Thickness Design

1972 AASHTO Method

AASHTO Method

Pavement engineers recognized early that pavements were being worn out by high axle loads. Lacking basic design principles, states were forced to impose axle load limits to keep their pavements intact. At first, each state had its own limits. During WWII, AASHO recommended an 18-kip load limit for dual-tire, single-axle trucks. After WWII, this limit was adopted as FHWA policy along with a 32-kip limit for tandem-axle trucks.

AASHTO Method

In an attempt to develop rational pavement design methods, engineers conducted experiments using test strips with different pavement layer thicknesses. At first these were built on existing U.S. highways and used existing traffic. Eventually, these gave way to test roads built specifically for experimentation that used trucks with specific axle loads that continuously traversed the test sections.

AASHTO Method

The first, built in Idaho in 1951, consisted of two identical test loops. On each loop, the northbound straightaways used 2" of hot mix asphalt over a 4" gravel base and the southbound straightaways used 4" of hot mix asphalt over a 2" gravel base. Each straightaway was separated into 300' sections. The different test sections were built with 0", 4", 8", 12", and 16" of subbase.

AASHTO Method

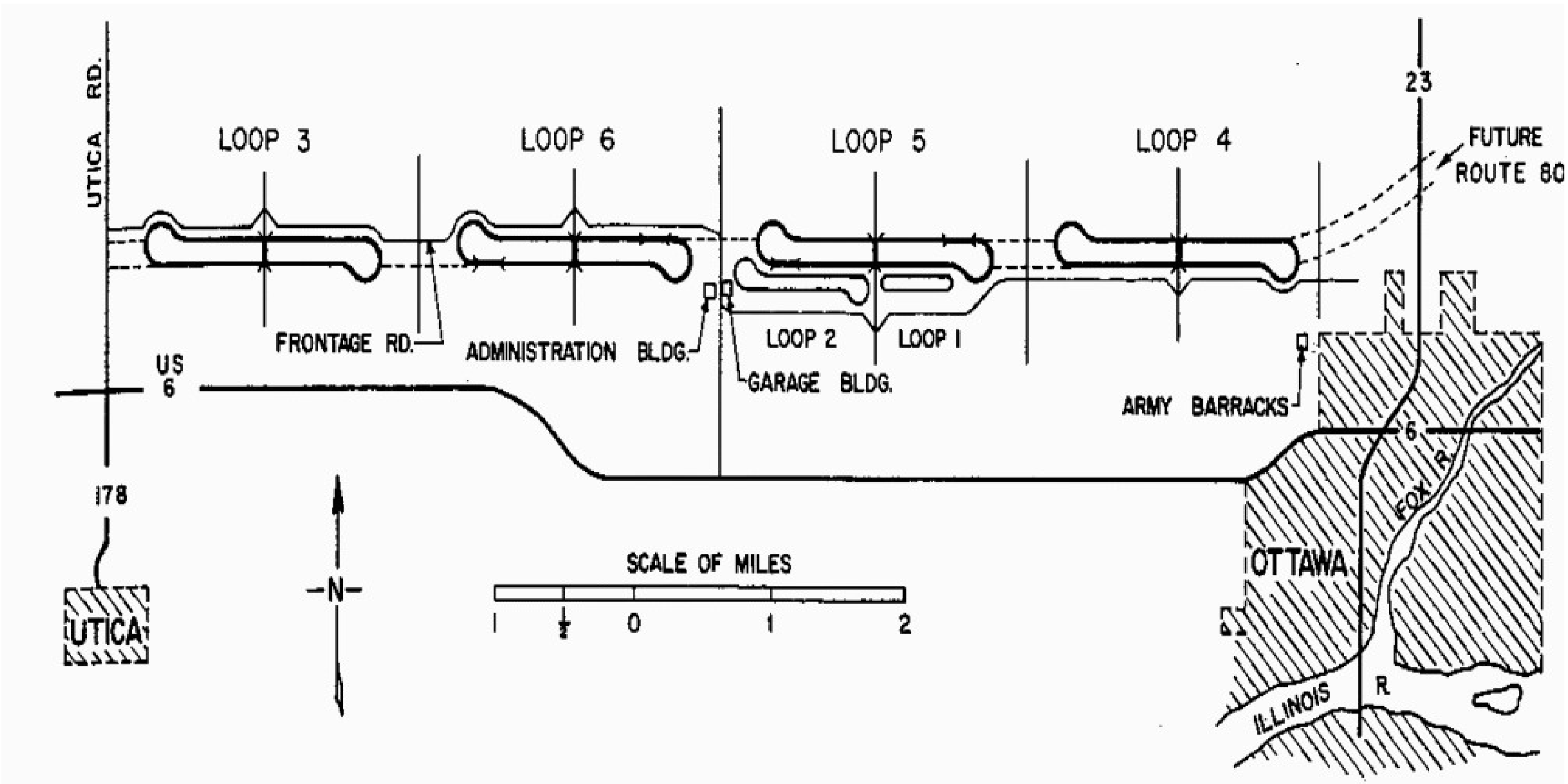
One loop was traversed exclusively by 18-kip single axle loads in the inner lanes and 22.4-kip single axle loads in the outer lanes. The other used 32-kip and 40-kip tandem axle loads.

The test ran for 18 months, accumulating 238,000 vehicle passages between the end of 1952 and the beginning of 1954.

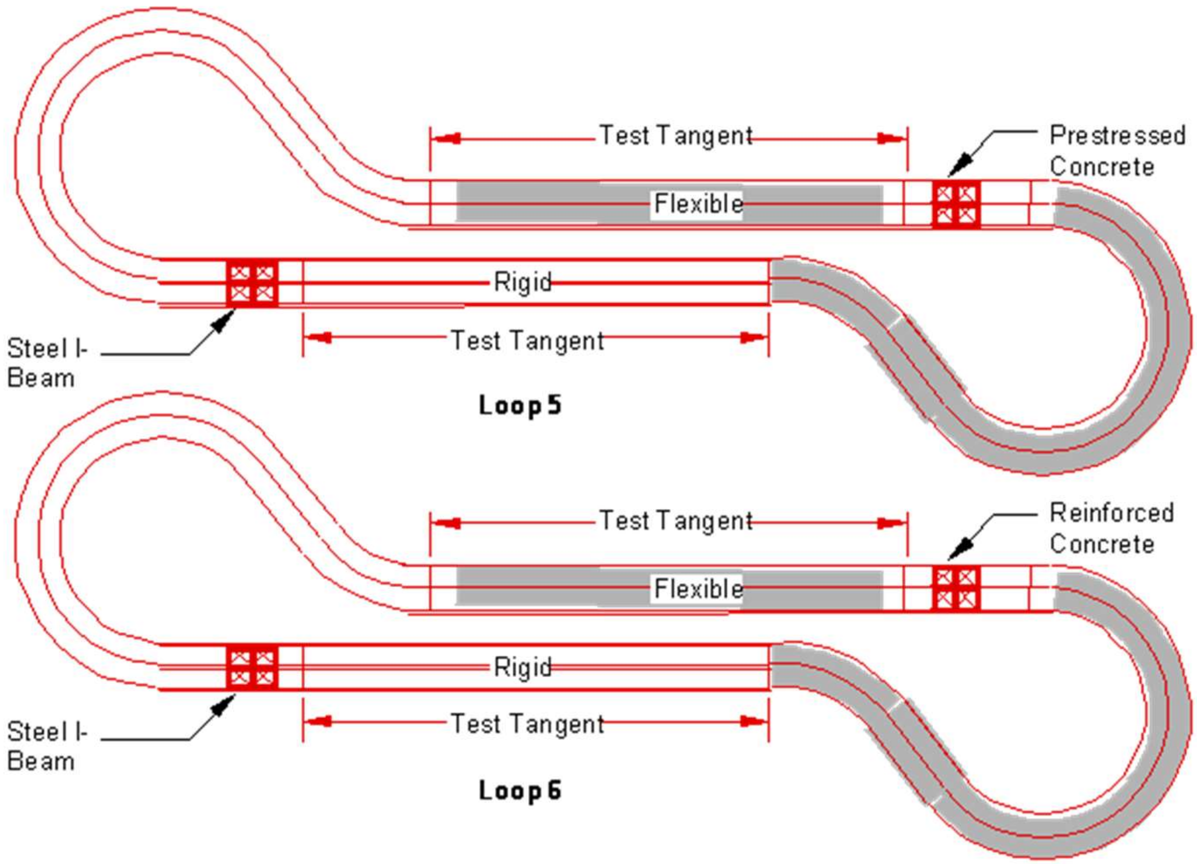
AASHTO Method

In 1956, the American Association of State Highway Officials (AASHO) followed up with an even more comprehensive road test in Ottawa, Illinois. The test road was constructed on the right-of-way of what was to become I-80. The setup consisted of four large loops and two small loops of 4-lane highway broken into 836 100-foot test segments. All of the northbound lanes were hot-mix asphalt and all of the southbound lanes were portland-cement concrete.

AASHO Road Test



AASHO Road Test



Source: WSDOT Pavement Guide Interactive CD-ROM

AASHTO Method

The flexible pavement sections were constructed with 1", 2", 3", 4", 5", or 6" of HMA surface course; 0", 3", 6", or 9" of base course; and 0", 4", 8", or 12" of subbase. Four types of base were used: gravel, crushed stone, cement-treated, and asphalt-treated.

AASHO Road Test

Table 5: AASHO Road Test Structural Design Thickness Summary

Loop No.	AC Thickness (in.)	Base Thickness (in.)	Subbase Thickness (in.)
1	1.0 3.0 5.0	0.0 6.0 --	0.0 8.0 16.0
2	1.0 2.0 3.0	0.0 3.0 6.0	0.0 4.0 8.0
3	2.0 3.0 4.0	0.0 3.0 6.0	0.0 4.0 --
4	3.0 4.0 5.0	0.0 3.0 6.0	4.0 8.0 12.0
5	3.0 4.0 5.0	3.0 6.0 9.0	4.0 8.0 12.0
6	4.0 5.0 6.0	3.0 6.0 9.0	8.0 12.0 16.0

Source: WSDOT Pavement Guide Interactive CD-ROM

AASHTO Method

The rigid pavements were constructed with slabs from 3½" thick to 12½" thick, in 1½" increments. The slabs were poured on 0", 3", 6", or 9" of subbase consisting of a sand and gravel mix with a CBR of 35%. The joints between the slabs were kept aligned with dowel bars of various lengths and diameters. These keep the slabs from moving independently under wheel loads so the individual slabs act as one continuous concrete road surface.

AASHO Road Test

Table 13: Rigid Pavement Structural Design Parameters

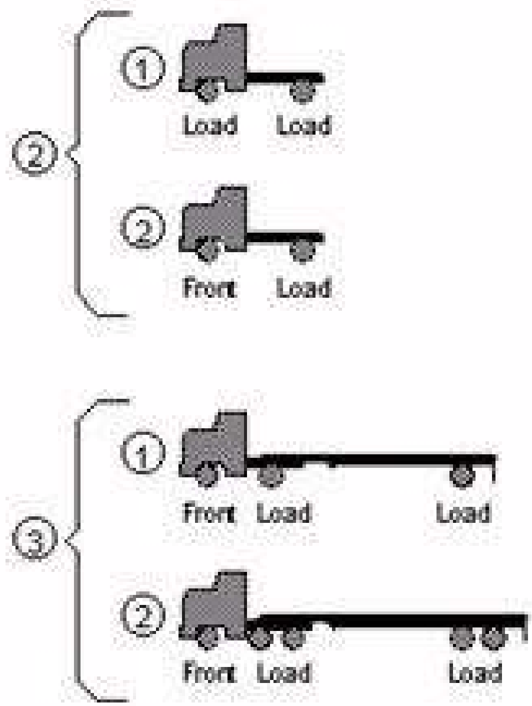
Loop No.	PCC Slab Thickness (in.)	Subbase Thickness (in.)	Transverse Dowel Bars (Diameter x Length)
1	2.5 5.0 9.5 12.5	0, 6.0 0, 6.0 0, 6.0 0, 6.0	3/8" x 12" 5/8" x 12" 1 1/4" x 18" 1 5/8" x 18"
2	2.5 3.5 5.0	0, 3.0, 6.0 0, 3.0, 6.0 0, 3.0, 6.0	3/8" x 12" 1/2" x 12" 5/8" x 12"
3	3.5 5.0 6.5 8.0	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	1/2" x 12" 5/8" x 12" 7/8" x 18" 1" x 18"
4	5.0 6.5 8.0 9.5	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	5/8" x 12" 7/8" x 18" 1" x 18" 1 1/4" x 18"
5	6.5 8.0 9.5 11.0	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	7/8" x 18" 1" x 18" 1 1/4" x 18" 1 3/8" x 18"
6	8.0 9.5 11.0 12.5	3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0 3.0, 6.0, 9.0	1" x 18" 1 1/4" x 18" 1 3/8" x 18" 1 5/8" x 18"

Source: WSDOT Pavement Guide Interactive CD-ROM

AASHTO Method

One of the small loops was left to serve as a control. The other was loaded by trucks with single axle loads of 2000-lb and 6000-lb. The larger loops were loaded by tractor-trailers with single axle loads of 12, 18, 22.4, and 20 kips and tandem axle loads of 24, 32, 40, and 48 kips. A fleet of 60 trucks operated 18½ hours a day, 6 days a week, 6 vehicles per lane at a speed of 35 mph for nearly 2 years. By the end of the test, 1.1 million axle loads had been applied!

