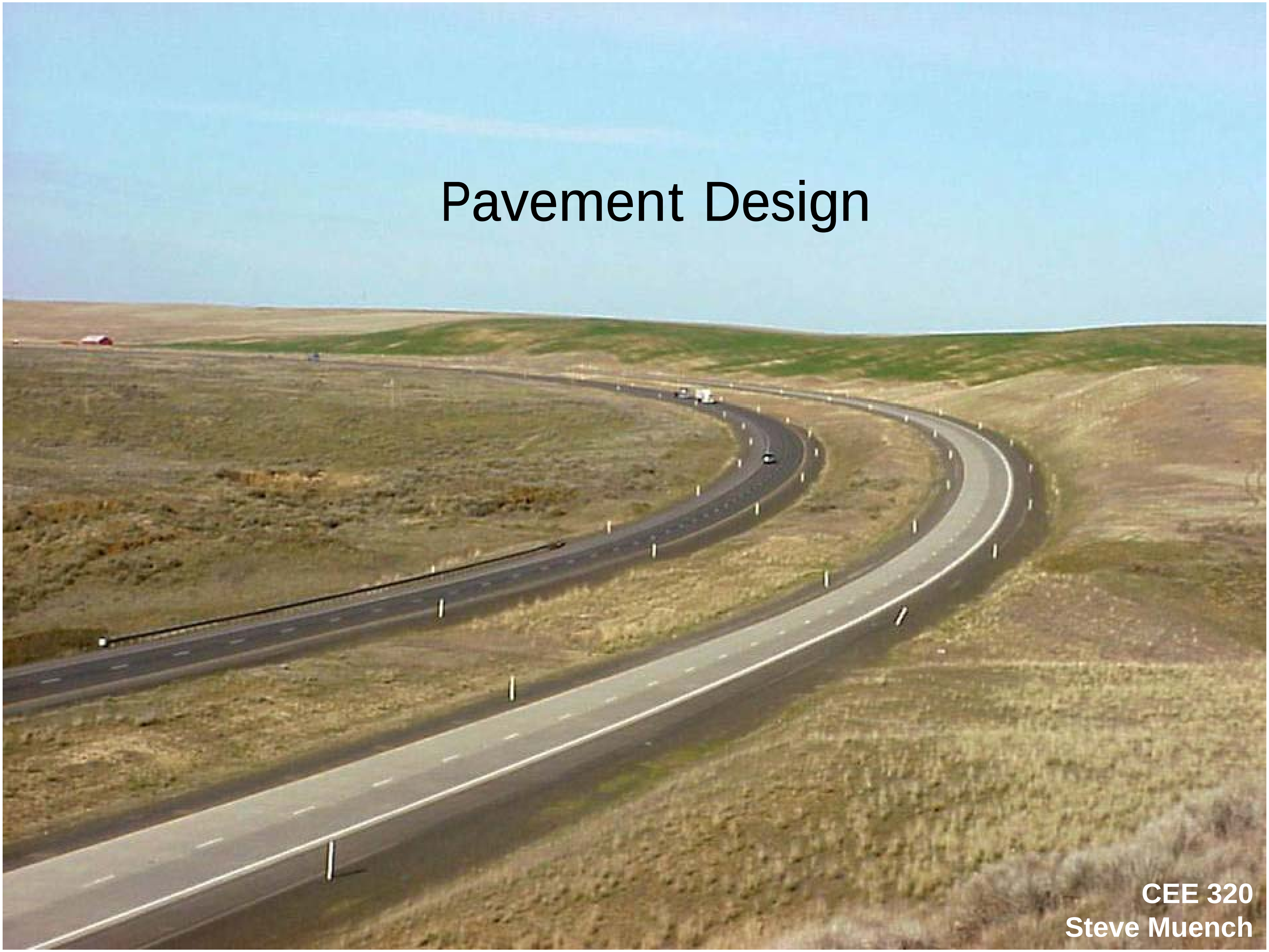
Pavement Design



CEE 320
Steve Muench

Outline

1. Pavement Purpose
2. Pavement Significance
3. Pavement Condition
4. Design Parameters
5. Pavement Types
    a. Flexible
    b. Rigid
6. Pavement Design
7. Example
8. Special projects in WA

Pavements serve several purposes

- Load support
- Smoothness
- Drainage

Dirt Road

Olympic Peninsula (ca. 1924)

Washington Localities Collection, UW Digital Collections

Muddy Dirt Road

County Road near Index, WA (1911)

UW Digital Collections

From Clay McShane's *Down the Asphalt Path, The Automobile and the American City* (1994)

The “pull” of pavements.

Surface Type	**Pull-to-Weight Ratio**
Sand, deep and loose	1/7
Dry earth, gravel on earth	1/15
Macadam, badly worn or little used	1/20
Broken stone on earth, cobblestones	1/35
Solid rubber wheels on reasonable surfaces	1/45
Broken stone on paved foundation, asphalt, wood	1/50
Pneumatic tire on reasonable surfaces	1/60
Well-made pavement, dry macadam	1/70
Brick	1/90
Best pavement	1/180
Steel plate or stone trackway	1/250

From M.G. Lay, *Ways of the World* (1992)

839·KYC

Pavements are THE significant part of U.S. transportation infrastructure.

		Miles
1	United States	4.03 million
2	India	2.10 million
3	China	1.16 million
4	Brazil	1.09 million
5	Canada	0.88 million

But, the U.S. ranks:

- 14th in per capita car ownership (behind Belgium)
- 11th in VMT per mile of road network (behind Luxembourg)
- 36th for vehicles per mile of road network (behind Cyprus/France)

Data from *the Economist* Pocket World in Figures, 2008 Edition

Pavements are THE significant part of U.S. transportation infrastructure.

- About 63% of U.S. roads are paved. That's a high percentage.
- About 95% are surfaced with hot mix asphalt (HMA)

	United States
Centerline Miles	4.03 million
Paved	2.58 million
HMA Surface	2.34 million
PCC Surface	0.24 million

Cost:

- About $50 billion/yr spent on U.S. pavement
- Over $100 million/yr spent in Washington
- By far the single biggest transportation infrastructure cost.

Pavement Condition

Pavement Condition

Pavement Condition

Pavement Condition

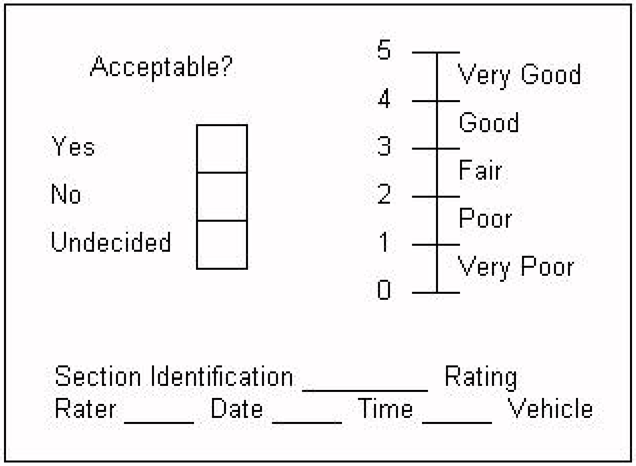
Pavement Condition

From WSDOT
I – 90 “fat driver” syndrome

Pavement Condition

- Defined by users (drivers)
- Relates physical attributes to driver ratings
- Result is usually a numerical scale

From the AASHO Road Test (1956 – 1961)



Present Serviceability Rating (PSR)

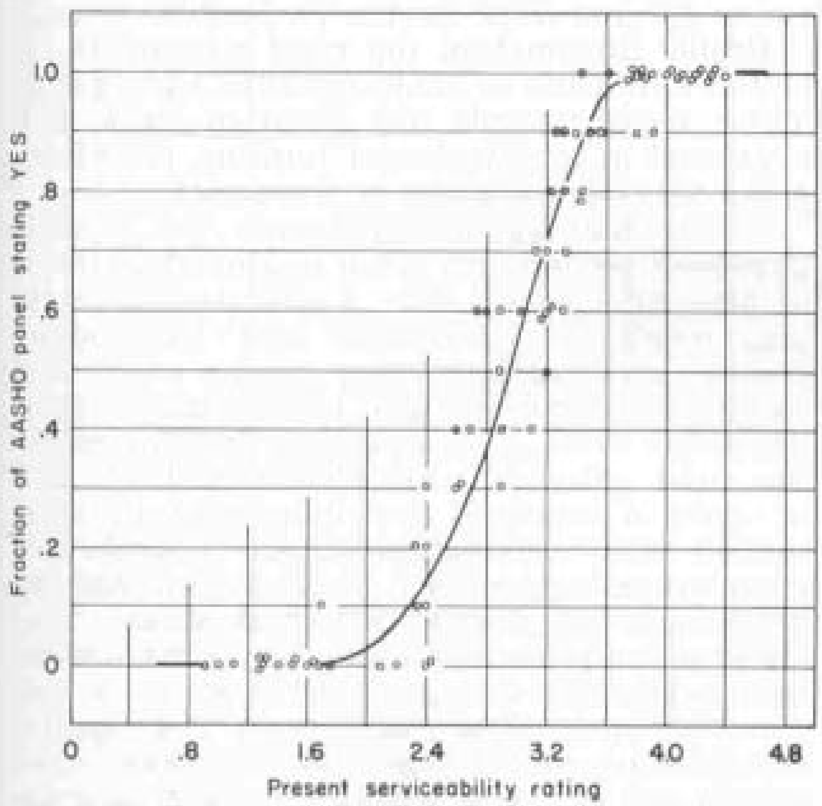


Figure 2–F. Acceptability vs present serviceability rating; 74 flexible pavements.

