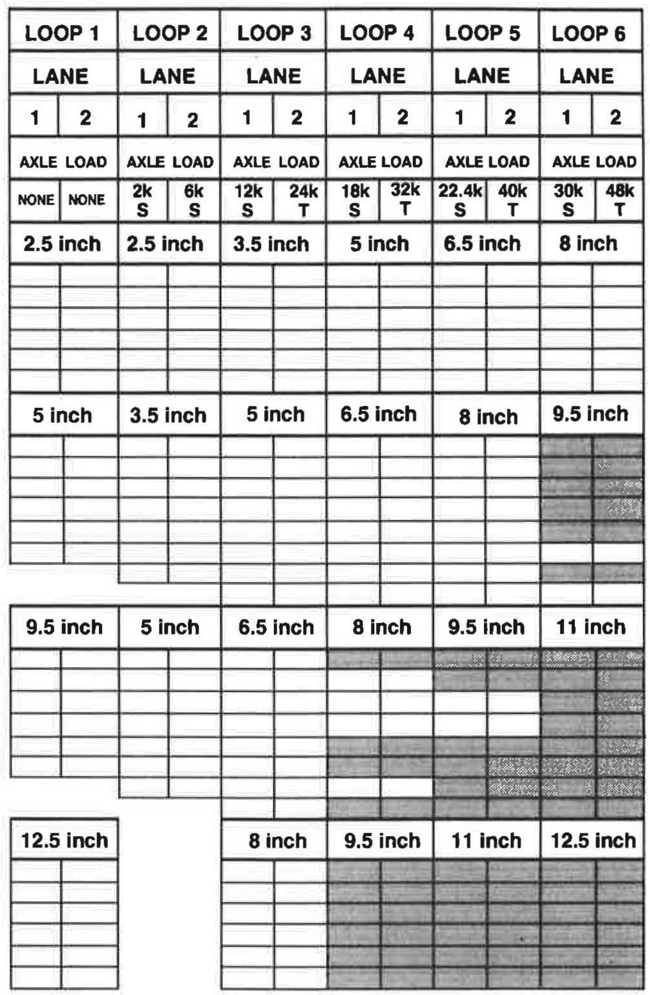

FIGURE 4 AASHO Road Test: rigid test sections included in I-80.

McKenzie theorized that the road test equation extrapolation in this area might be improved by further analysis.

Little and McKenzie (*2*) performed an analysis of the improved data on the additional trafficking of the test sections using the same least-squares analysis as was originally performed. Being careful to take data from five different traffic levels (usually 1968, 1969, 1971, 1972, and 1974), the analysis was performed and the following revised performance equation was reported (assuming beta equal to 1):

$$\log W_{18} = 2.724 + 4.50 \log(D_2 + 1) + G$$

This equation can be compared with the original AASHO equation in the same format:

$$\log W_{18} = -0.058 + 7.35 \log(D_2 + 1) + G$$

PROJECTION OF SMALL/WINSTON ANALYSIS WITH ILLINOIS DOT DATA

Because Small and Winston (*3*) reference the Illinois DOT data to support their findings, it was assumed that their analysis would concur with the findings of Little and McKenzie (*2*). The data from the Illinois study were applied to the Small/Winston method of survival analysis, and the results were surprising.

The Small/Winston analysis used only three 9.5-in. test sections (339, 340, and 371). All 41 remaining 9.5-in. test sections were censored at 1.114 million axle passes. However, 18 of the original 9.5-in. test sections and several 11- and 12.5-in. test sections could now be included into the analysis with additional traffic. By rerunning the Small/Winston analysis with this additional traffic data from the Illinois study, new coefficients of the Small/Winston performance equation could be computed.

Illinois DOT was contacted, but the exact data used in the study were not available other than those tabulated in the report. The Illinois report (*2*) states that only two 9.5-in. sections reached a 2.5 PSI after 12 years of traffic. The Small/Winston data were run with one of the Loop 4 sections and one of the Loop 6 sections as observations assuming to reach 2.5 PSI at 9.6 and 18.6 million ESALs; the 16 remaining 9.5-in. pavements in the high traffic lane were censored at their respective ESALs.

To further define the equation, the 11- and 12.5-in. pavements were added into the analysis using the same procedure. The six 12.5-in. pavements in Loop 6, Lane 2, were censored at 18.6 million ESALs. The 11-in. pavements in Loop 5, Lane 2, were censored at 14 million ESALs, and the 11-in. pavements in Loop 6, Lane 2, were censored at 18.6 million ESALs. The analysis was run with the sections shown in Figure 5, and the results are presented in Table 3. Table 4 presents a comparison of the AASHO, Small/Winston, and revised Small/Winston performance equations.

To prevent possible criticism of the use of mixed ESAL traffic as calculated by AASHTO, and to test the sensitivity of the findings, the analysis was run with different assumptions of traffic. All mixed traffic was assumed to be 32-kip tandem axle loads from typical five-axle tractor-trailer combinations, and the number of passes that would have been the AASHTO equivalent of 10 million ESALs was backcalculated. It was then possible to substitute the additional traffic into the LIFEREG procedure as 32-kip tandem axle loads rather than 18-kip single axle equivalents to see if this change would make a significant difference. The LIFEREG procedure was then rerun, with very little change in results:

- Load coefficient (A_2) = 4.35, standard error = 0.212; and
- Thickness coefficient (A_1) = 6.52, standard error = 0.242.