AASHO Road Test

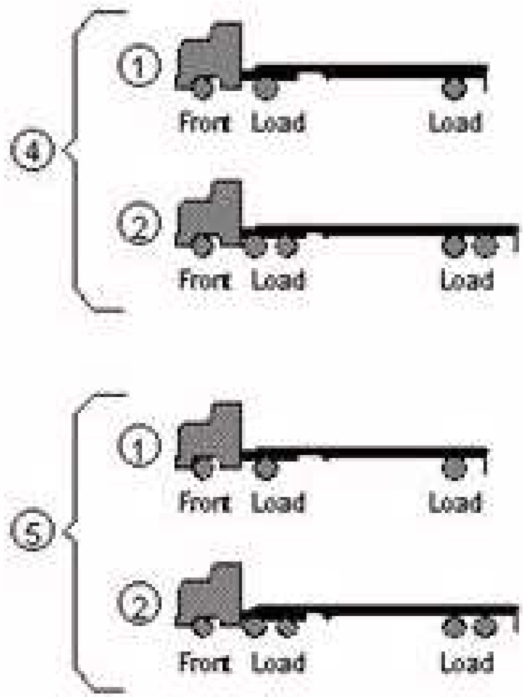


Weight in Kips

Loop	Lane	Front Axle	Load Axle	Gross Weight
2	1	2	2	4
2	2	2	6	8
3	1	4	12	28
3	2	6	24	54

Source: WSDOT Pavement Guide Interactive CD-ROM

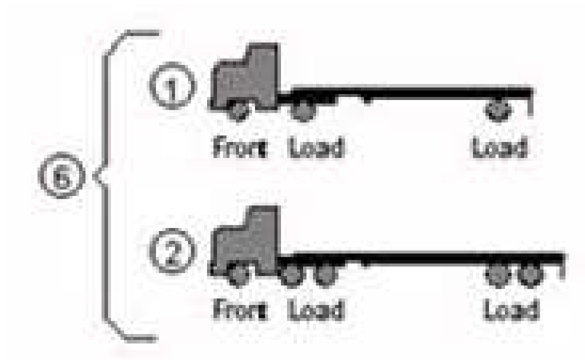
AASHO Road Test



Weight in Kips		
Front Axle	Load Axle	Gross Weight
6	18	42
9	32	73
6	22.4	50.8
9	40	89

Source: WSDOT Pavement Guide Interactive CD-ROM

AASHO Road Test



Weight in Kips

	Front Axle	Load Axle	Gross Weight
1	9	30	69
2	12	48	108

Source: WSDOT Pavement Guide Interactive CD-ROM

AASHO Road Test

Source: http://www.fhwa.dot.gov

AASHTO Method

This test generated an enormous amount of data. To make sense of it all, they analyzed rigid and flexible pavements separately.

For the flexible pavements, they reduced everything to just three index variables encapsulating (a) the structure of the pavement, (b) the condition of the pavement, and (c) the traffic loads applied to the pavement at any point in time.

AASHTO Method

The structure of the pavement is quantified by the ***structural number*** (SN) which captures the thickness and stiffness of the various pavement layers.

The condition of the pavement at any point in time is quantified by the ***present serviceability index*** (PSI) which captures the ride quality of the pavement.

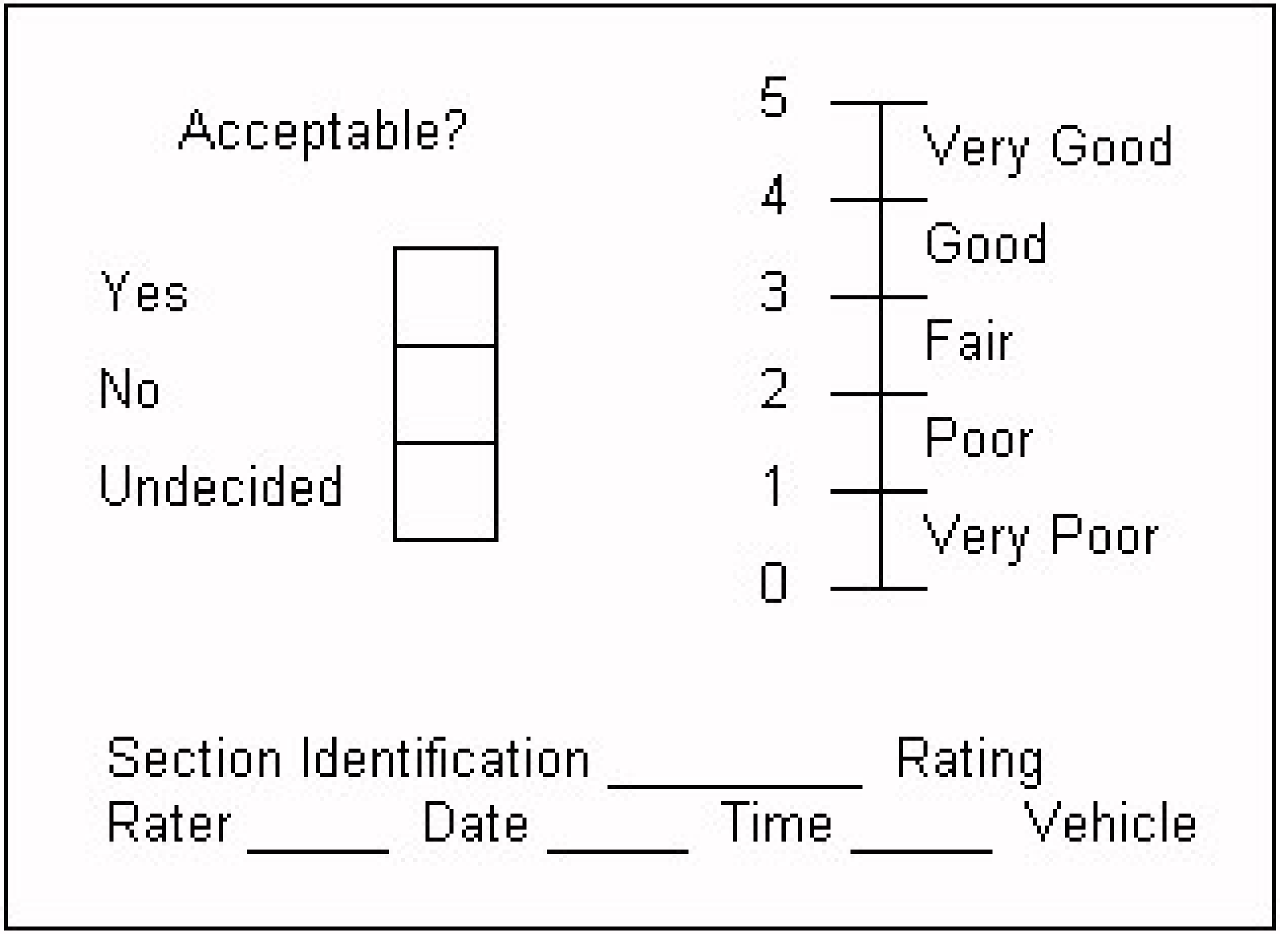
The traffic loads are quantified by the number of 18-kip ***equivalent single axle loads*** (ESALs).

Present Serviceability Rating

During the road test, the condition of the pavement was periodically assessed by measuring things like the amount of cracking, patching and rutting.

At the same time, the ride quality of the pavement was assessed by teams riding in passenger cars. Each team member scored the ride quality on a scale from 0 to 5 and indicated whether or not they found the ride quality acceptable.

Present Serviceability Rating



Acceptable?

Yes

No

Undecided

5

Very Good

4

Good

3

Fair

2

Poor

1

Very Poor

0

Section Identification __________ Rating

Rater _____ Date _____ Time _____ Vehicle

Acceptable Ride Quality

PSR	Acceptable?
3.0	88%
2.5	45%
2.0	15%

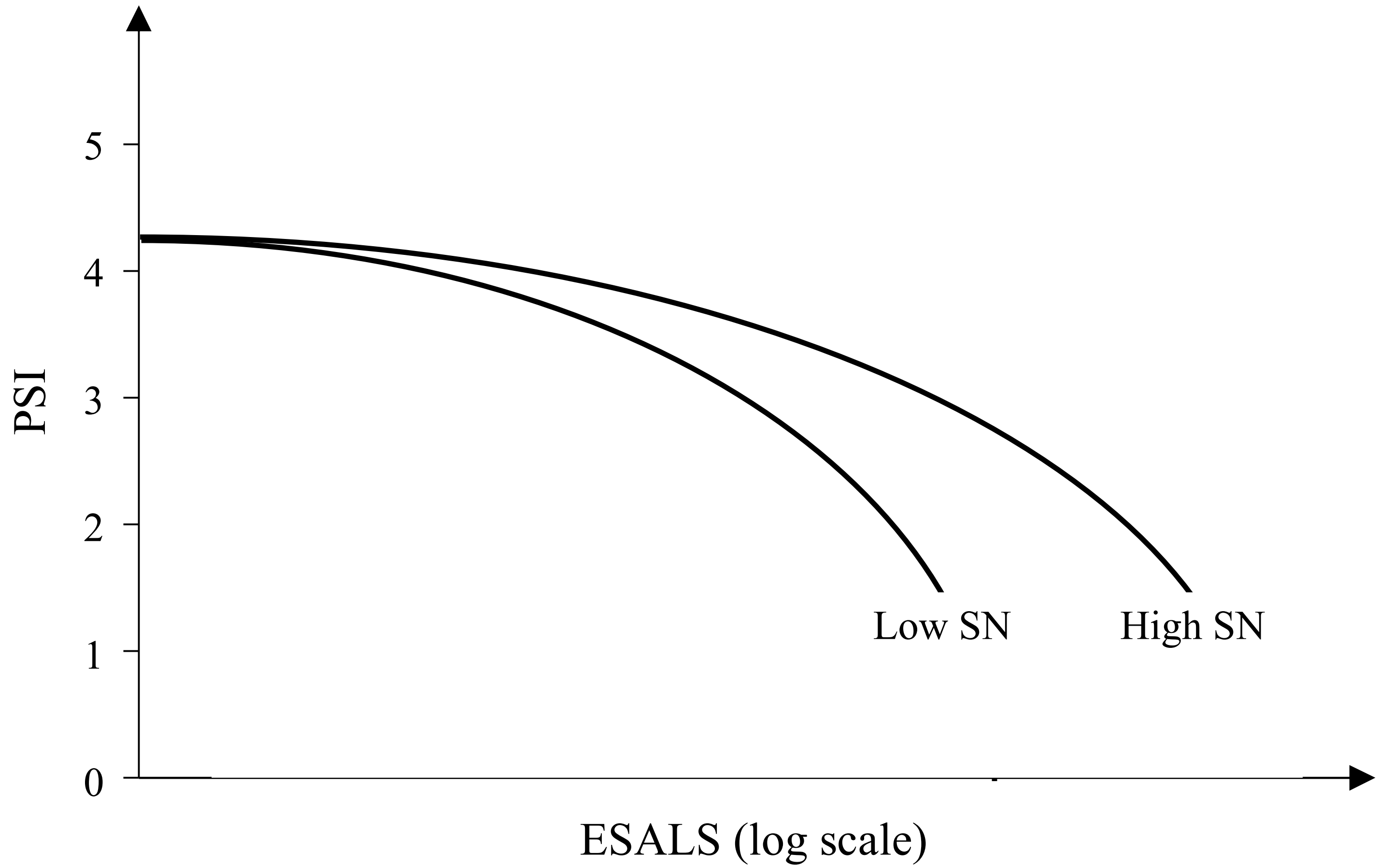
Present Serviceability Index

The highly subjective ride quality ratings were later correlated with the measurable quantities of distress to form the ***present serviceability index*** (PSI). That way, you didn't need teams of riders any more; you could predict what the average rider would assess the ride quality to be from the measurements of rutting, cracking, etc.

Present Serviceability Index

Having reduced the very complex road test results to just three variables (PSI, SN, and ESALs), AASHO engineers developed a regression model relating the change in PSI over time to the number of ESALs as a function of the structural number. Pavements with a high SN can withstand more ESALs before they fail than can pavements with a low SN.