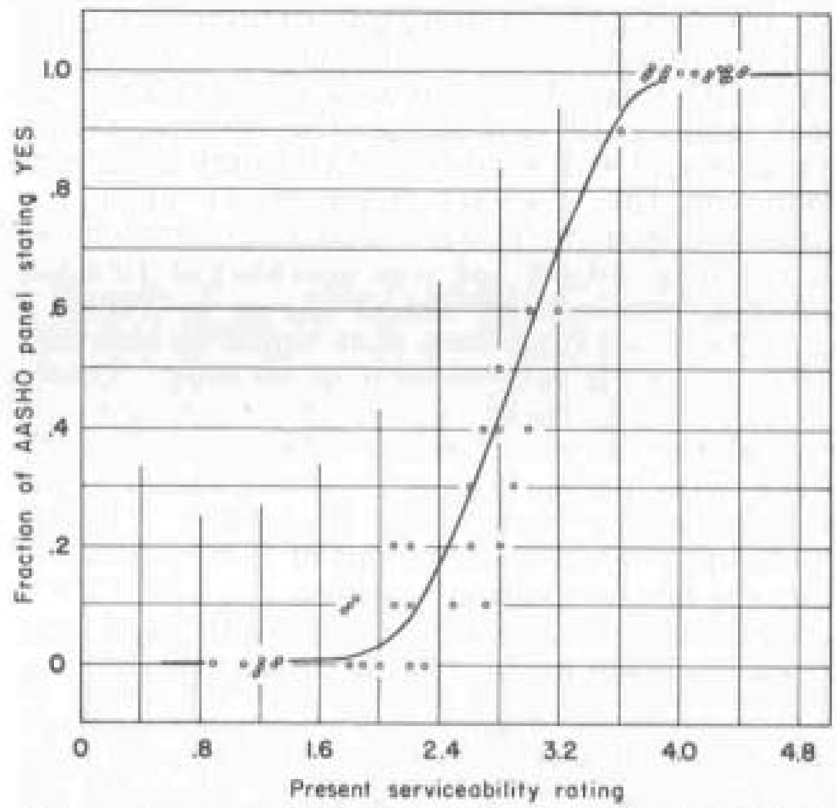


Figure 3–F. Acceptability vs present serviceability rating; 49 rigid pavements.

Picture from: Highway Research Board Special Report 61A-G

Present Serviceability Index (PSI)

- Values from 0 through 5
- Calculated value to match PSR

$$PSI = 5.41 - 1.80\log\left(1 + \overline{SV}\right) - 0.9\sqrt{C + P}$$

SV = mean of the slope variance in the two wheelpaths
(measured with the CHLOE profilometer or BPR Roughometer)

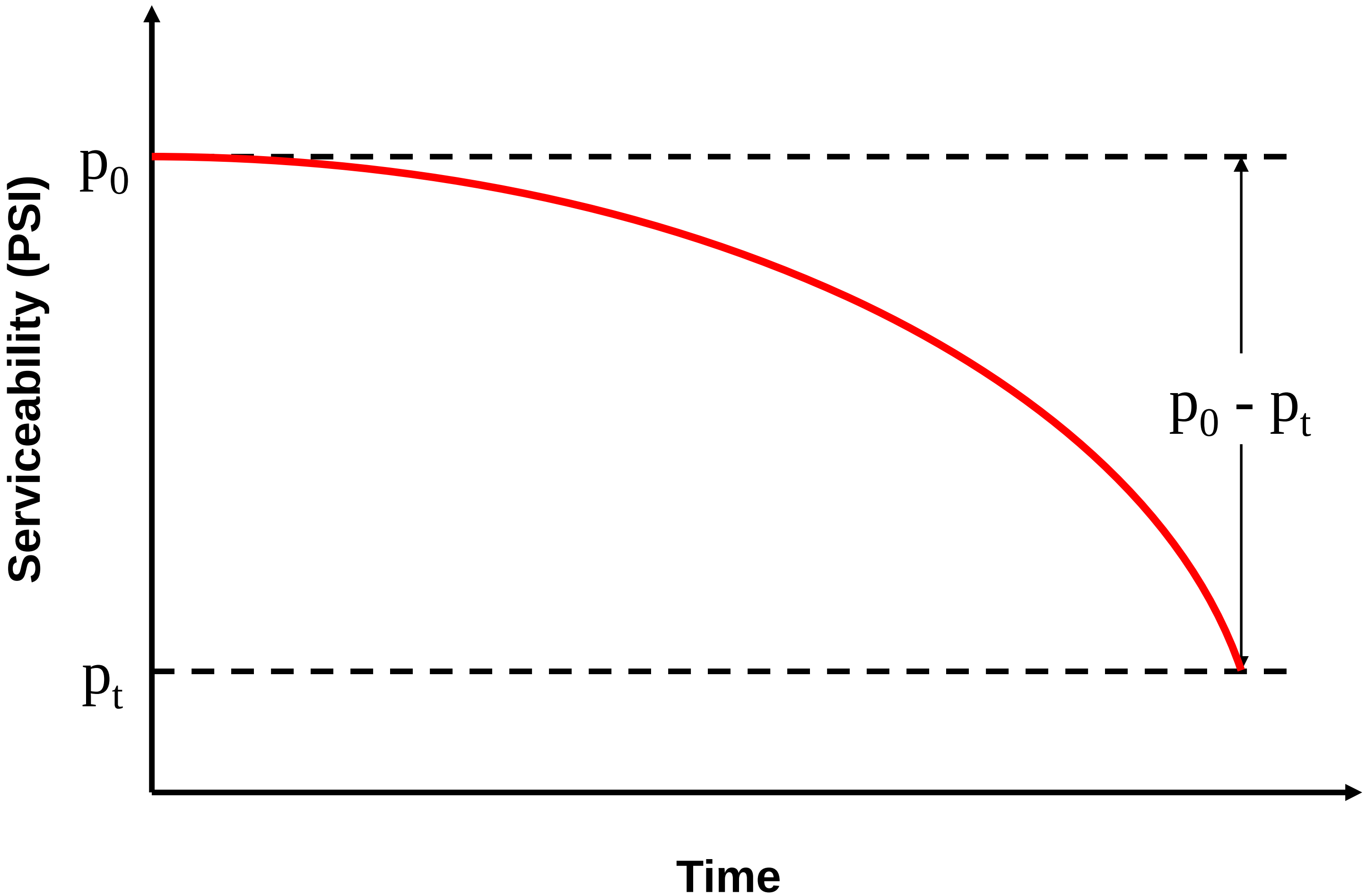
C, P = measures of cracking and patching in the pavement surface

C = total linear feet of Class 3 and Class 4 cracks per 1000 ft^2 of pavement area.
A Class 3 crack is defined as opened or spalled (at the surface) to a width of 0.25 in. or more over a distance equal to at least one-half the crack length.
A Class 4 is defined as any crack which has been sealed.

P = expressed in terms of ft^2 per 1000 ft^2 of pavement surfacing.

FYI – NOT TESTABLE

Typical PSI vs. Time



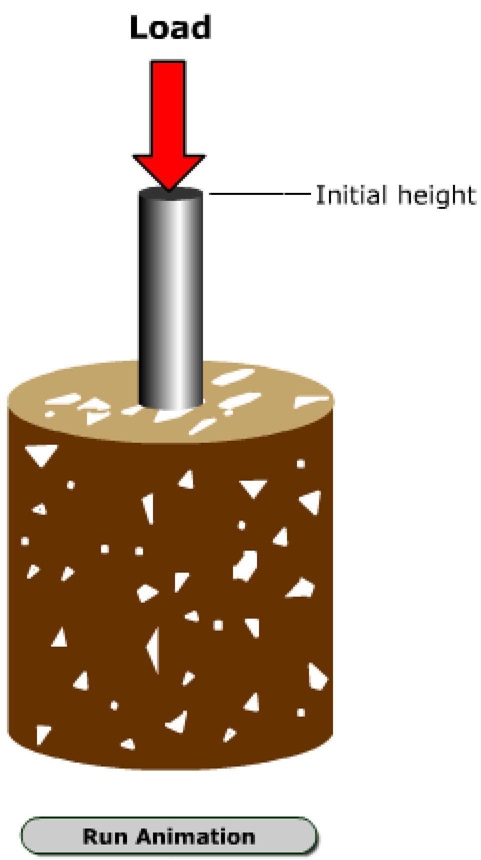
Design Parameters

Pavement are designed with 3 inputs.