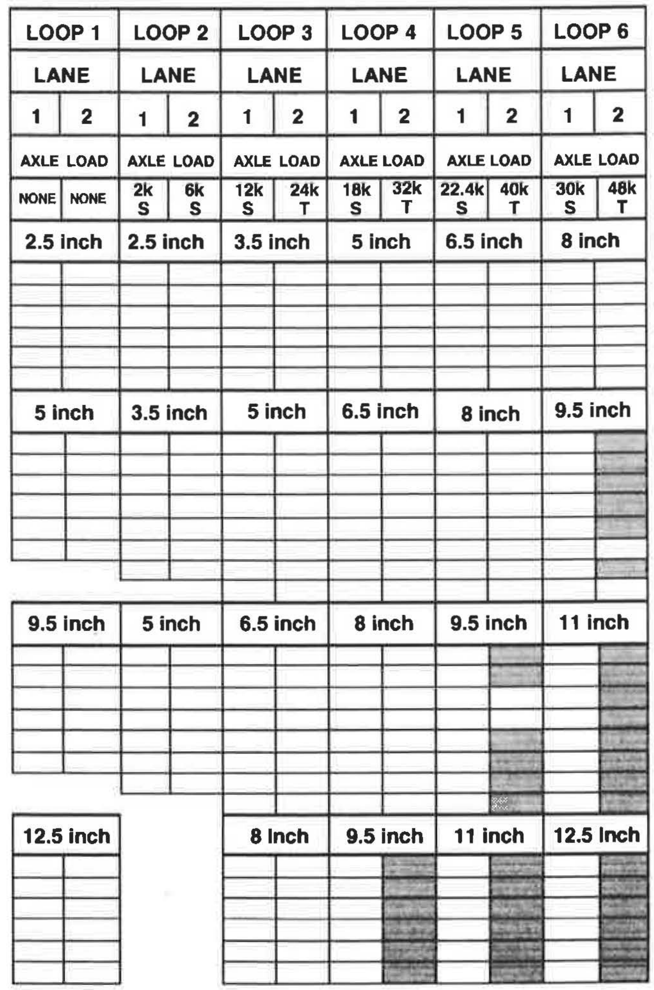

FIGURE 5 AASHO Road Test: rigid test sections added in revised analysis.

The survival analysis method uses only one PSI point in time for each observed test section versus the five minimum PSI points of the AASHO least-squares analysis. The large error in the *Road Work* model exists because so few thick rigid sections were uncensored (only 3 at 9.5 in. or thicker); the least-squares analysis at least attempts to extrapolate when the other 81 (9.5 in. or thicker) test sections will reach terminal serviceability. The censored test sections in the survival analysis have no PSI value; therefore, the analysis cannot estimate whether the censored test section is at 2.6 PSI or still nearly smooth at 4.5 or greater PSI. As more traffic was recorded, fewer test sections were censored and many others were censored at higher traffic levels, thus increasing the accuracy.

COMPARISON OF AASHTO, ILLINOIS DOT, AND SMALL/WINSTON ANALYSES

Figure 6 shows a graphical depiction of the AASHO, Illinois DOT, Small/Winston, and revised Small/Winston performance equations. Because the Small/Winston performance equations only predict loading at 2.5 PSI and no beta term

TABLE 3 DISTRIBUTION OF TEST SECTIONS BY THICKNESS

PAVEMENT THICKNESS	CENSORED @ 1.114 MILLION AXLE PASSES	CENSORED @ 11.6 MILLION ESALS	CENSORED @ 14 MILLION ESALS	CENSORED @ 18.6 MILLION ESALS	OBSERVED
2.5	8				4
3.5	14				12
5.0	22				20
6.5	24				20
8.0	42				14
9.5	23	5	6	5	5
11.0	14		6	8	0
12.5	6			6	0
TOTALS:	153	5	12	19	75

RESULTS:

LOAD COEFFICIENT A_2 = 4.46 STANDARD ERROR = 0.247

THICKNESS COEFFICIENT A_1 = 6.72 STANDARD ERROR = 0.277

TABLE 4 COMPARISON OF PERFORMANCE EQUATIONS

	A_0	(Std Error)	A_1	(Std Error)	A_2	(Std Error)	A_3	(Std Error)	Predicted (Millions)
AASHO	13.53		7.08		4.53		3.17		28.6
Small/Winston	13.51	(0.307)	5.04	(0.329)	3.24	(0.260)	2.27	(0.242)	9.3
Revised Small/Winston	14.02	(0.379)	6.72	(0.277)	4.46	(0.247)	3.09	(0.257)	24.1

$\ln N = A_0 + A_1 \ln (D + 1) - A_2 \ln (L_1 + L_2) + A_3 \ln (L_2)$
where
D = thickness;
L_1 = load in Kips;
L_2 = number of axles.