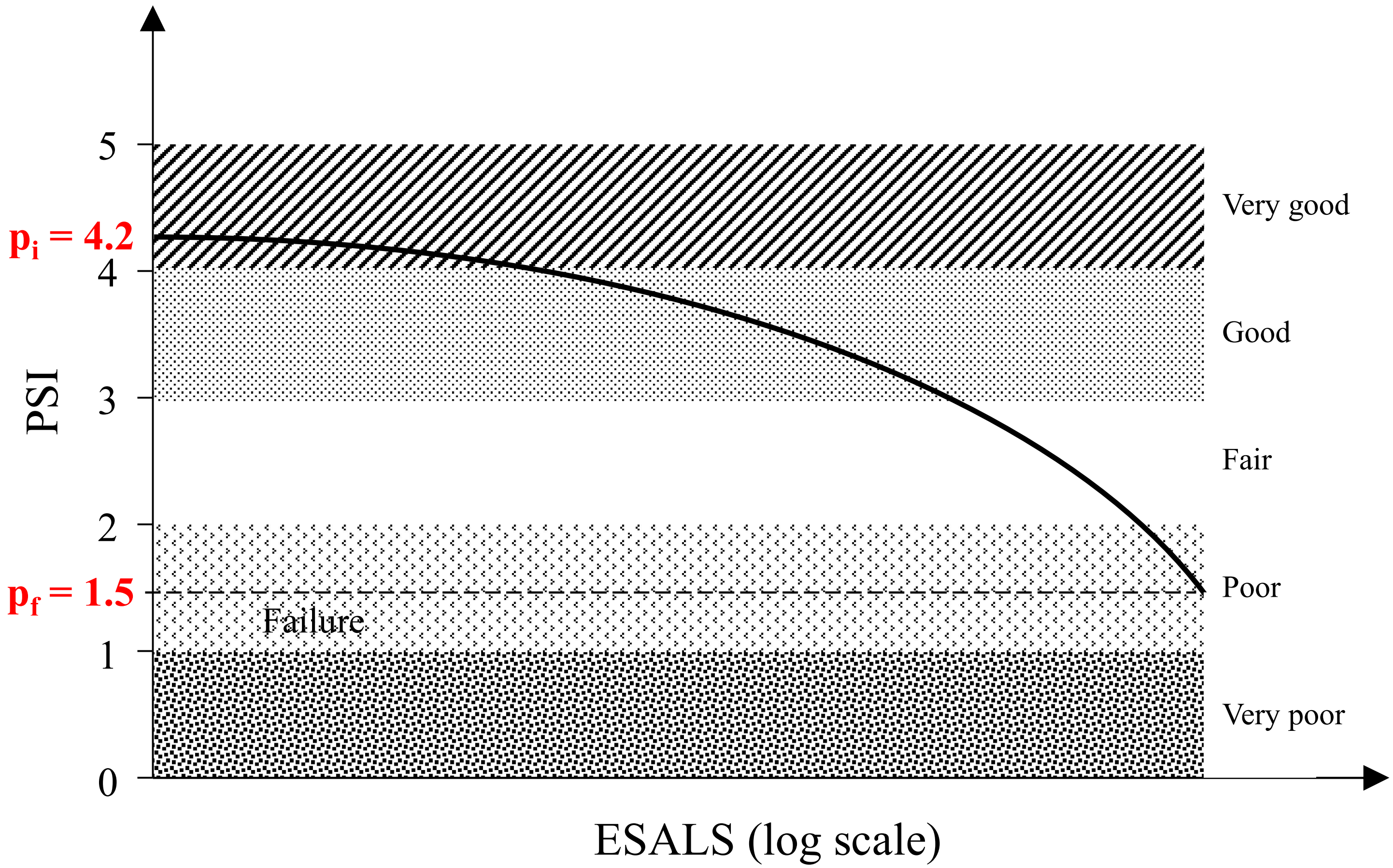
Ride Quality Over Time



Present Serviceability Index

The average ride quality of the pavements when they were first constructed was PSI = 4.2. The engineers deemed PSI = 1.5 to represent failure. At that point, none of the ride quality evaluators found the ride to be of acceptable quality.

Ride Quality Over Time

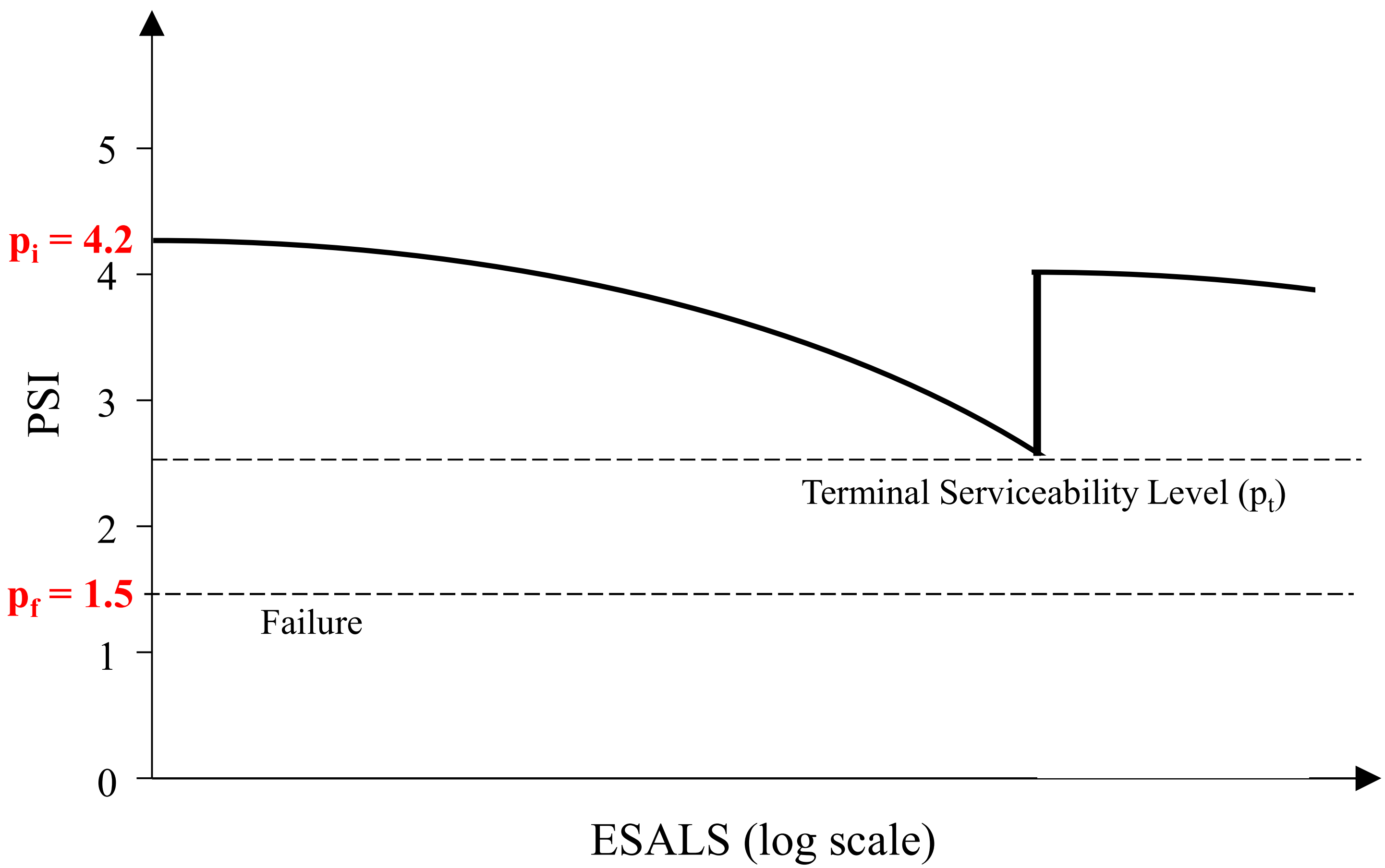


Present Serviceability Index

You really don’t want the roads to reach the point of failure because (a) the motoring public would deem the roads unfit and (b) they would be unsafe because it would be difficult to keep your car in the lane.

The goal, then, is to design the road to accommodate the requisite number of ESALs over its design life without the ride quality falling below some ***terminal serviceability*** level. The road would then be repaved or rebuilt and the clock would start over.

Ride Quality Over Time



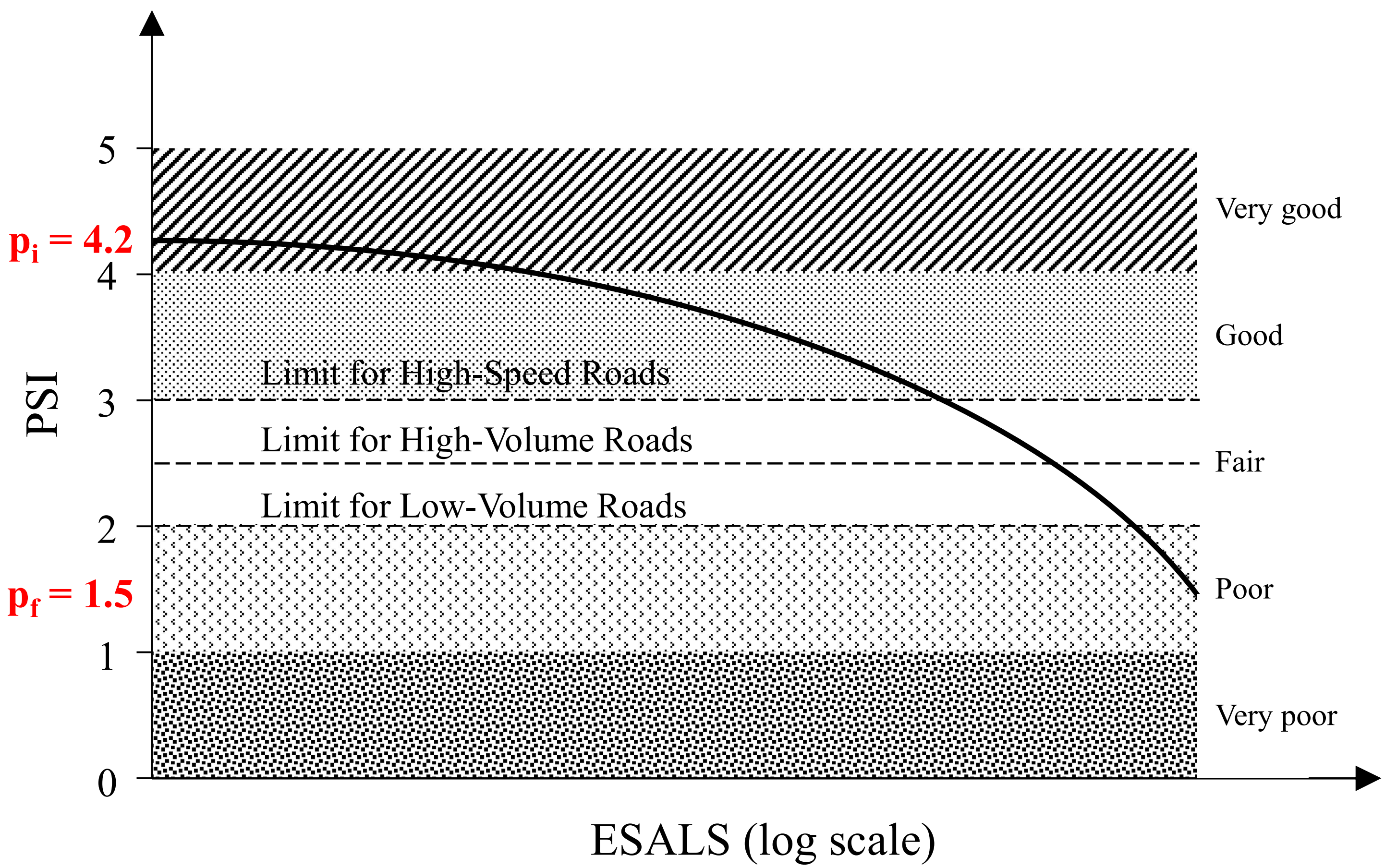
Present Serviceability Index

For low volume roads (like residential streets) you might allow the ride quality drop as low as PSI = 2 before remediating the pavement.

For high volume, lower speed roads (like Poplar Ave. or Germantown Rd.) you would typically design for a terminal serviceability level of 2.5.

For high-speed roads (like highways) it would be unsafe to let the PSI drop much below 3.

Ride Quality Over Time



AASHTO Design Equation

The final regression model developed by the AASHO engineers relates the log of the number of ESALs to the structural number of the pavement system (SN) and the terminal serviceability level (p_t) you want to achieve before rehabilitating the pavement.

AASHTO Design Equation

Ride Quality Threshold

1966

$$\log_{10} W_{18} = 9.36 \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{4.2 - p_t}{4.2 - 1.5}\right)}{0.4 + \frac{1094}{(SN+1)^{5.19}}}$$

Lifetime ESALs

Structural Number (Flexural Rigidity)

AASHTO Design Equation

One drawback to this equation is that it completely neglects the subgrade support. The pavements for the road test were all built on a 3-foot embankment of the local clayey subgrade soil (CBR = 2) so there was no data to account for the effects of subgrade quality nor the effects of seasonal changes in subgrade support.

AASHTO Design Equation

After publishing the 1966 design equation, engineers set out to incorporate subgrade support in the model.

Their initial attempt (published in 1972) incorporated a ***regional factor*** (R) to account for seasonal changes in subgrade support and a ***soil support value*** (S) that could be related to measures such as the CBR, the group index, and the Hveem resistance value.

AASHTO Design Equation

1972

$$\log_{10} W_{18} = 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\dfrac{4.2-p_t}{4.2-1.5}\right)}{0.4+\dfrac{1094}{(SN+1)^{5.19}}} + \log\frac{1}{R} + 0.372(S_i - 3.0)$$

Lifetime ESALs

Structural Number (Flexural Rigidity)

Ride Quality Threshold

Regional Factor

Subgrade Support

Regional Factor (R)

The regional factor was based on an index value that ranged from a high of 5 for wet, sloppy subgrades such as occur during the spring thaw to a low of 1/5 for frozen subgrades such as occur in the middle of the winter in northern parts of the country.

These regional factors could be averaged over the entire year to arrive at a single value that could be used in the design equation.