- Subgrade
- Loads
- Environment

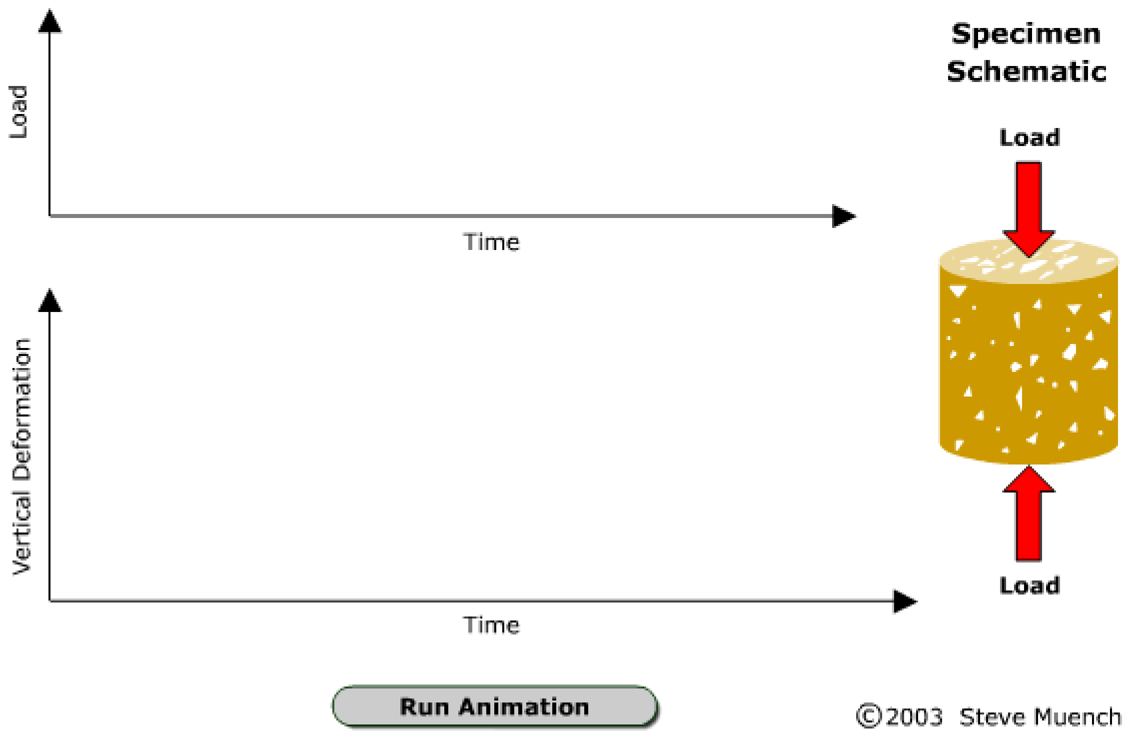
Subgrade (what's underneath) is characterized by strength or stiffness.

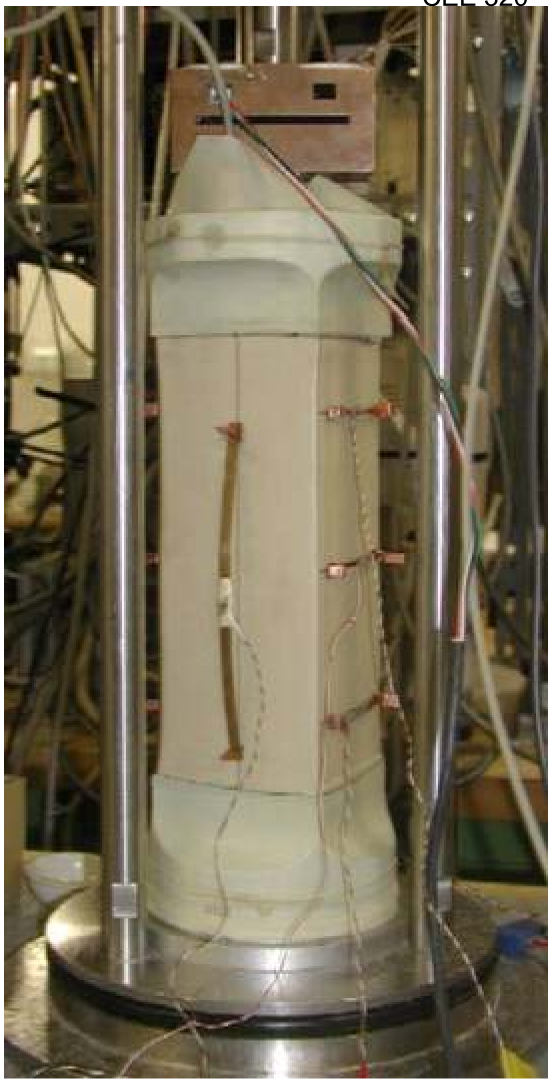
- California Bearing Ratio (CBR)
  - Measures shearing resistance
  - Units: percent
  - Typical values: 0 to 20



Subgrade (what's underneath) is characterized by strength or stiffness.

- Resilient Modulus (M_R)
  - Measures stress-strain relationship
  - Units: psi or MPa
  - Typical values: 3,000 to 40,000 psi





Picture from University of Tokyo Geotechnical Engineering Lab

Subgrade

Some Typical Values

Classification	CBR	M_R (psi)	Typical Description
Good	≥ 10	20,000	Gravels, crushed stone and sandy soils. GW, GP, GM, SW, SP, SM soils are often in this category.
Fair	5 – 9	10,000	Clayey gravel and clayey sand, fine silt soils. GM, GC, SM, SC soils are often in this category.
Poor	3 – 5	5,000	Fine silty sands, clays, silts, organic soils. CL, CH, ML, MH, CM, OL, OH soils are often in this category.

Loads are characterized in a number of ways.

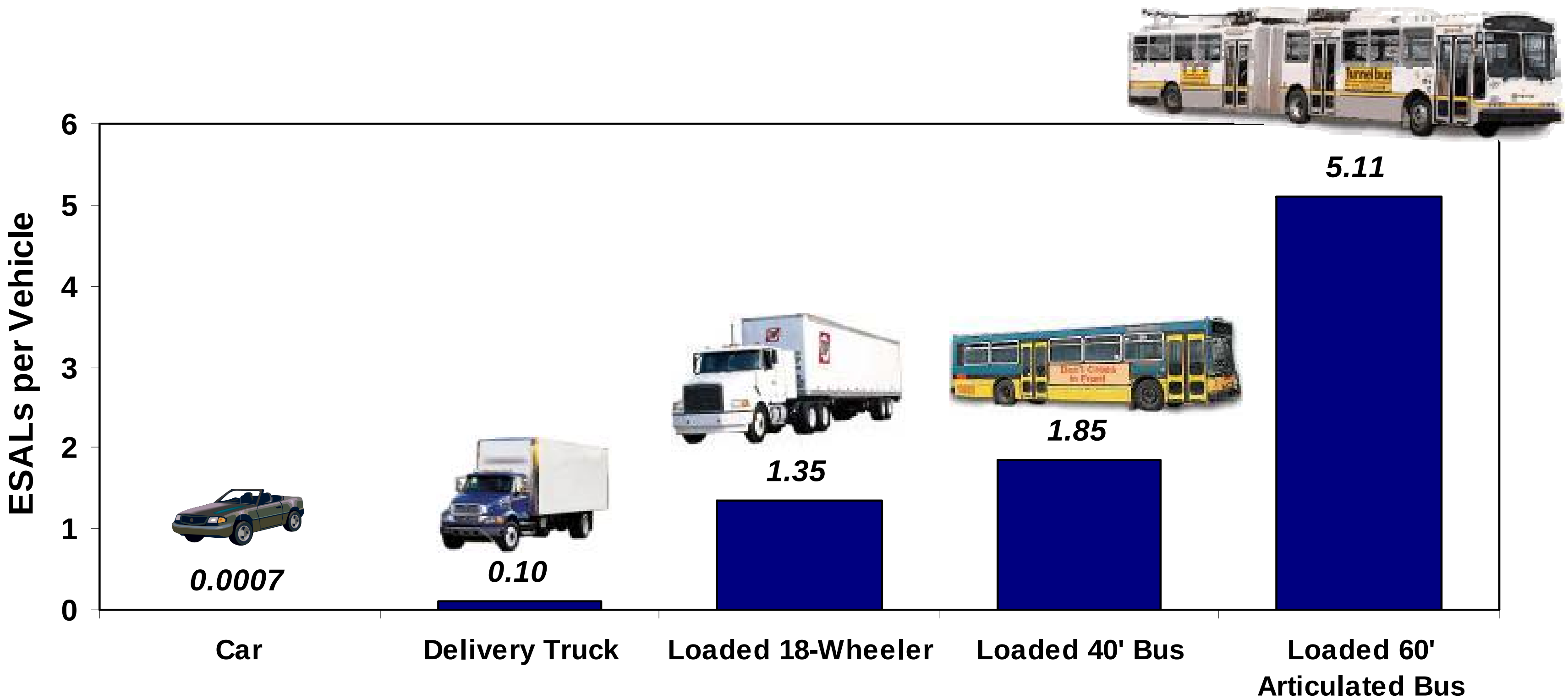
- Tire loads
- Axle and tire configurations
- Load repetition
- Traffic distribution
- Vehicle speed

Loads are typically quantified using the Equivalent Single Axle Load (ESAL).