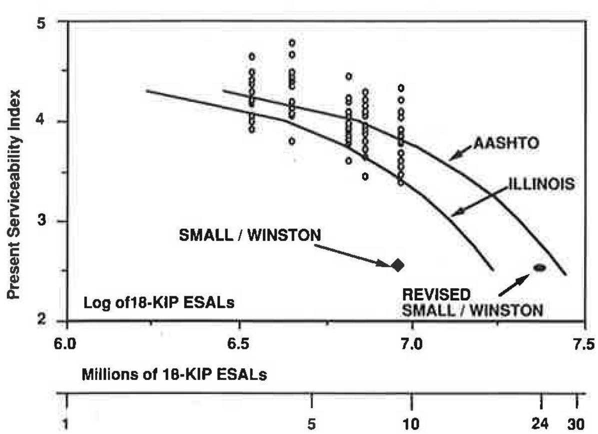

FIGURE 6 Performance of 10-in. rigid sections of rehabilitated AASHO roadway.

exists to convert to a terminal serviceability index other than 2.5, they are graphically represented only as a point.

When compared with the new 10-in. rigid test sections of the rehabilitated Illinois roadway, it is clear that the original Small/Winston analysis significantly underestimates the life of 10-in. rigid pavements (see Figure 6). The revised Small/Winston analysis is very close to the AASHO and Illinois performance equations for 2.5 PSI. The Illinois performance equation is a little more conservative in its prediction of pavement life than the AASHO equation because it underestimates most of the observed test sections. The AASHO equation seems to predict the average of the performance of the test sections with nearly half underestimated and half overestimated.

Figure 7 shows a graphical depiction of the ESAL prediction of the four different performance equations for a terminal serviceability index of 2.5 over a range of thickness. This

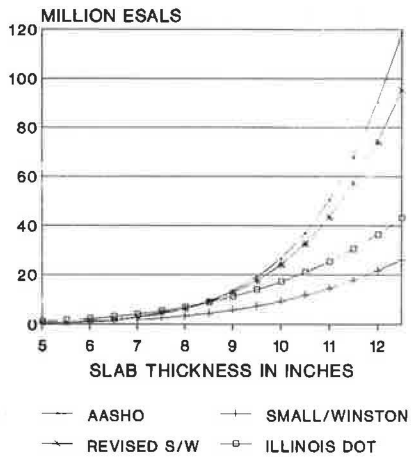

FIGURE 7 Comparison of predicted ESALs.

figure shows that the revised Small/Winston model predicts an even greater number of ESALs than the Illinois study for pavement thickness greater than 9 in.

LOAD POWER FACTOR

The fourth power law commonly referred to by engineers is more properly called a load power factor. The load power factor gives a measure of the sensitivity of load equivalence factor (LEF) to load. It is defined as the log of LEF divided by the log of the load ratio (R), where R is the ratio of the load divided by the reference load—usually 18 kips.

LEFs estimate the amount of damage done by a given load compared with the damage from a standard 18-kip axle. The *AASHTO Interim Design Guide* gives a table of LEFs for a wide range of loads, axles, and pavement thicknesses. Similar LEFs can be calculated using the Small/Winston model by dividing the number of predicted 18-kip axle passes to failure by the predicted axle passes for the nonstandard load; the results are different from those of AASHTO.

The load power factor given by AASHTO is approximately 4.3. Using the above method, Figure 8 shows the load power factor to be 3.01 for the Small/Winston model and 4.05 for the revised Small/Winston model.

CONCLUSIONS

1. The AASHTO performance equation overestimates the prediction of traffic for thicknesses greater than 9.5 in.
2. The Small/Winston analysis of the AASHO Road Test data provides a poor prediction of the serviceability of thick rigid pavements and severely underestimates the lifetimes of rigid pavements greater than 8.0 in. in thickness.
3. The Small/Winston method of analysis is excellent if sufficient data for thick rigid pavements are used. The revision to the Small/Winston performance equation that was based on additional traffic data for the original AASHO thick rigid test sections is an excellent analytical procedure.
4. The revised Small/Winston performance equation gives even higher predictions of 18-kip ESAL loads than does the original AASHO performance equation revised by Little and McKenzie when both used the data of additional trafficking of the thick rigid test sections.
5. The load power factor for equivalent loading is not a third power as claimed in the *Road Work* analysis but is at least a fourth power, as confirmed by the revised Small/Winston model.

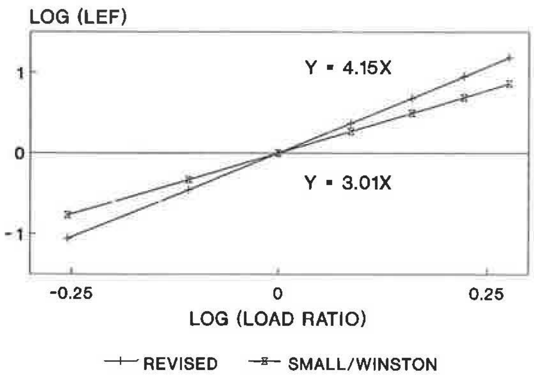

FIGURE 8 Determination of load factor.

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