Regional Factor (R)

Condition	R value
Roadbed materials frozen to a depth of 5 in. or more (winter)	0.2 – 1.0
Roadbed materials dry (summer and fall)	0.5 – 1.5
Roadbed materials wet (spring thaw)	4.0 – 5.0

Regional Factor (R)

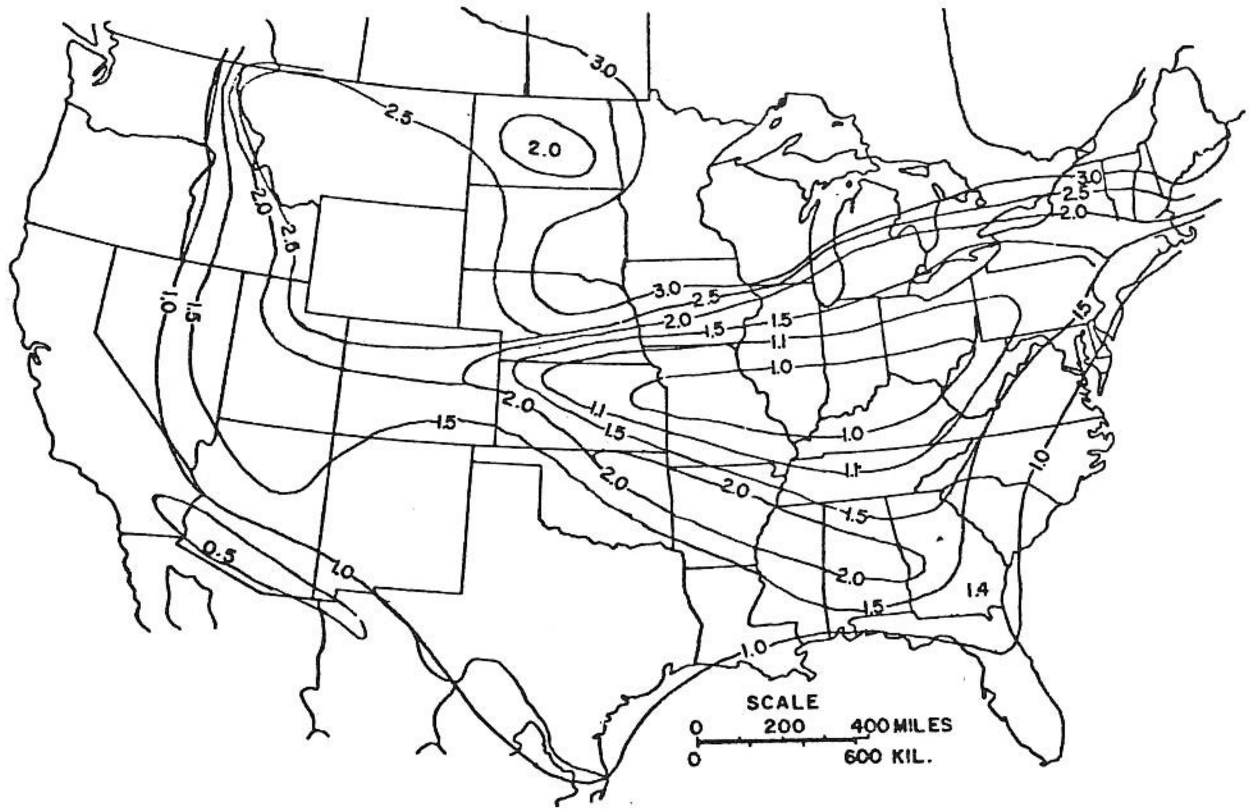


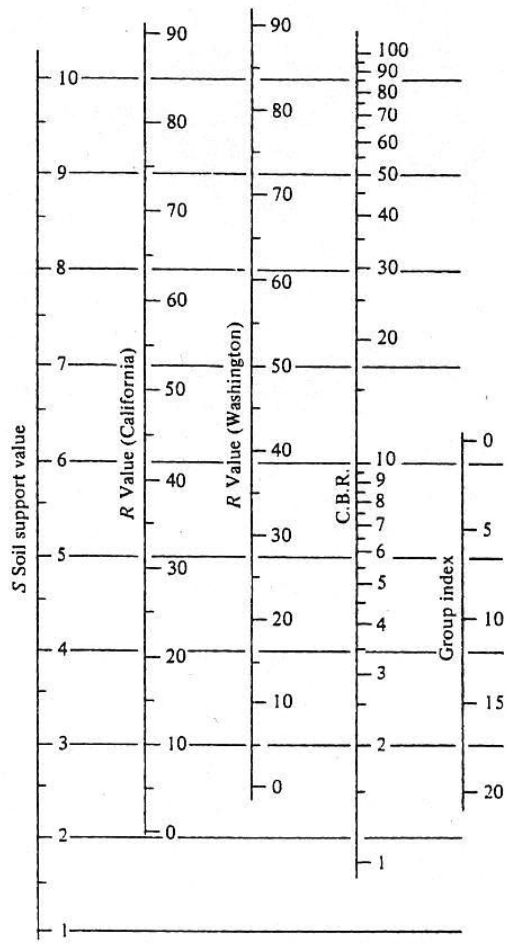
Figure 15.2. Generalized regional map of the United States. (From Van Til et al., NCHRP 128.)

Soil Support Value (S)

The regional factor was carefully chosen so it would have a value of 1 for Ottawa, Illinois. That way, the R term in the design equation dropped out, leaving the original model alone.

The same was done with the soil support value. It was chosen to have a value of 3 for Ottawa, Illinois so the S term in the design equation would evaluate to zero.

Soil Support Value (S)



AASHTO Design Equation

1972

Ride Quality Threshold

Subgrade Support

$$\log_{10} W_{18} = 9.36 \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{4.2 - p_t}{4.2 - 1.5}\right)}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + \log\frac{1}{R} + 0.372(S_i - 3.0)$$

Lifetime ESALs

Regional Factor

Structural Number (Flexural Rigidity)

AASHTO Design Equation

The way this equation is used, you determine values for S and R based on your project location, choose a suitable terminal serviceability level (p_t), then try to find a value of SN that provides the required number of ESALs (W_{18}) over the design life of the pavement.

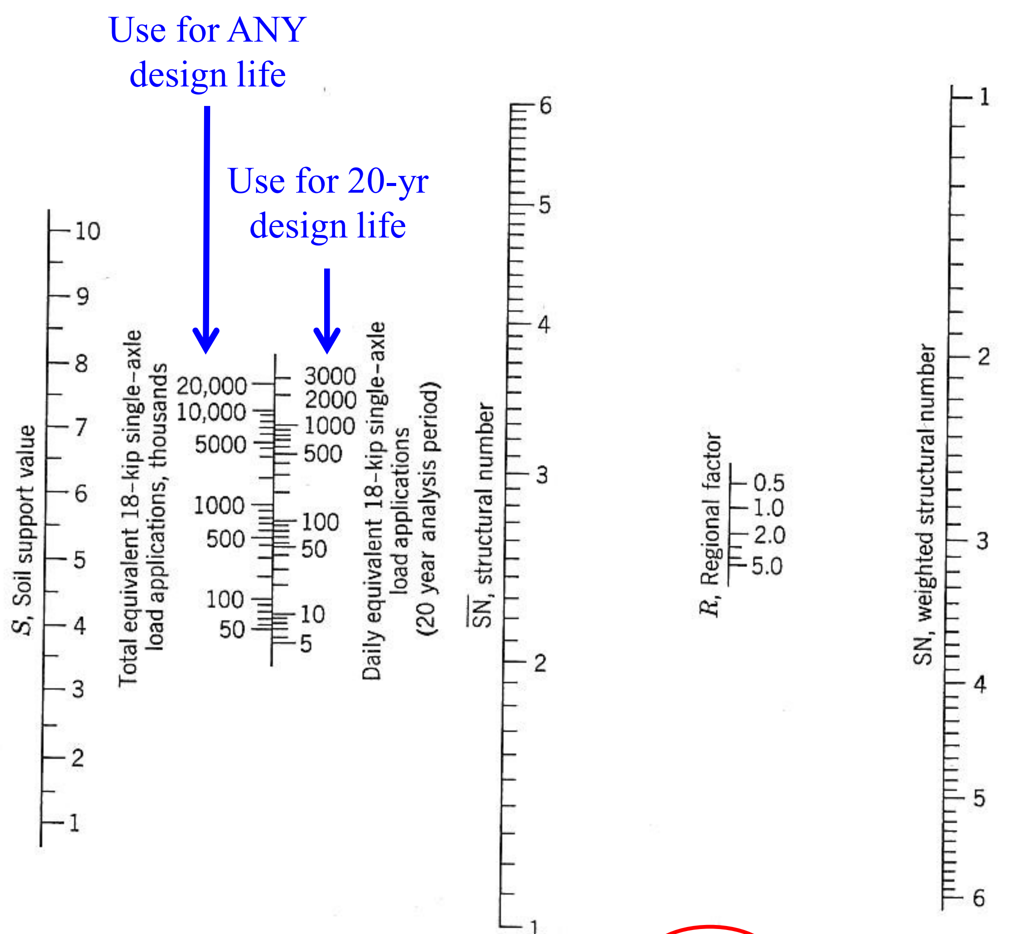
It is not possible to rearrange this equation to get SN on the left-hand side of the equal sign. It has to be solved by trial-and-error.

Soil Support Value (S)

To make matters worse, there were no such things as personal computers or pocket calculators in the late 1960s and early 1970s; logarithms were found by looking up values in tables and multiplication and division were done using slide rules!

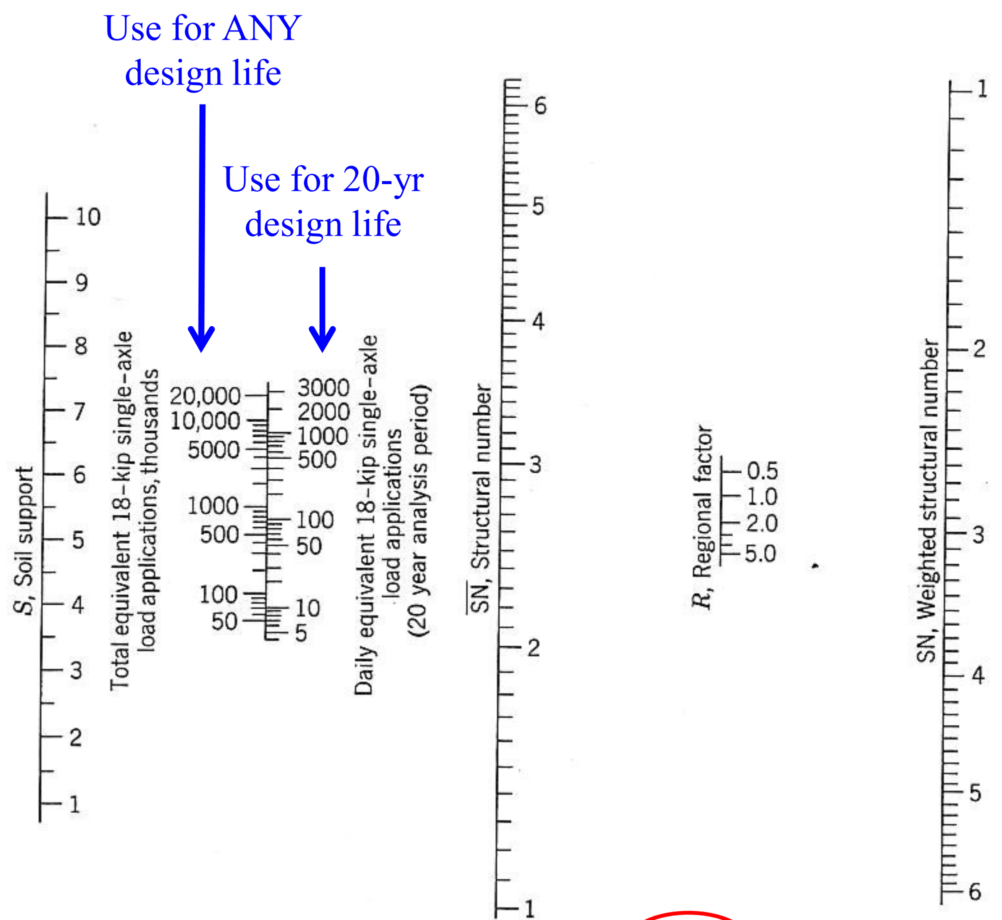
To make the design equation usable, the engineers developed ***nomographs***, which are graphical equation solvers.