- Equivalent Single Axle Load (ESAL)
  - Converts wheel loads of various magnitudes and repetitions ("mixed traffic") to an equivalent number of "standard" or "equivalent" loads
  - Based on the amount of damage they do to the pavement
  - Commonly used standard load is the 18,000 lb. equivalent single axle load
- Load Equivalency
  - Generalized fourth power approximation

$$\left(\frac{\text{load}}{18{,}000\ \text{lb.}}\right)^4 = \text{relative damage factor}$$

Some typical load equivalent factors (LEFs).



Notice that cars are insignificant and thus usually ignored in pavement design.

LEF Example

The standard axle weights for a standing-room-only loaded Metro articulated bus (60 ft. Flyer) are:

Axle	Empty	Full
Steering	13,000 lb.	17,000 lb.
Middle	15,000 lb.	20,000 lb.
Rear	9,000 lb.	14,000 lb.

Using the 4^{th} power approximation, determine the total equivalent damage caused by this bus in terms of ESALs when it is empty. How about when it is full?

Environment

- Temperature extremes
- Frost action
  - Frost heave
  - Thaw weakening

Pavement Types

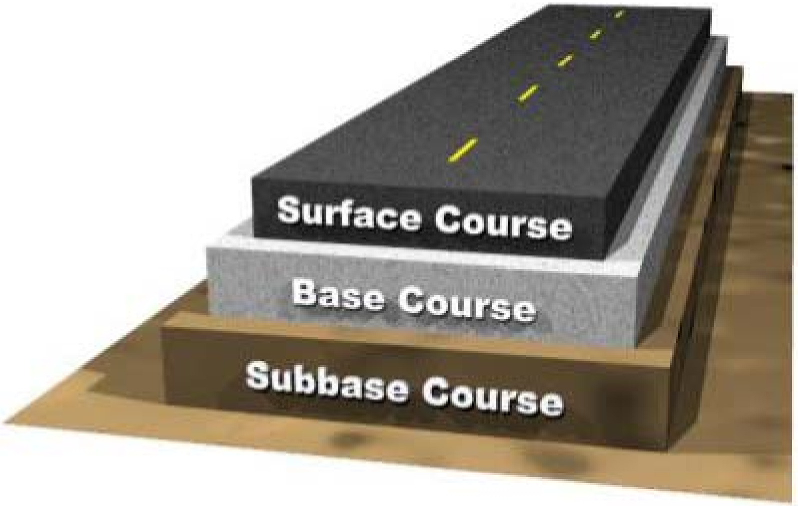
There are two basic pavement types.

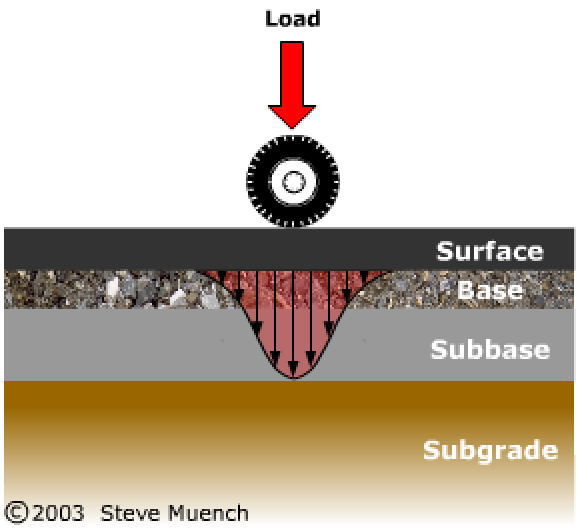
- Flexible Pavement
  - Hot mix asphalt (HMA) pavements
  - Called "flexible" since the total pavement structure bends (or flexes) to accommodate traffic loads
  - About 82.2% of paved U.S. roads use flexible pavement
  - About 95.7% of paved U.S. roads are *surfaced* with HMA/BST

- Rigid Pavement
  - Portland cement concrete (PCC) pavements
  - Called “rigid” since PCC’s high modulus of elasticity does not allow them to flex appreciably
  - About 17.8% of paved U.S. roads use PCC pavement
  - About 4.3% of paved U.S. roads are *surfaced* with PCC

Flexible Pavement

- Structure
  - Surface course
  - Base course
  - Subbase course
  - Subgrade





Types of Flexible Pavement


ROADTEC

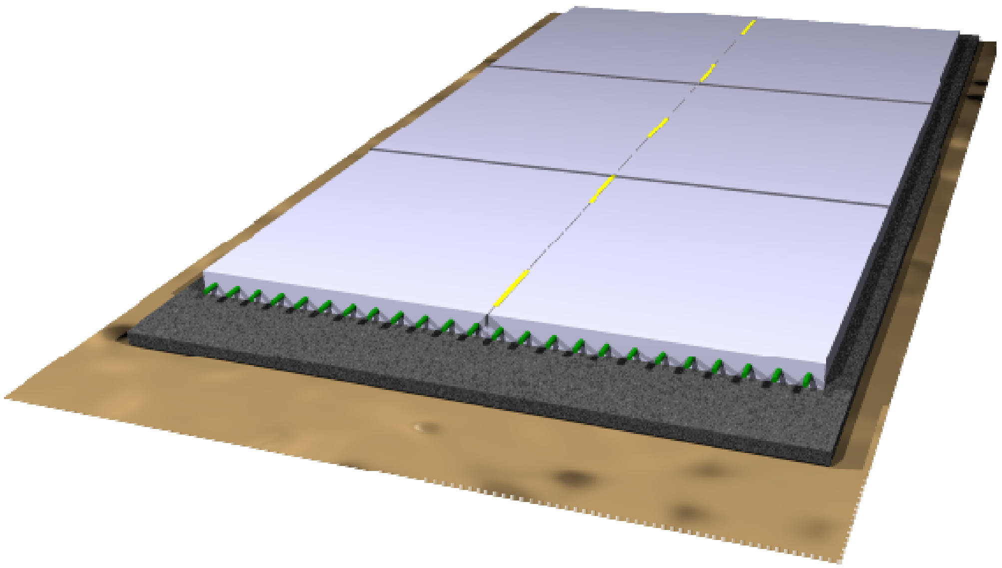

WILDER
BLAW-KNOX

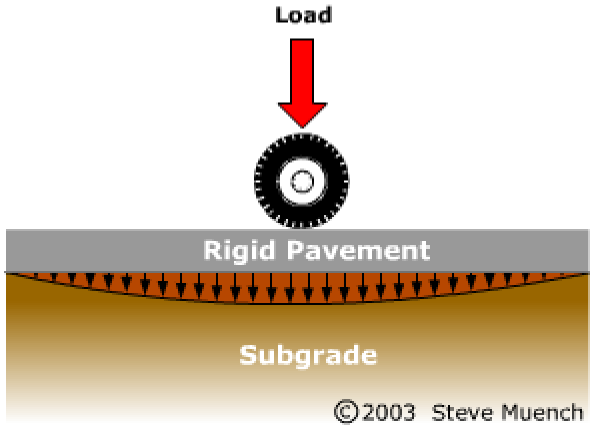
IR Ingersoll-Rand


NE 75th St., Seattle, WA
Lakeside Industries
9/29/2006

Rigid Pavement

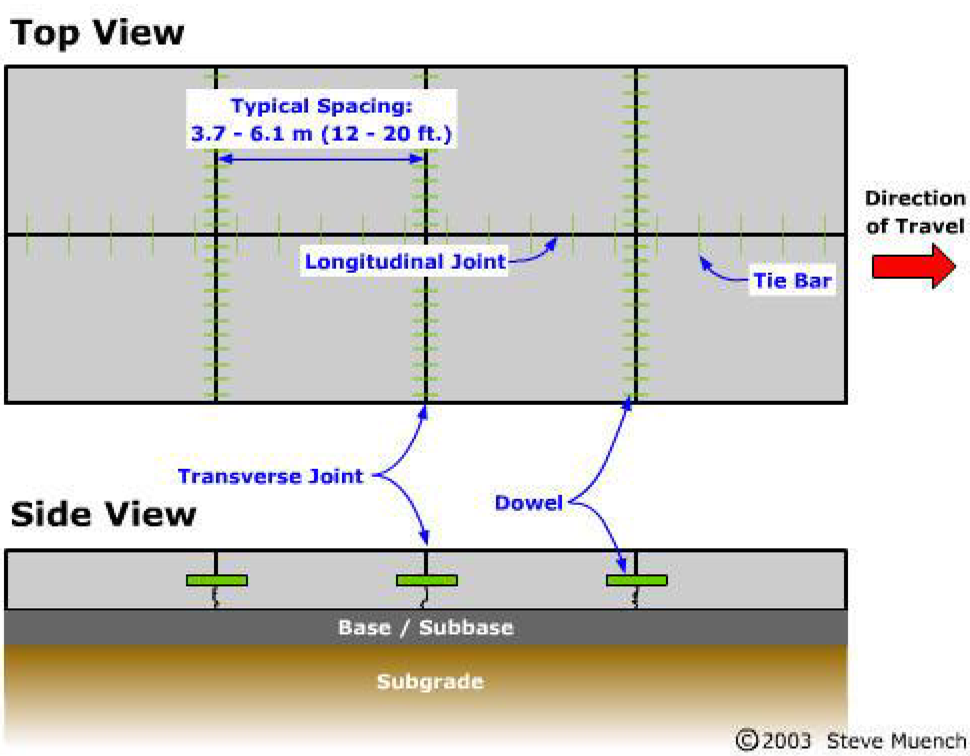
- Structure
  - Surface course
  - Base course
  - Subbase course
  - Subgrade