AASHTO Design Nomograph



Design chart for flexible pavements, $p_t = 2.5$

AASHTO Design Nomograph

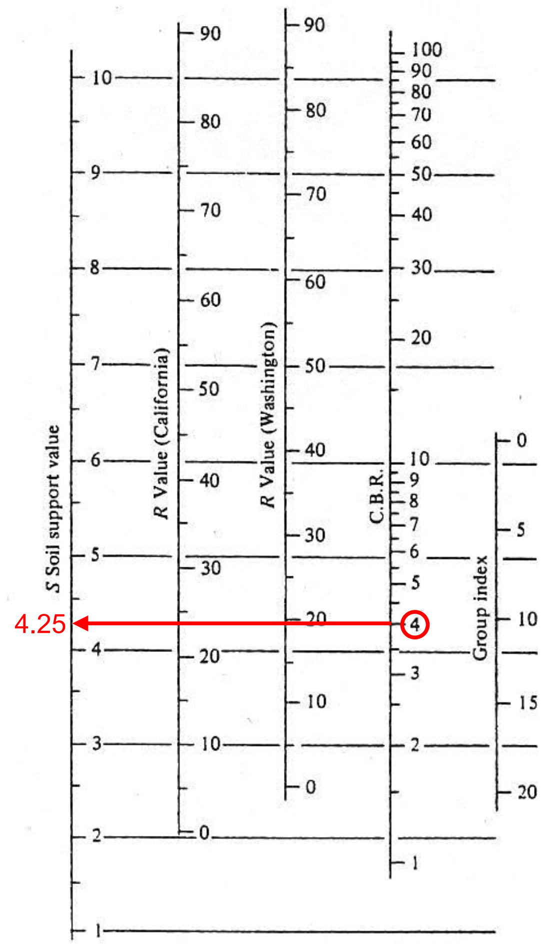


Design chart for flexible payments, $p_t = 2.0$

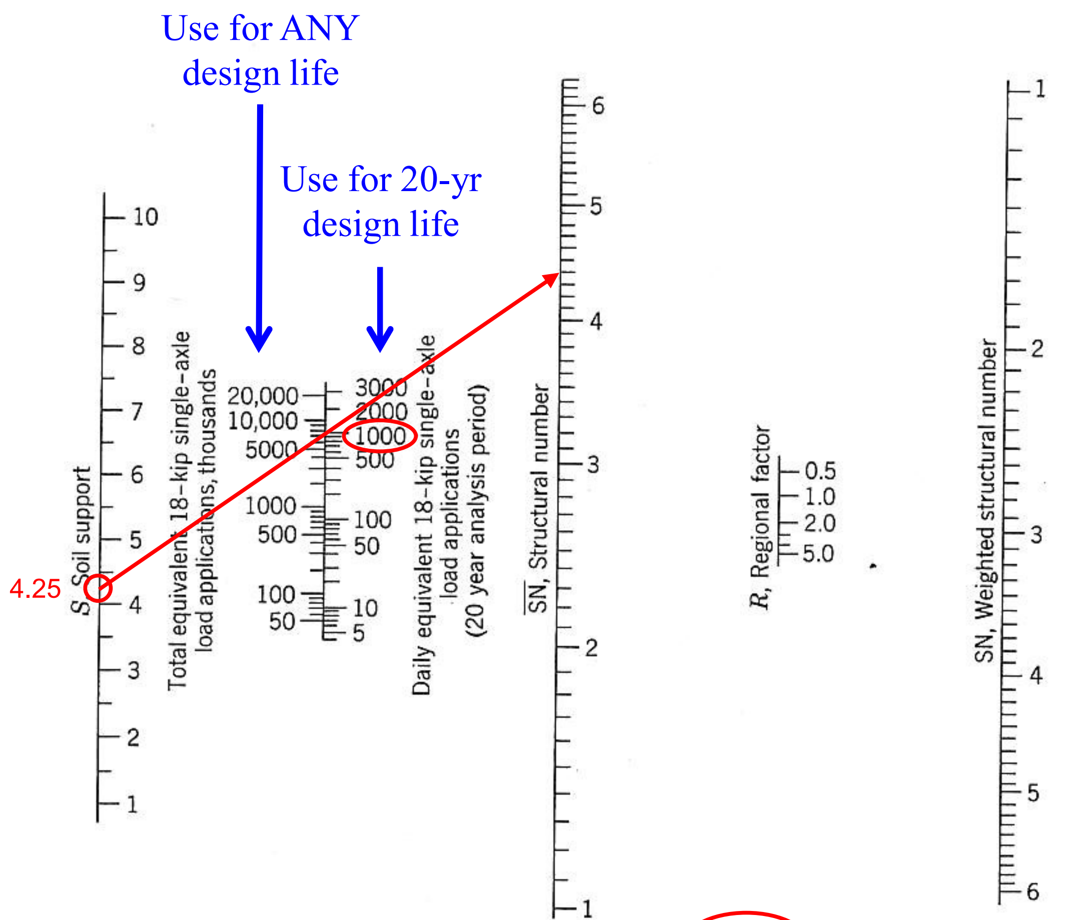
Example

A proposed highway near Vicksburg, MS will experience 1000 ESALs per day, on average, over the next 20 years. The subgrade soil is a silty clay with a CBR of 4. Find the required SN for a terminal serviceability level of 2.0.

Soil Support Value (S)



AASHTO Design Nomograph



Design chart for flexible payments, $p_t = 2.0$

Regional Factor (R)

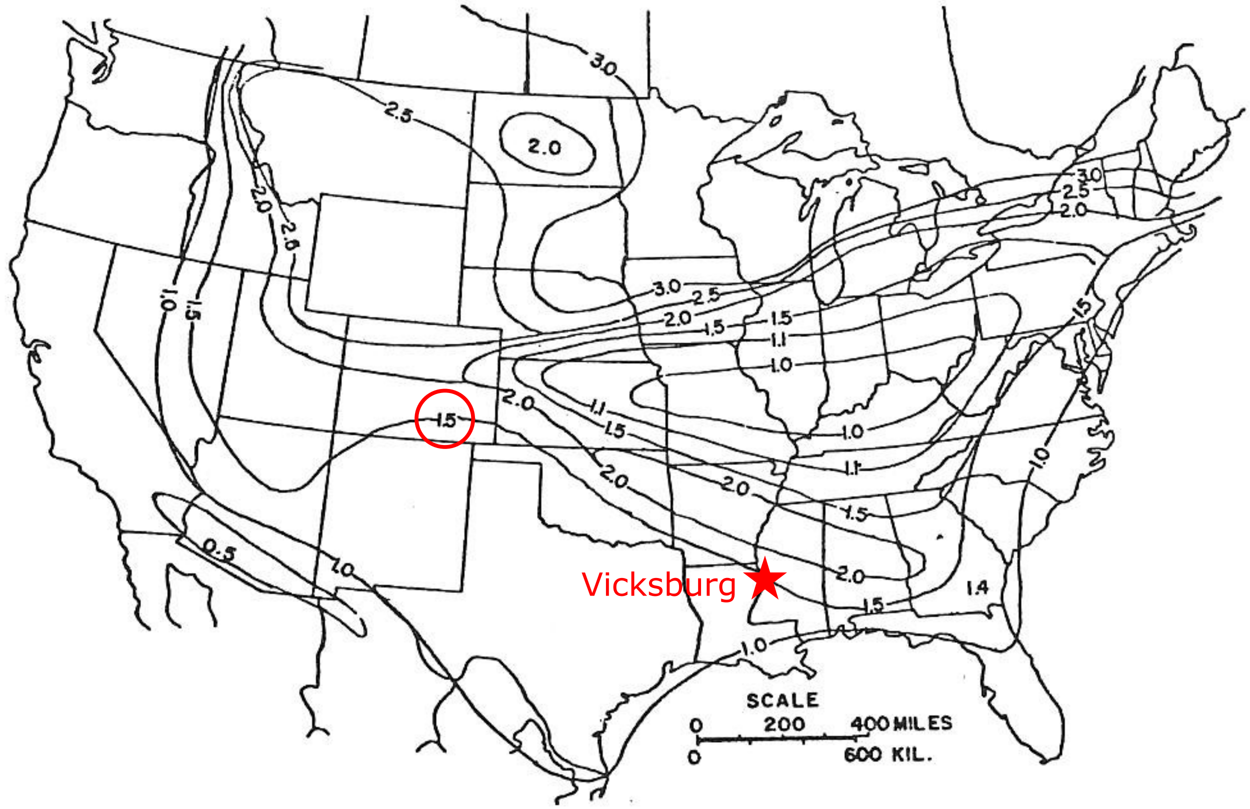
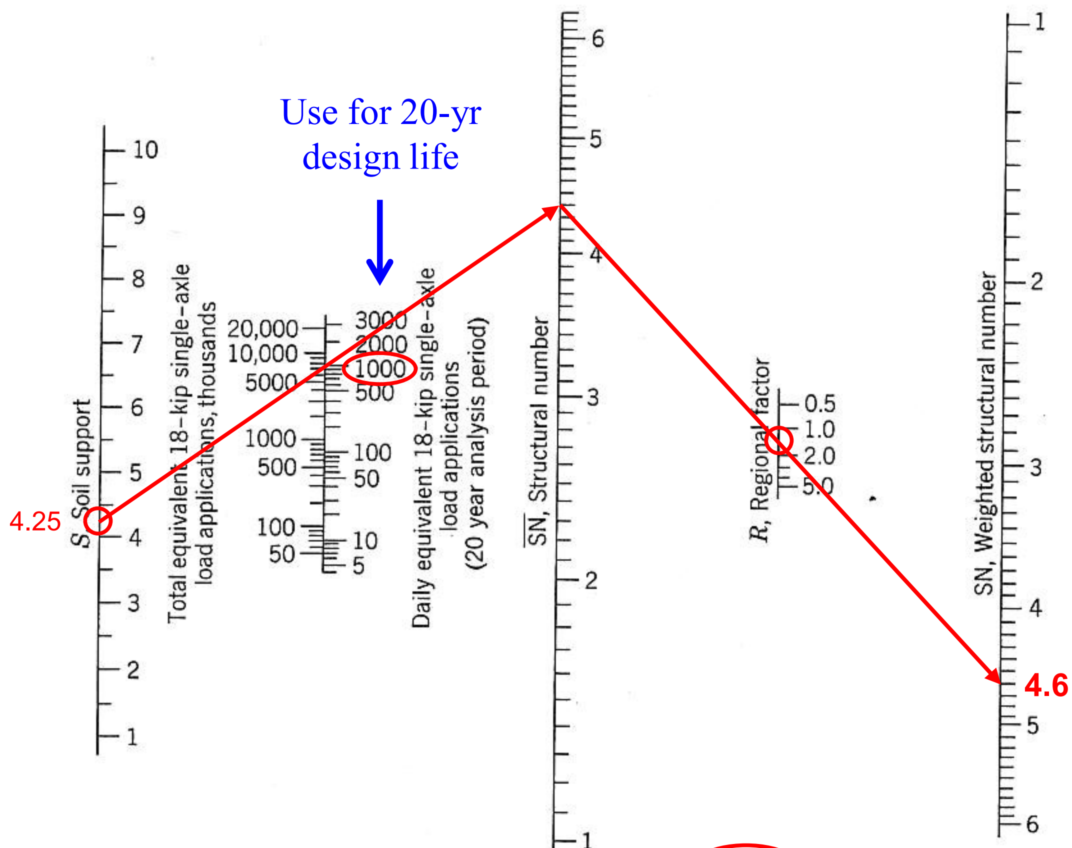


Figure 15.2. Generalized regional map of the United States. (From Van Til et al., NCHRP 128.)

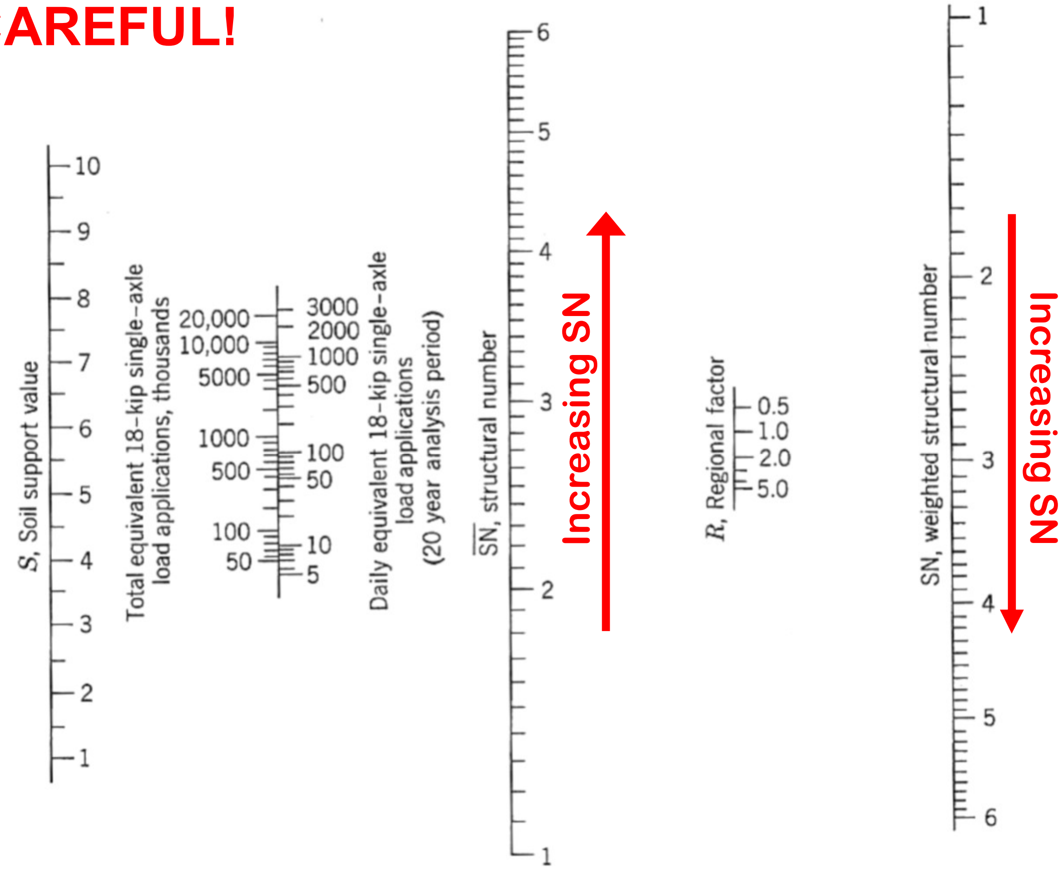
AASHTO Design Nomograph



Design chart for flexible payments, $p_t = 2.0$

AASHTO Design Nomograph

BE CAREFUL!

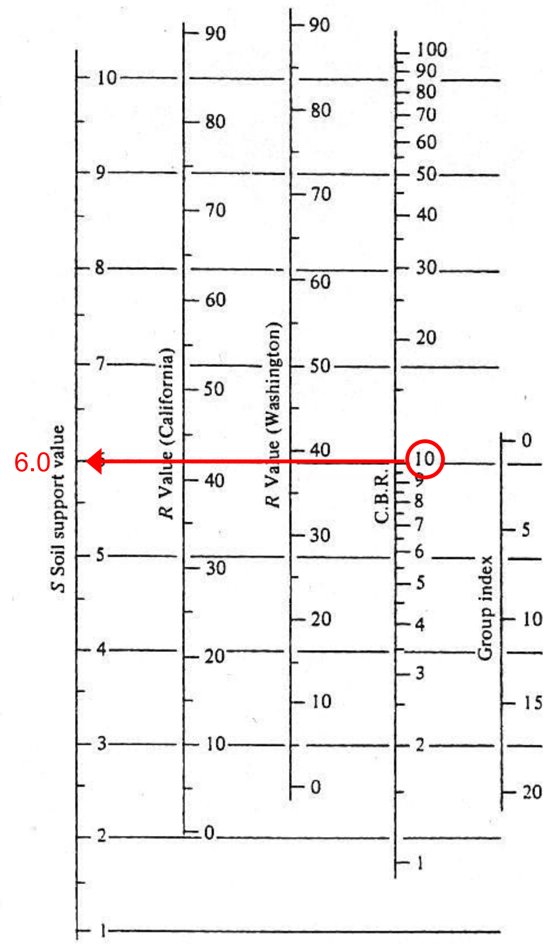


Design chart for flexible pavements, p_t = 2.5

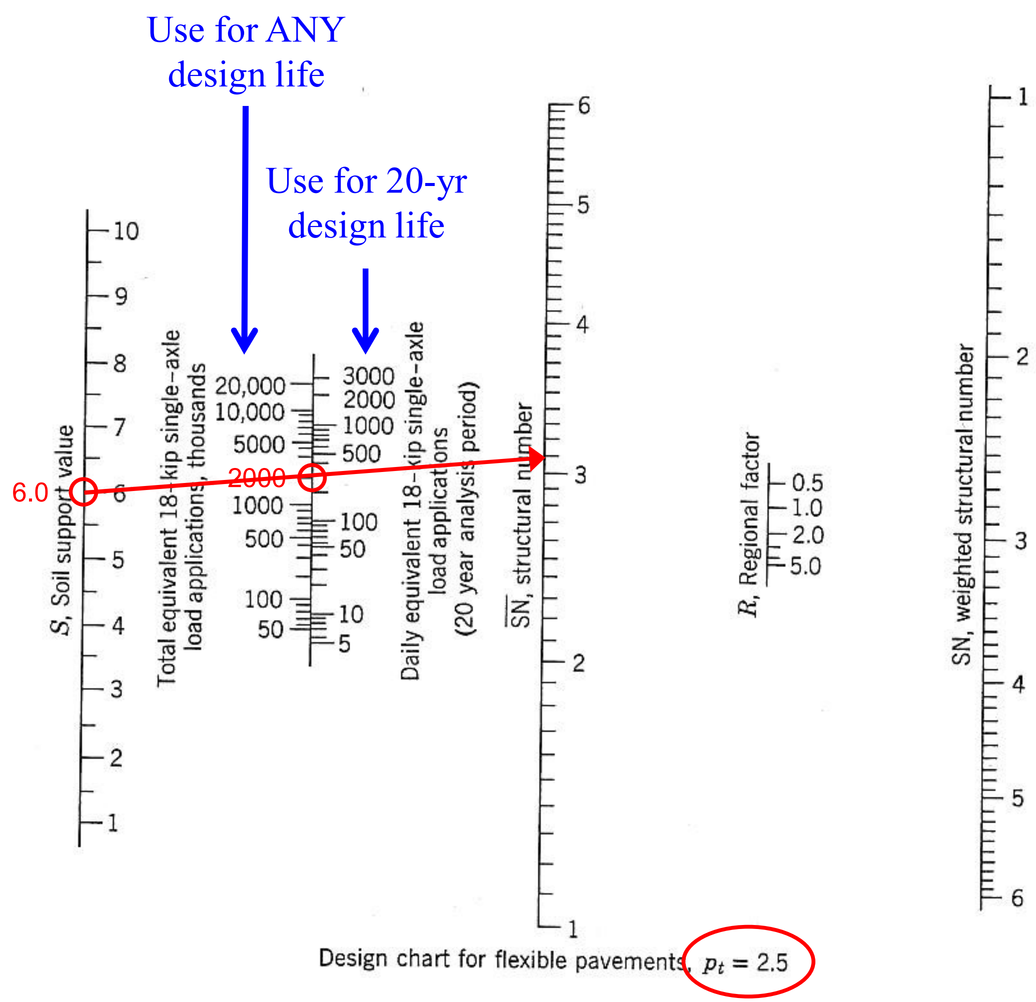
Example

A proposed highway outside Pierre, SD will experience 2,000,000 ESALs over the next 25 years. The subgrade soil is a fat clay that has been amended with lime to produce a soaked CBR of 10. Find the required SN for a terminal serviceability level of 2.5.

Soil Support Value (S)



AASHTO Design Nomograph



Regional Factor (R)

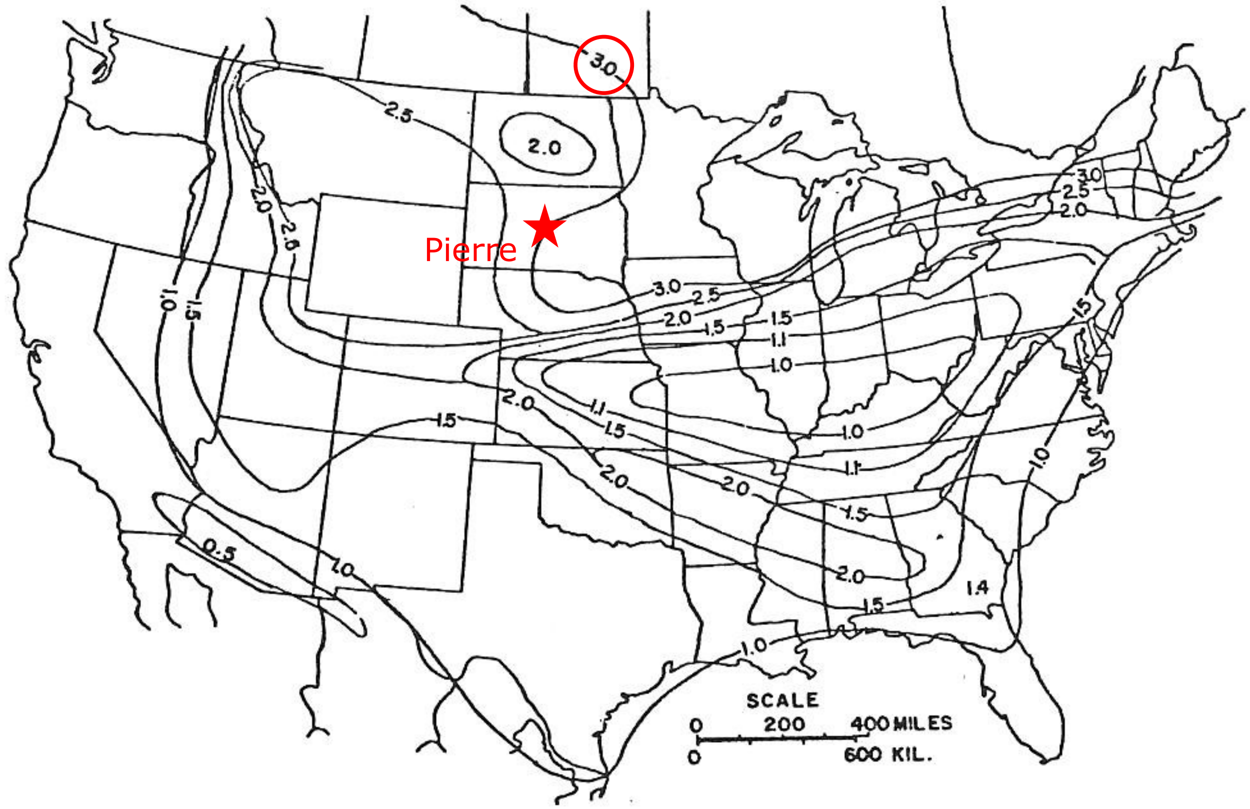
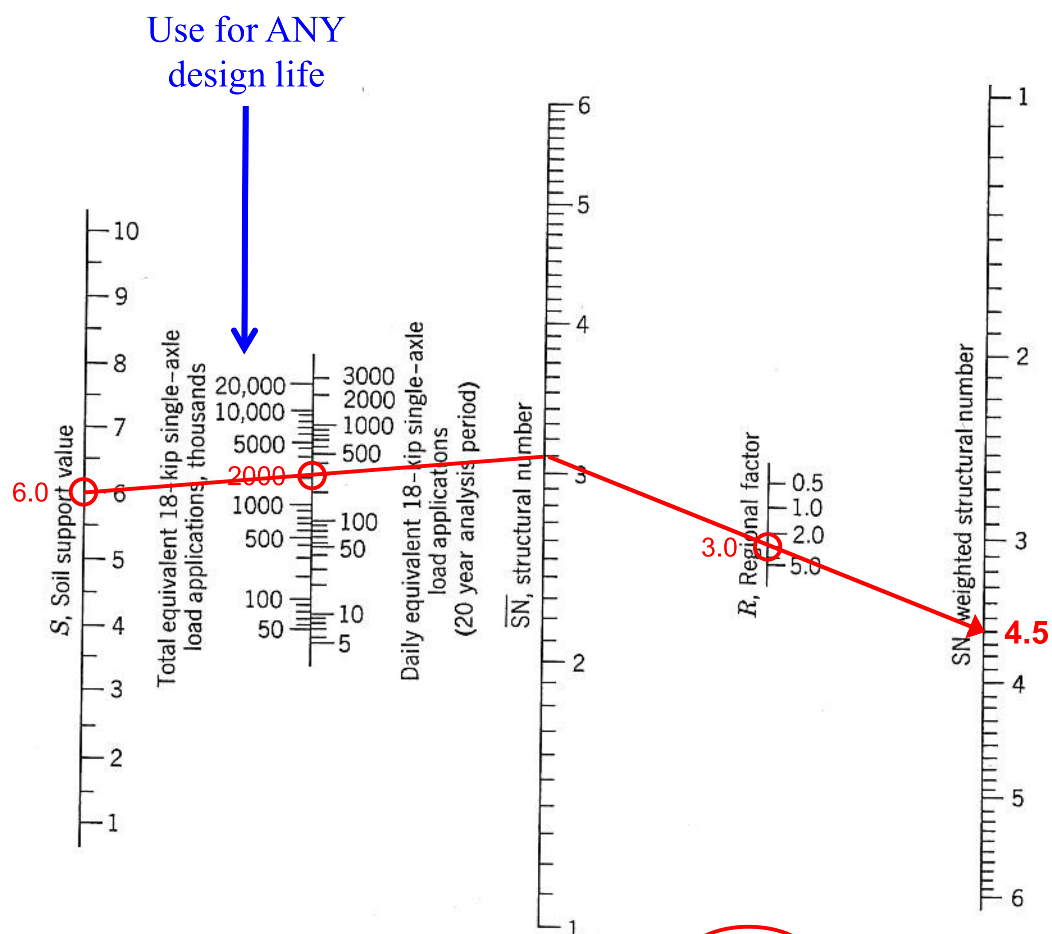


Figure 15.2. Generalized regional map of the United States. (From Van Til et al., NCHRP 128.)

AASHTO Design Nomograph



Design chart for flexible pavements, $p_t = 2.5$

Structural Number (SN)

The ***structural number*** is an index value that tries to capture the flexural rigidity of all the pavement layers above the subgrade in a single value.

Each pavement layer is assigned a ***structural layer coefficient*** (a_i) whose value depends on the quality of the material used and its location in the pavement system. (For example, a sandy gravel has a lower value when used as a base course than as a subbase because the stresses are higher in the base course.)

Structural Number (SN)

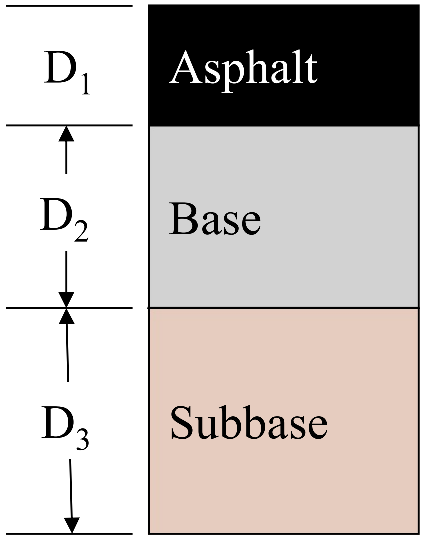
The ***structural number*** for the entire pavement is then computed by multiplying each structural layer coefficient by the thickness of the layer (in inches).

The design goal, then, is to put together a pavement system that has the structural number determined by the design nomograph. The choice of materials and layer thicknesses depends on construction costs and the local availability of materials.

AASHTO Pavement Design

AASHTO Structural Number Equation
$SN = a_1D_1 + a_2D_2 + \ldots + a_nD_n$, where
SN = structural number for the pavement
a_i = layer coefficient and D_i = thickness of layer (inches).

Source: NCEES *FE Supplied Reference Handbook*



AASHTO Layer Coefficients

AASHTO published suggested layer coefficients to use for different materials in different layers. It also published a series of charts and nomographs that the designer could use to determine appropriate layer coefficients based on measurements of strength and stiffness obtained from the actual materials being used on the project.