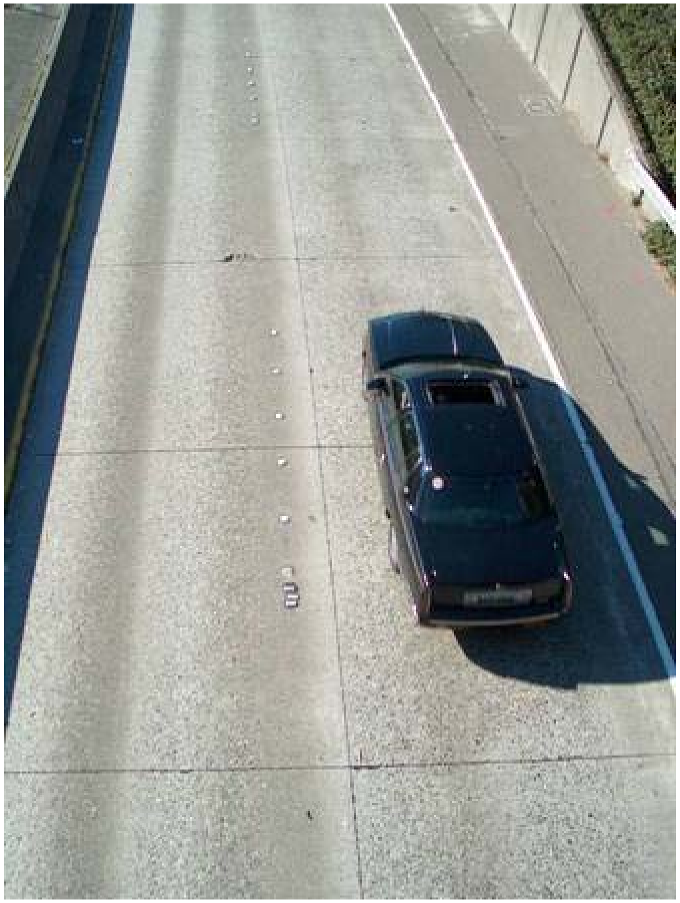




Types of Rigid Pavement

- Jointed Plain Concrete Pavement (JPCP)





Types of Rigid Pavement

- Continuously Reinforced Concrete Pavement (CRCP)

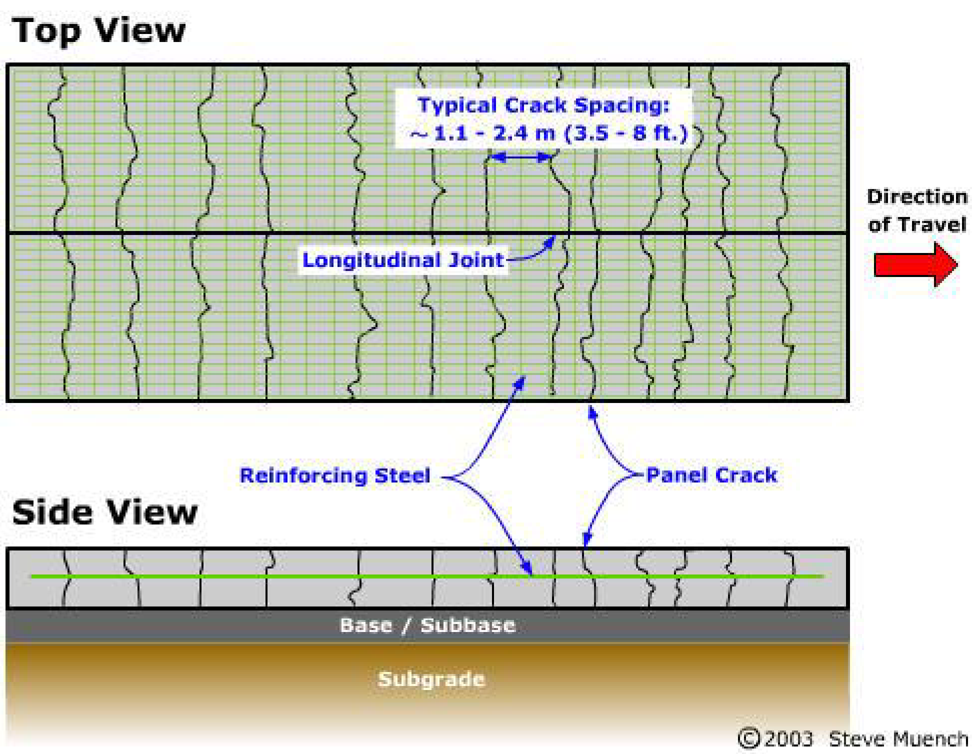


Photo from the Concrete Reinforcing Steel Institute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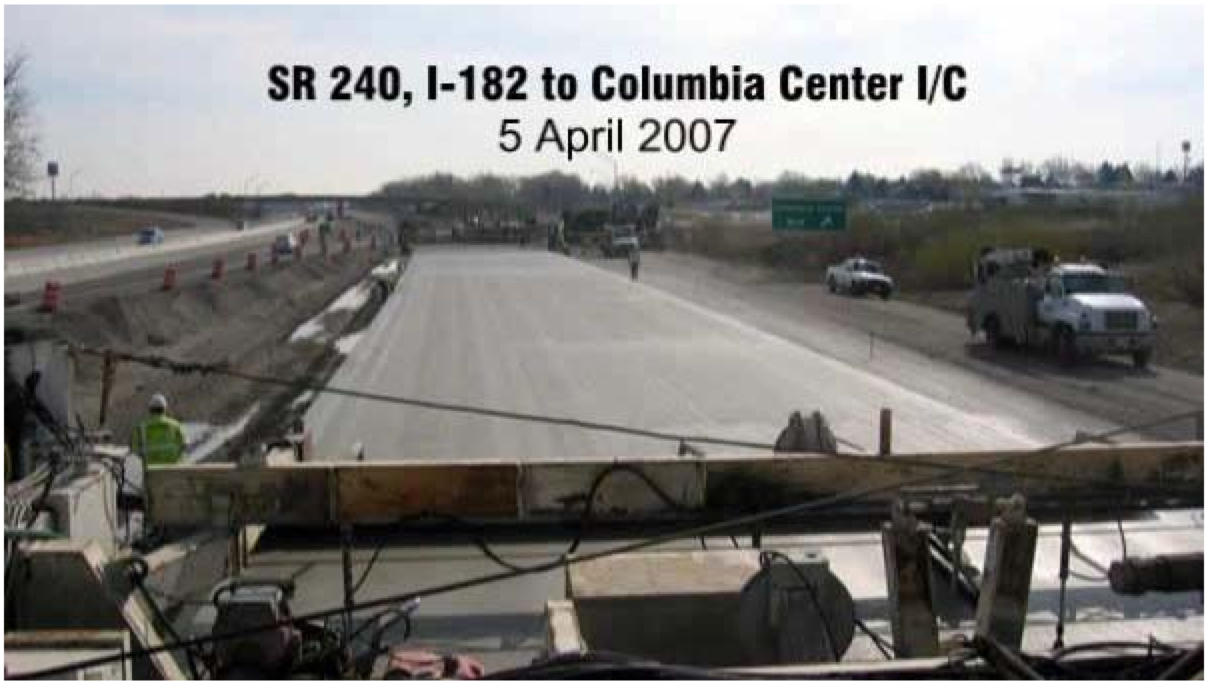
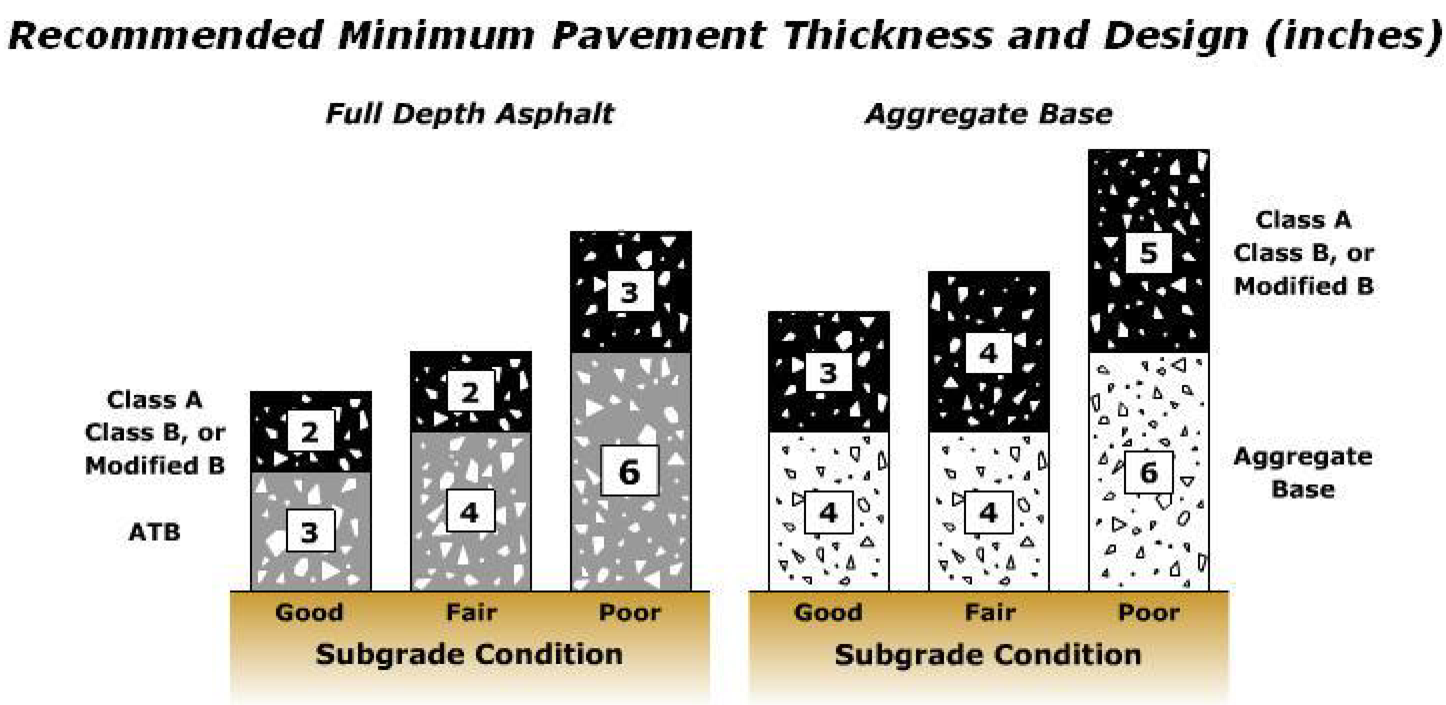