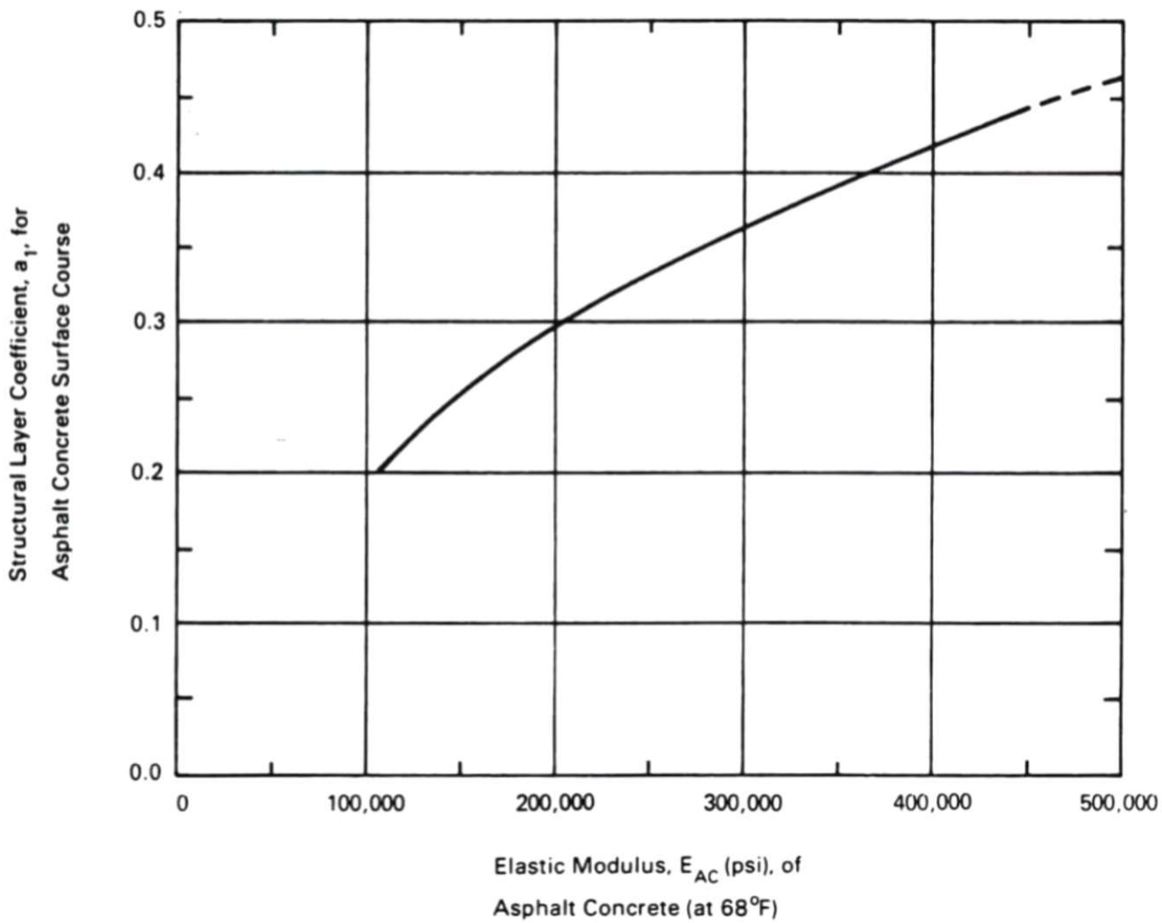
AASHTO Layer Coefficients

Table 5–1 Suggested Values for Strength Coefficients*

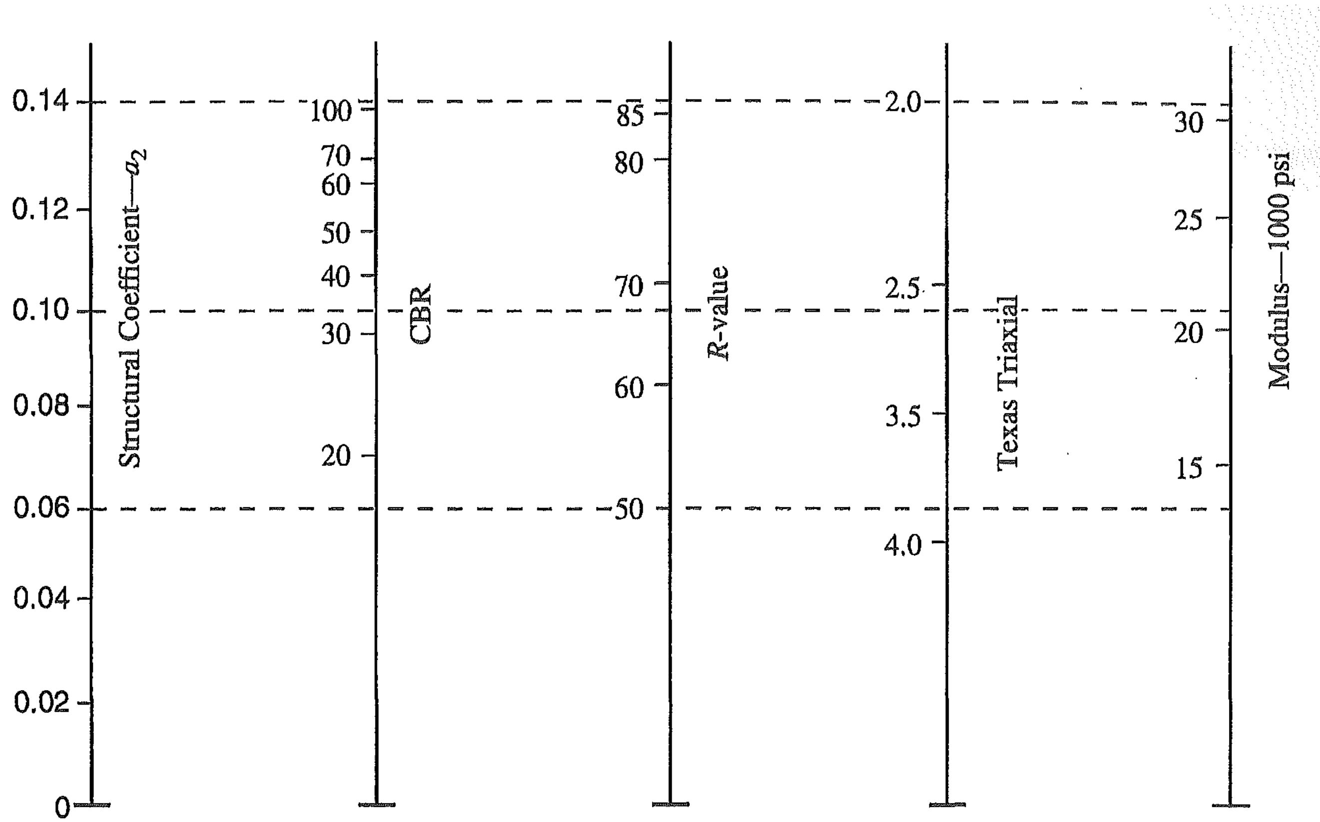
Pavement Component	*Coefficient*
Surface Course (a_1)	
Roadmix (low stability)	0.20
Plantmix (high stability)	0.44
Sand asphalt	0.40
Base Course (a_2)	
Sandy gravel	0.07
Crushed stone	0.14
Cement-treated (no-soil cement)	
Compressive strength @ 7 days	
650 psi or more (4.48 MPa)	0.23
400 to 650 psi (2.76 to 4.48 MPa)	0.20
400 psi or less (2.76 MPa)	0.15
Bituminous-treated	
Coarse-graded	0.34
Sand asphalt	0.30
Lime-treated	0.15–0.30
Subbase Course (a_3)	
Sandy gravel	0.11
Sandy or sandy clay	0.05–0.10

* From *AASHTO Interim Guide for Design of Pavement Structures*, © 1972 by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission.

Asphalt Layer Coefficient (a_1)

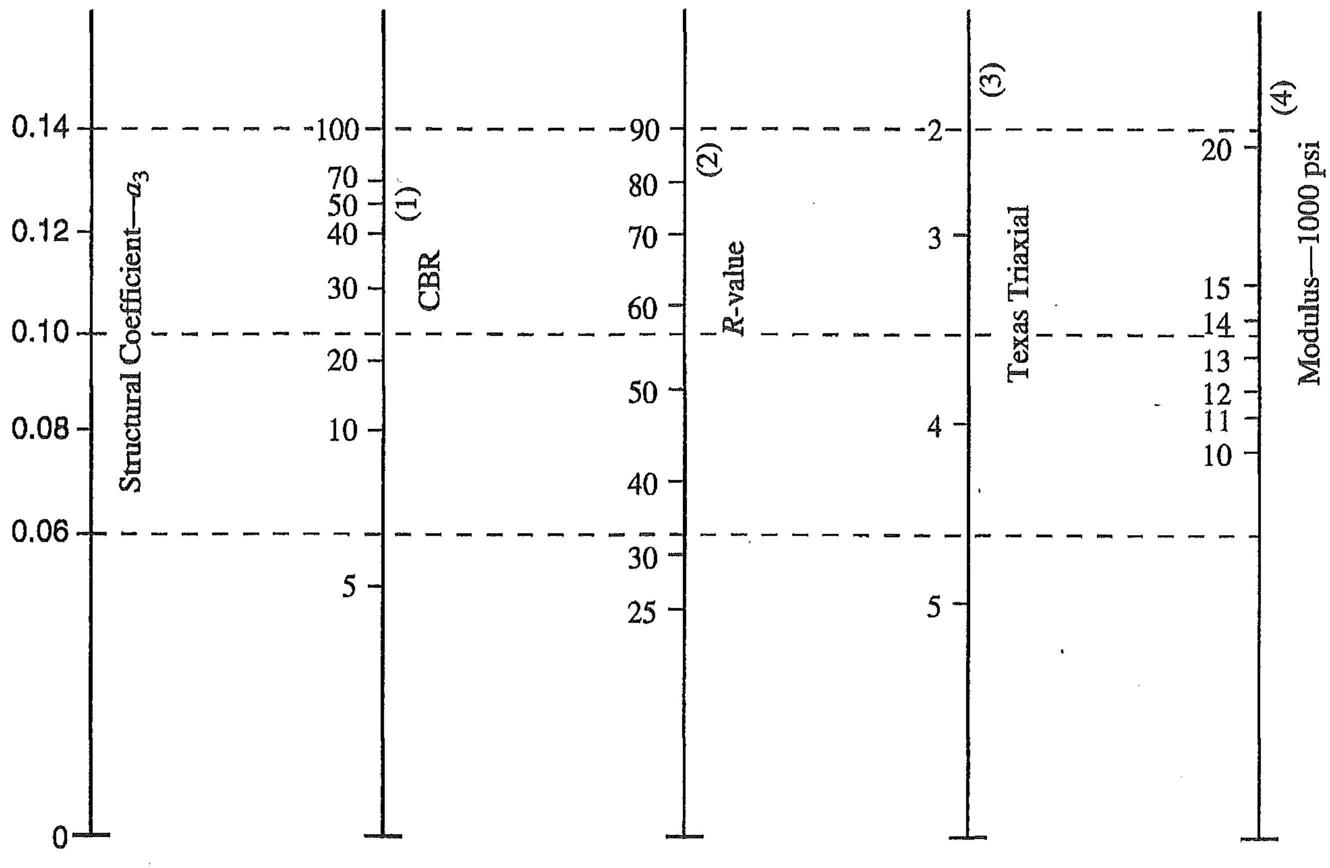


Base Layer Coefficient (a_2)



(a) Values of a_2 (base)

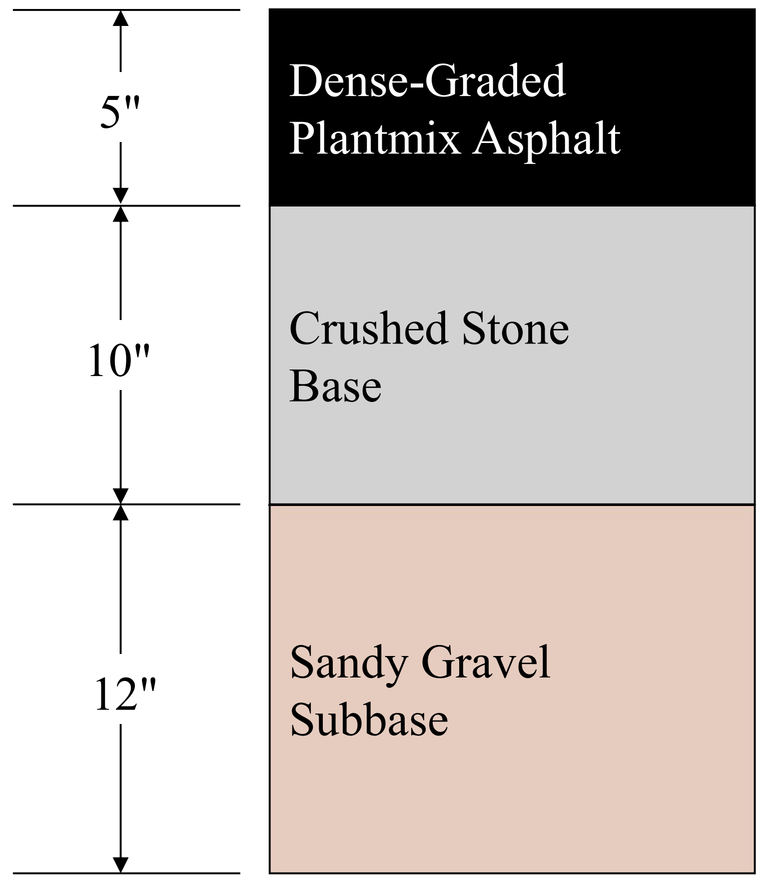
Subbase Layer Coefficient (a_3)



(b) Values of a_3 (subbase)

Pavement Design

SN = ??