SR 240, I-182 to Columbia Center I/C
5 April 2007

Pavement Design

- Several typical methods
  - Design catalog
  - Empirical
    - 1993 AASHTO method
  - Mechanistic-empirical (not covered here)
    - Various methods
      - New AASHTO method
      - PerRoad
      - Local procedures

Design Catalog



Example design catalog from the Washington Asphalt Pavement Association (WAPA) for residential streets

Empirical

- 1993 AASHTO Flexible Equation

$$\log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

- 1993 AASHTO Rigid Equation

$$\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{(S_c')(C_d)(D^{0.75}) - 1.132}{215.63(J)\left(D^{0.75} - \frac{18.42}{\left(E_c/k\right)^{0.25}}\right)}\right]$$

Terms – Flexible

- W_{18} (loading)
  - Predicted number of ESALs over the pavement's life.
- SN (structural number)
  - Abstract number expressing structural strength
  - $SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 + \ldots$
- ΔPSI (change in present serviceability index)
  - Change in serviceability index over the useful pavement life
  - Typically from 1.5 to 3.0
- M_R (subgrade resilient modulus)
  - Typically from 3,000 to 30,000 psi (10,000 psi is pretty good)

Terms – Rigid

- D (slab depth)
  - Abstract number expressing structural strength
  - $SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 + \ldots$
- S'_c (PCC modulus of rupture)
  - A measure of PCC flexural strength
  - Usually between 600 and 850 psi
- C_d (drainage coefficient)
  - Relative loss of strength due to drainage characteristics and the total time it is exposed to near-saturated conditions
  - Usually taken as 1.0

Terms – Rigid

- J (load transfer coefficient)
  - Accounts for load transfer efficiency
  - Lower J-factors = better load transfer
  - Between 3.8 (undoweled JPCP) and 2.3 (CRCP with tied shoulders)

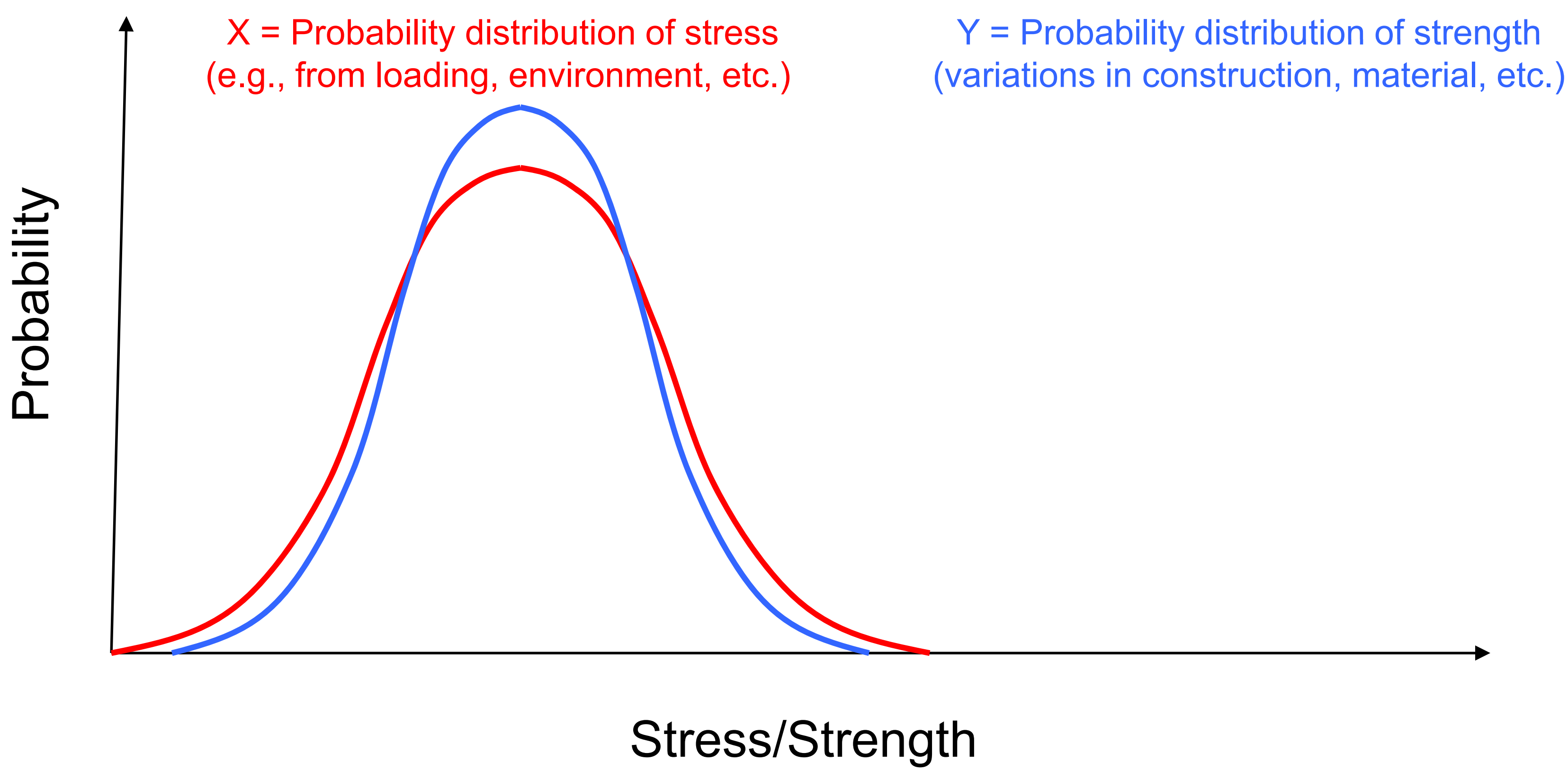
Faulting

- E_c (PCC elastic modulus)
  - 4,000,000 psi is a good estimate
- k (modulus of subgrade reaction)
  - Estimates the support of the PCC slab by the underlying layers
  - Usually between 50 and 1000 psi/inch

Reliability

Reliability = P [Y > X]

$$P[Y > X] = \int_{-\infty}^{\infty} f_x(x)\left[\int_{x}^{\infty} f_y(y)dy\right]dx$$