AASHTO Layer Coefficients

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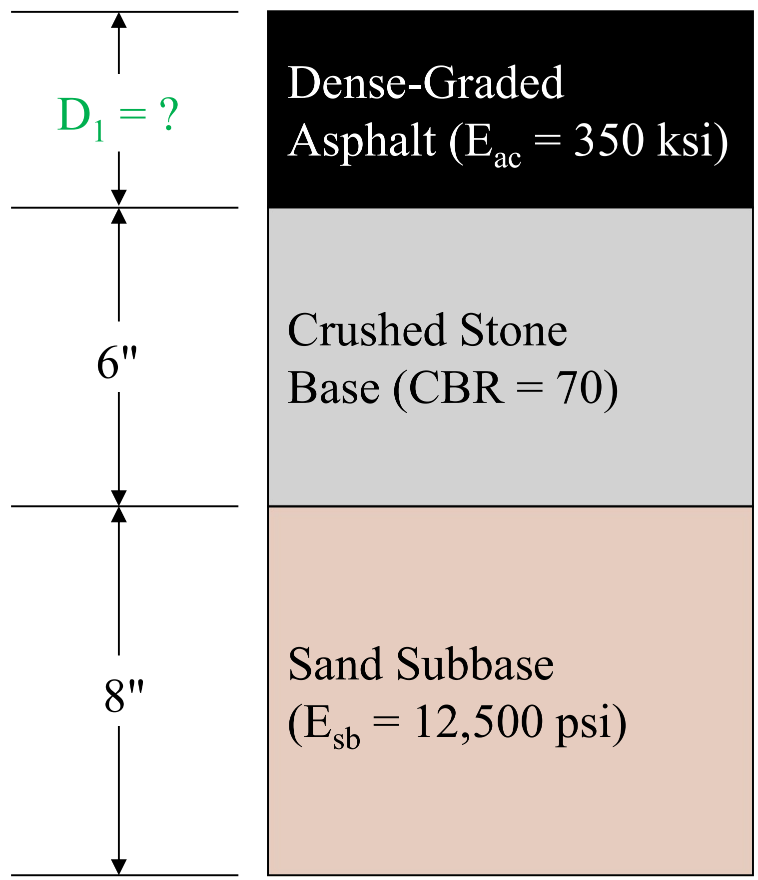
Lime-treated	0.15–0.30
Subbase Course (a_3)	
Sandy gravel	0.11
Sandy or sandy clay	0.05–0.10

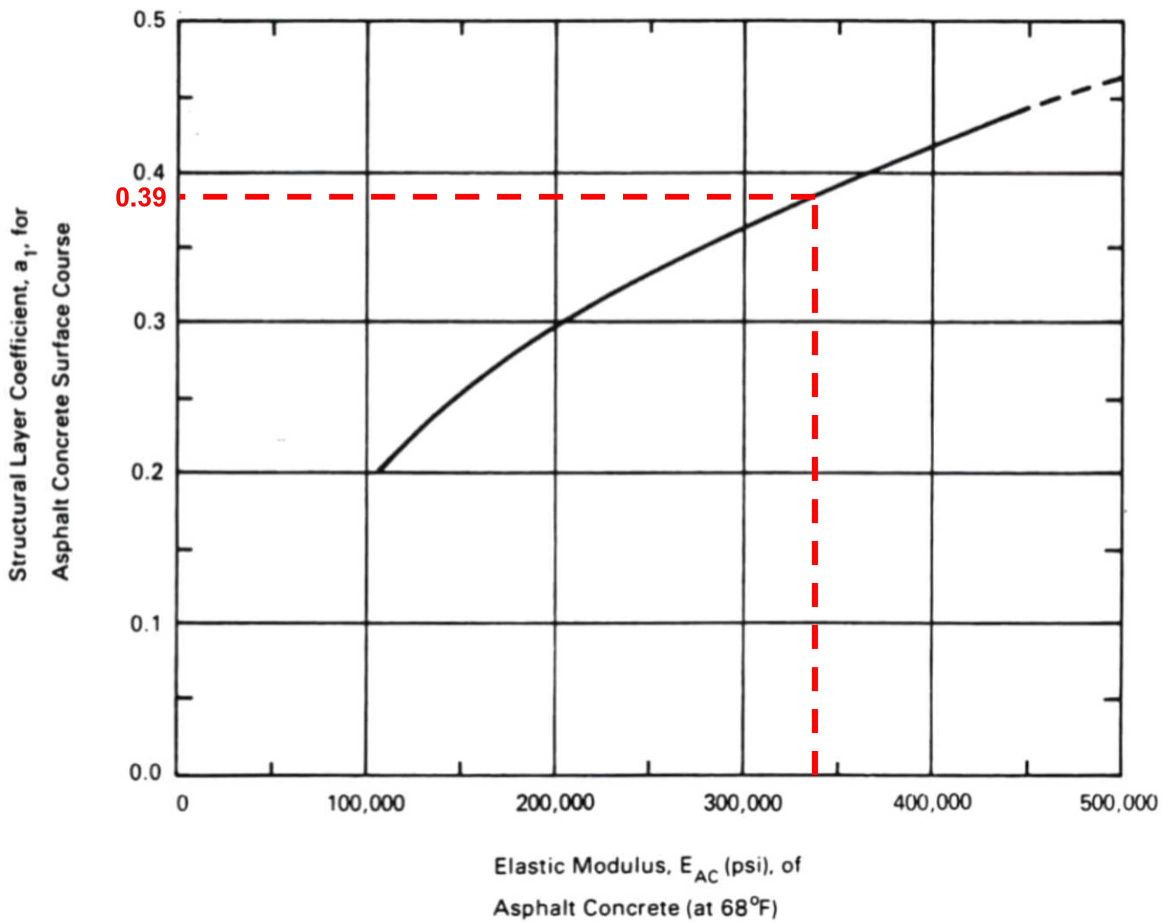
* From *AASHTO Interim Guide for Design of Pavement Structures*, © 1972 by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission.

Pavement Design

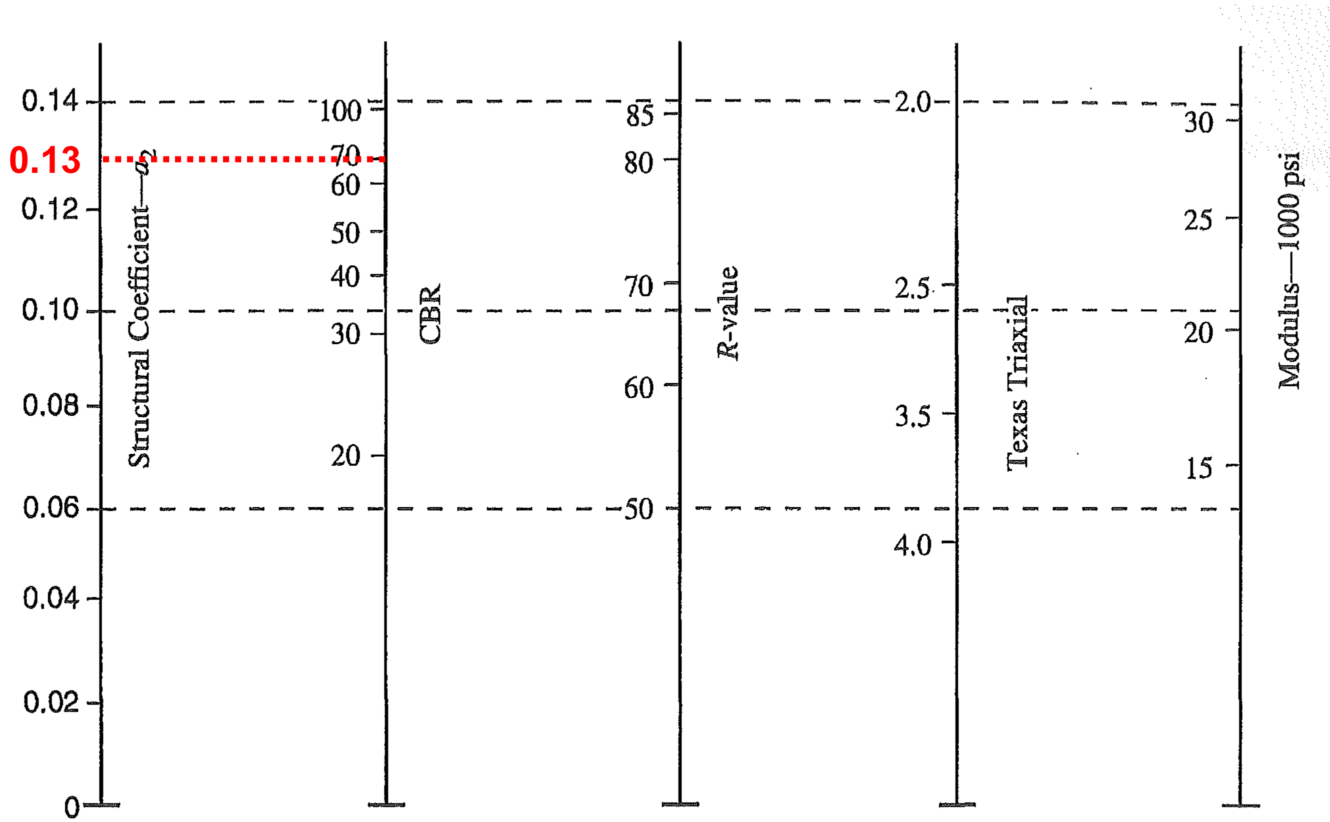
$SN = 2.7$



Asphalt Layer Coefficient (a_1)

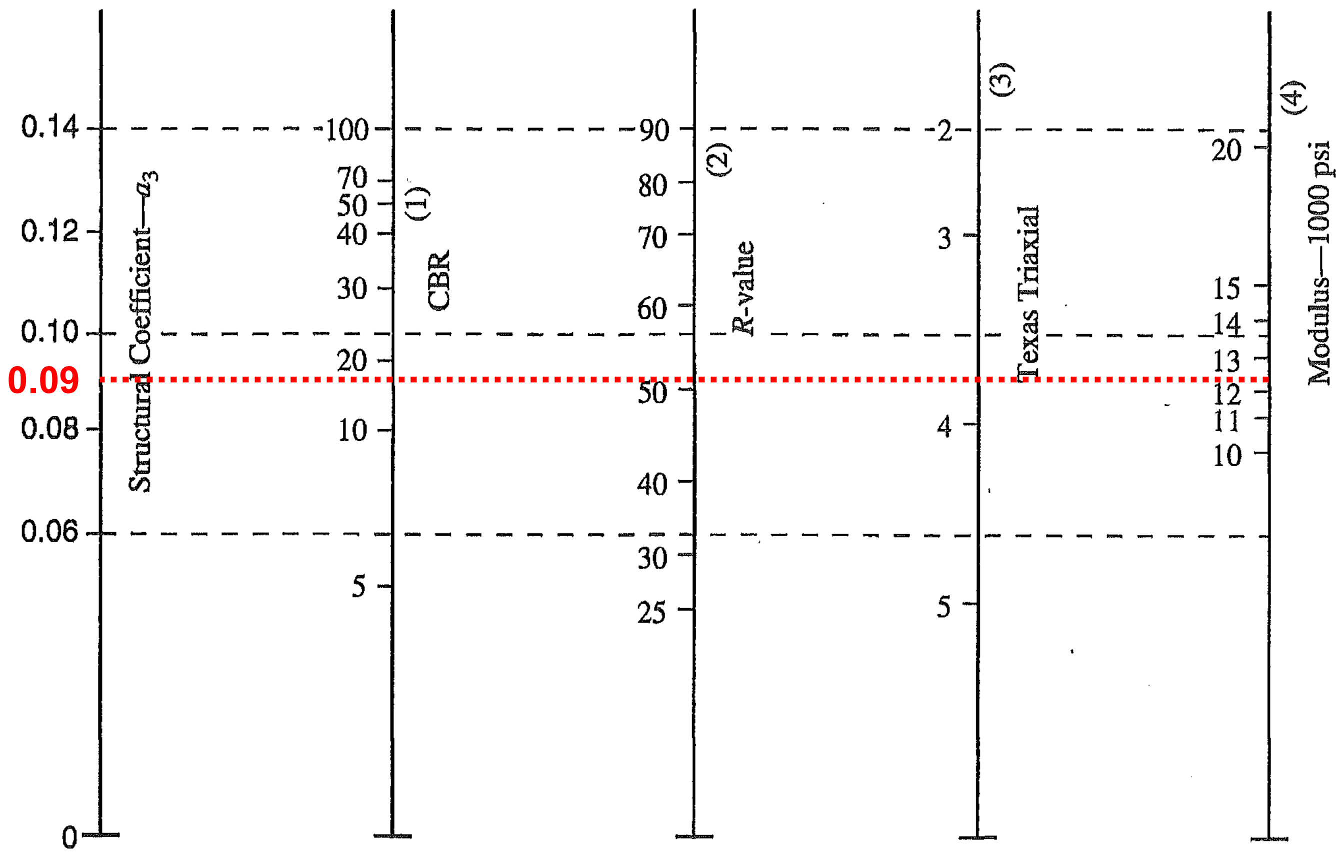


Base Layer Coefficient (a_2)



(a) Values of a_2 (base)

Subbase Layer Coefficient (a_3)



(b) Values of a_3 (subbase)

AASHTO Design Equation

In 1986, AASHTO revised their design equation once more, replacing the regional factor and soil support terms with a single subgrade support term based on a seasonally adjusted resilient modulus (M_R) value.

The seasonally adjusted value is a single year-round M_R that results in the same loss of ESALs as would occur based on the seasonally varying M_R values.

AASHTO Design Equation

Ride Quality Threshold

1986

$$\log_{10} W_{18} = 9.36 \log_{10}\left(SN+1\right) - 0.20 + \frac{\log_{10}\left(\frac{4.2-p_t}{4.2-1.5}\right)}{0.4+\frac{1094}{\left(SN+1\right)^{5.19}}} + 2.32\log_{10}\left(M_R\right) - 8.07$$

Lifetime ESALs

Seasonally Adjusted Subgrade Support

Structural Number (Flexural Rigidity)