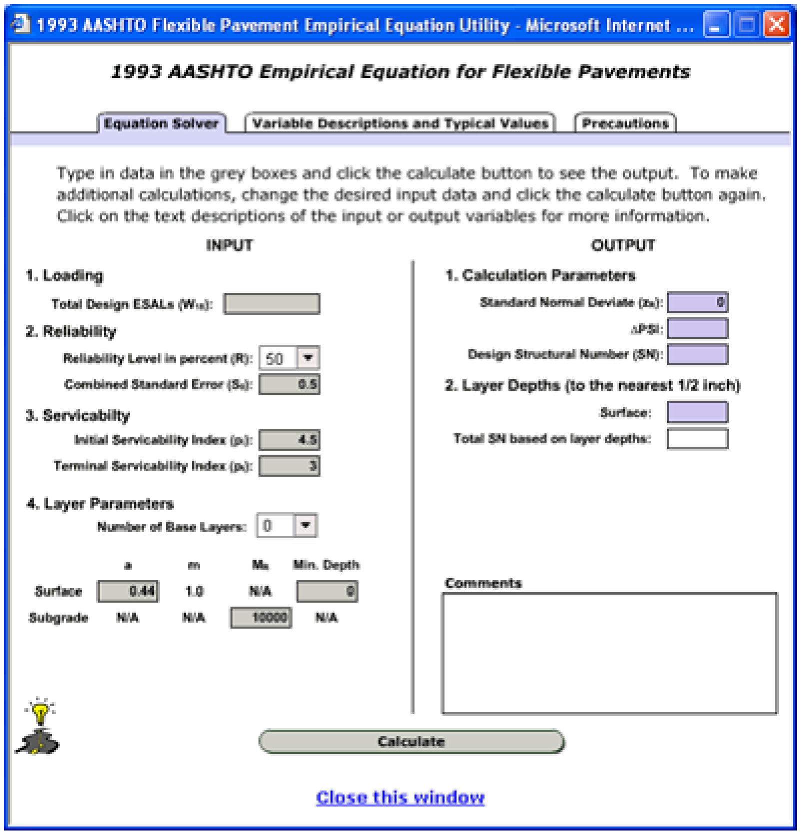


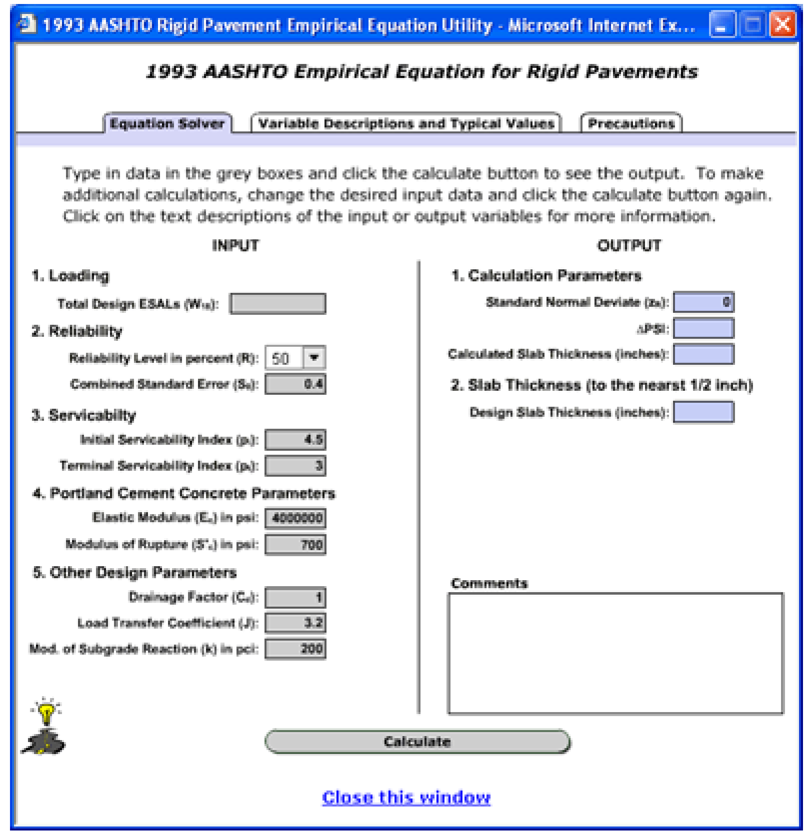
WSDOT Design Table

50-year ESALs	Reliability Level	Flexible Pavement		Rigid Pavement		
		HMA	Base	PCC	Base	
≤ 5,000,000	85%	6 inches	6 inches	8 inches	GB only	4.2 inches
5,000,000 to 10,000,000	95%	8 inches	6 inches	9 inches	HMA over GB	4.2 + 4.2
10,000,000 to 25,000,000	95%	9 inches	6 inches	10 inches	HMA over GB	4.2 + 4.2
25,000,000 to 50,000,000	95%	11 inches	7 inches	11 inches	HMA over GB	4.2 + 4.2
50,000,000 to 100,000,000	95%	12 inches	8 inches	12 inches	HMA over GB	4.2 + 4.2
100,000,000 to 200,000,000	95%	13 inches	9 inches	13 inches	HMA over GB	4.2 + 4.2

GB = gravel base
Reliability = 85% for ≤ 5 million ESALs, 95% for all others

Design Utilities





From *Pavement Interactive*

http://pavementinteractive.org/index.php?title=Module:Structural_Design

(see lower right of page for the "design utilities")

Design Example – Part 1

A WSDOT traffic count on Interstate 82 in Yakima gives the following numbers:

Parameter	Data	WSDOT Assumptions
AADT	18,674 vehicles	
Singles	971 vehicles	0.40 ESALs/truck
Doubles	1,176 vehicles	1.00 ESALs/truck
Trains	280 vehicles	1.75 ESALs/truck

Assume a 40-year pavement design life with a 1% growth rate compounded annually. How many ESALs do you predict this pavement will by subjected to over its lifetime if its lifetime were to start in the same year as the traffic count?

$$Total = \frac{P\left(\left(1+i\right)^{n} - 1\right)}{i}$$

Design Example – Part 2

Design a flexible pavement for this number of ESALs using (1) the WSDOT table, and (2) the design equation utility in the WSDOT *Pavement Guide Interactive*. Assume the following:

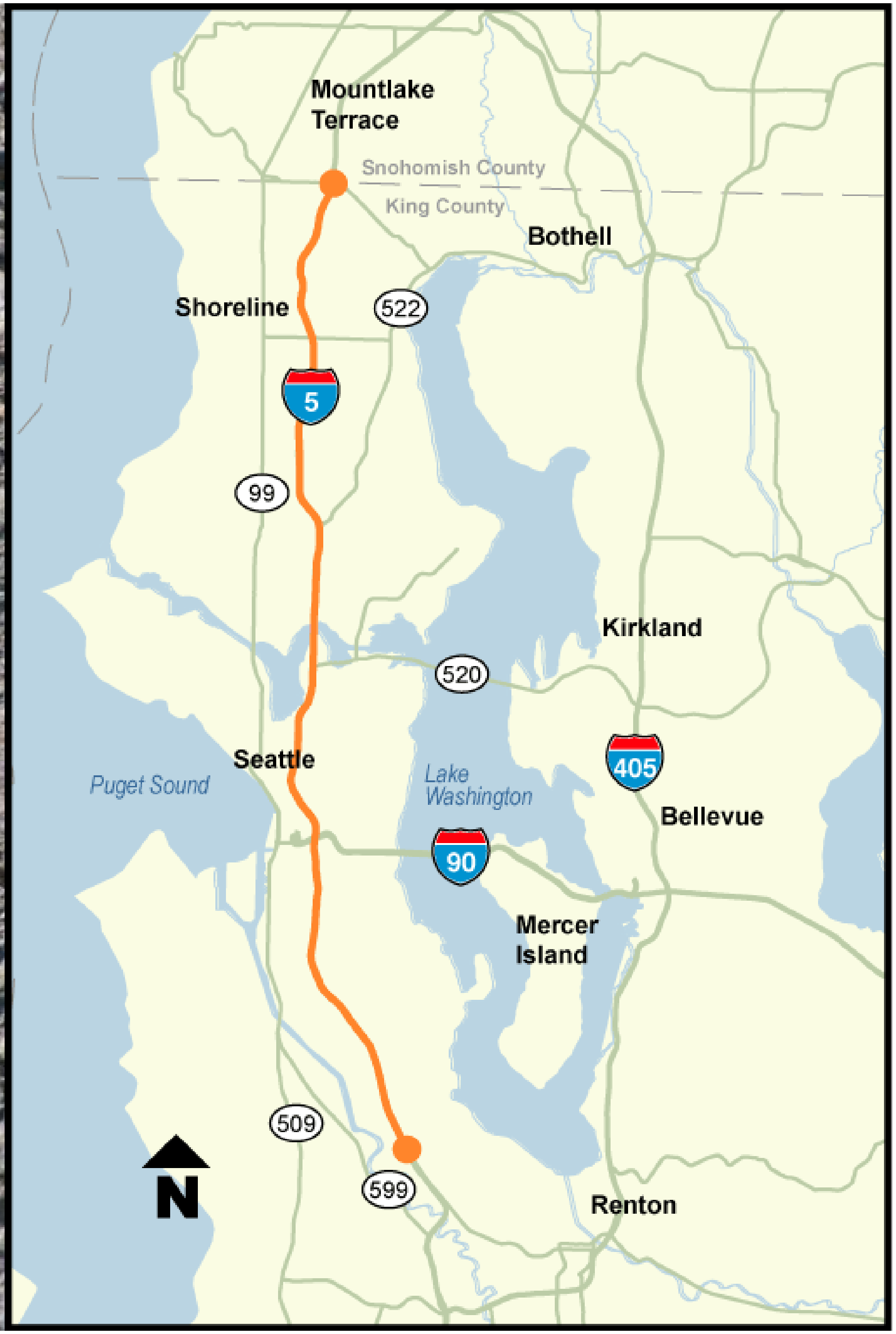
- Reliability = 95% (Z_R = -1.645 , S_0 = 0.50)
- ΔPSI = 1.5 (p_0 = 4.5, p_t = 3.0)
- 2 layers (HMA surface and crushed stone base)
  - HMA coefficient = 0.44, minimum depth = 4 inches
  - Base coefficient = 0.13, minimum depth = 6 inches
  - Base M_R = 28,000 psi
- Subgrade M_R = 9,000 psi

Design Example – Part 3

Design a doweled JPCP rigid pavement for this number of ESALs using (1) the WSDOT table, and (2) the design equation utility in the WSDOT *Pavement Guide Interactive*. Assume the following:

- Reliability = 95% (Z_R = -1.645 , S_0 = 0.40)
- ΔPSI = 1.5 (p_0 = 4.5, p_t = 3.0)
- E_{PCC} = 4,000,000 psi
- S'_C = 700 psi
- Drainage factor (C_d) = 1.0
- Load transfer coefficient (J) = 2.7
- Modulus of subgrade reaction (k) = 400 psi/in
  HMA base material

I-5 Triage Project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Terrace
Snohomish County
King County
Bothell
Shoreline
522
5
99
Kirkland
520
Seattle
Puget Sound
Lake
Washington
405
Bellevue
90
Mercer
Island
509
599
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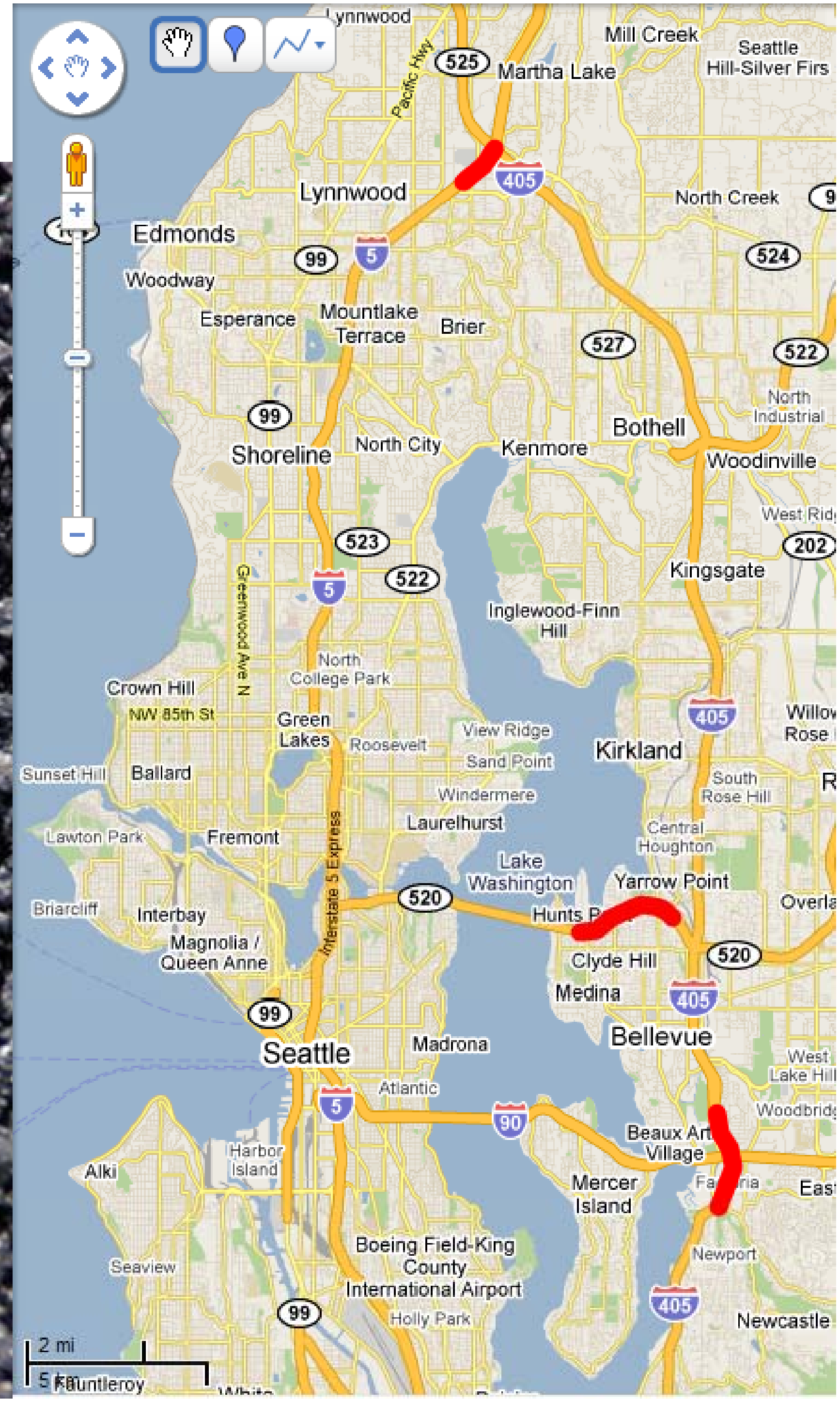
Renton

I-5 Triage Project

I-5 Triage Project

I-5 Triage Project

Quiet Pavement (I-5, SR 520, I-405)

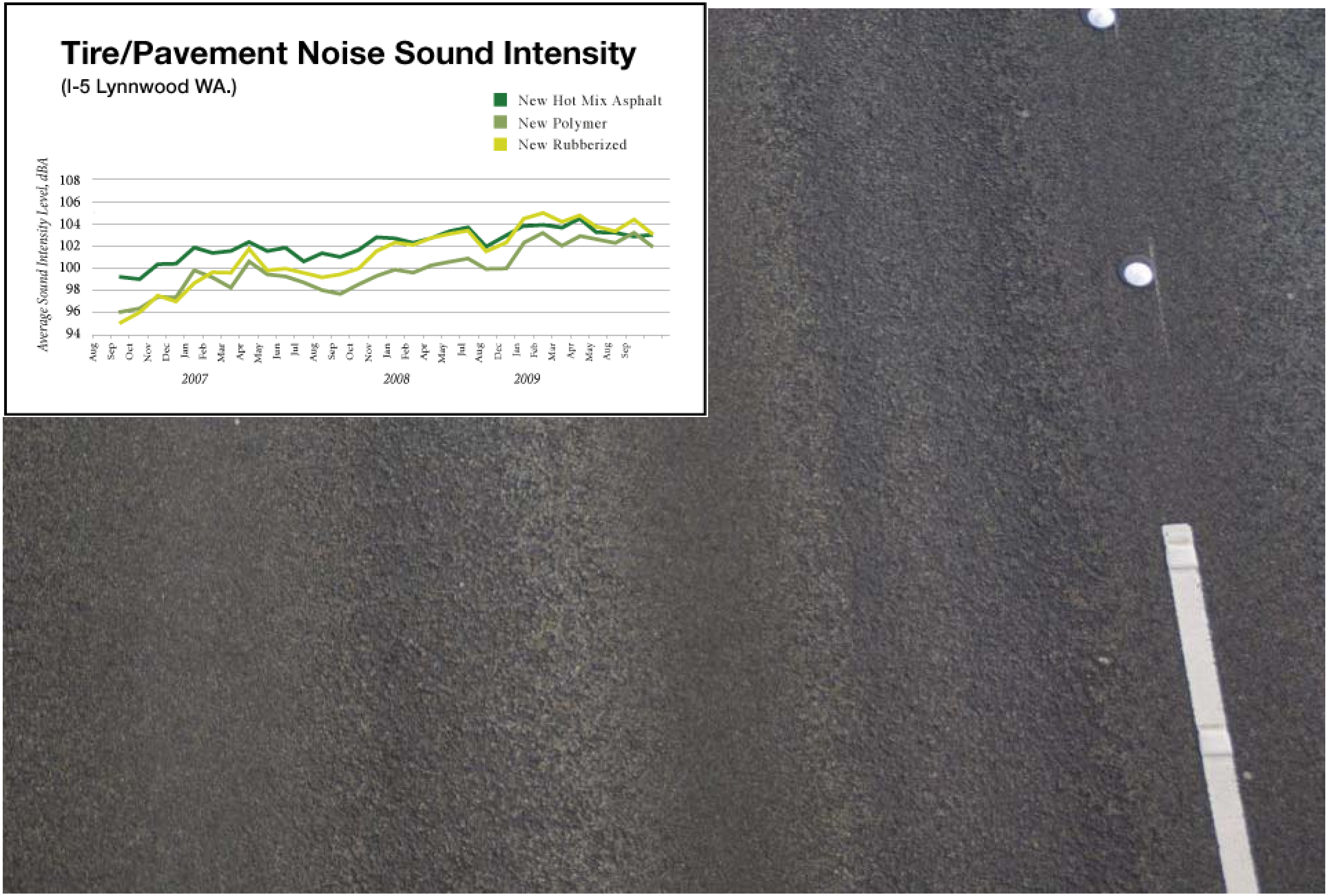


Quiet Pavement (I-405)

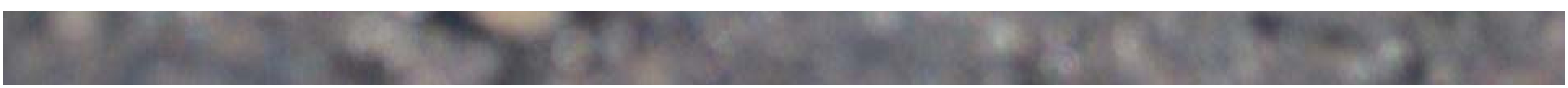
Quiet Pavement (SR 520)

Quiet Pavement (I-5)

Quiet pavements: with studded tires it doesn't work



Hot in-place recycling (SR 542)

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ROADTEC


SLOW

Primary References

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- Muench, S.T.; Mahoney, J.P. and Pierce, L.M. (2009) *Pavement Interactive*. University of Washington, Seattle, WA. http://pavementinteractive.org

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