CONCRETE PAVEMENT DESIGN AND SUSTAINABILITY

2012 NWPMA CONFERENCE

October 23, 2012

Vancouver, WA

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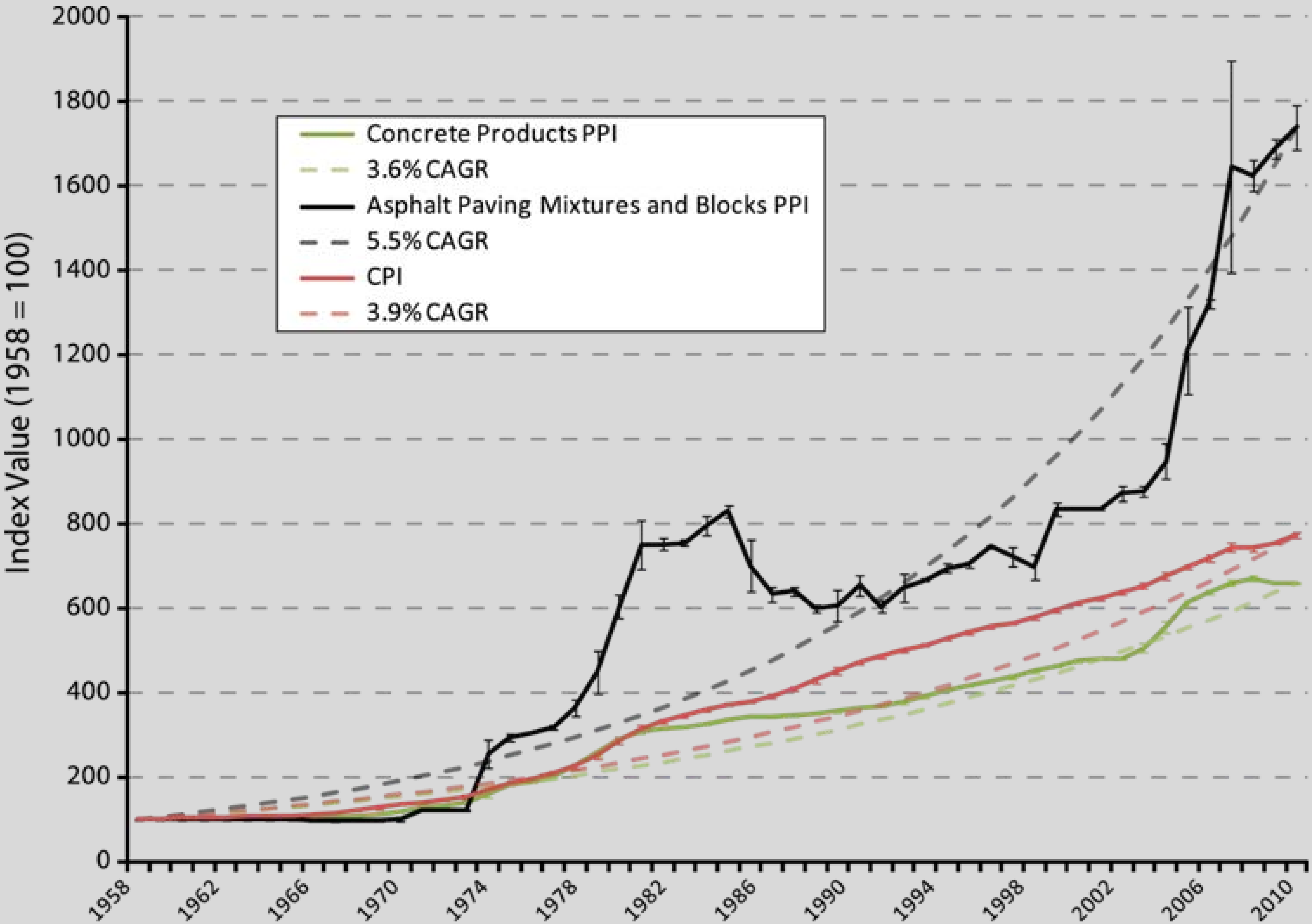
ACPA NORTHWEST CHAPTER

The New Paving Reality



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Concrete Pavement Sustainability

- Longevity is the hallmark of concrete pavements
  - >50 year old pavements common…
- Benefits beyond longevity

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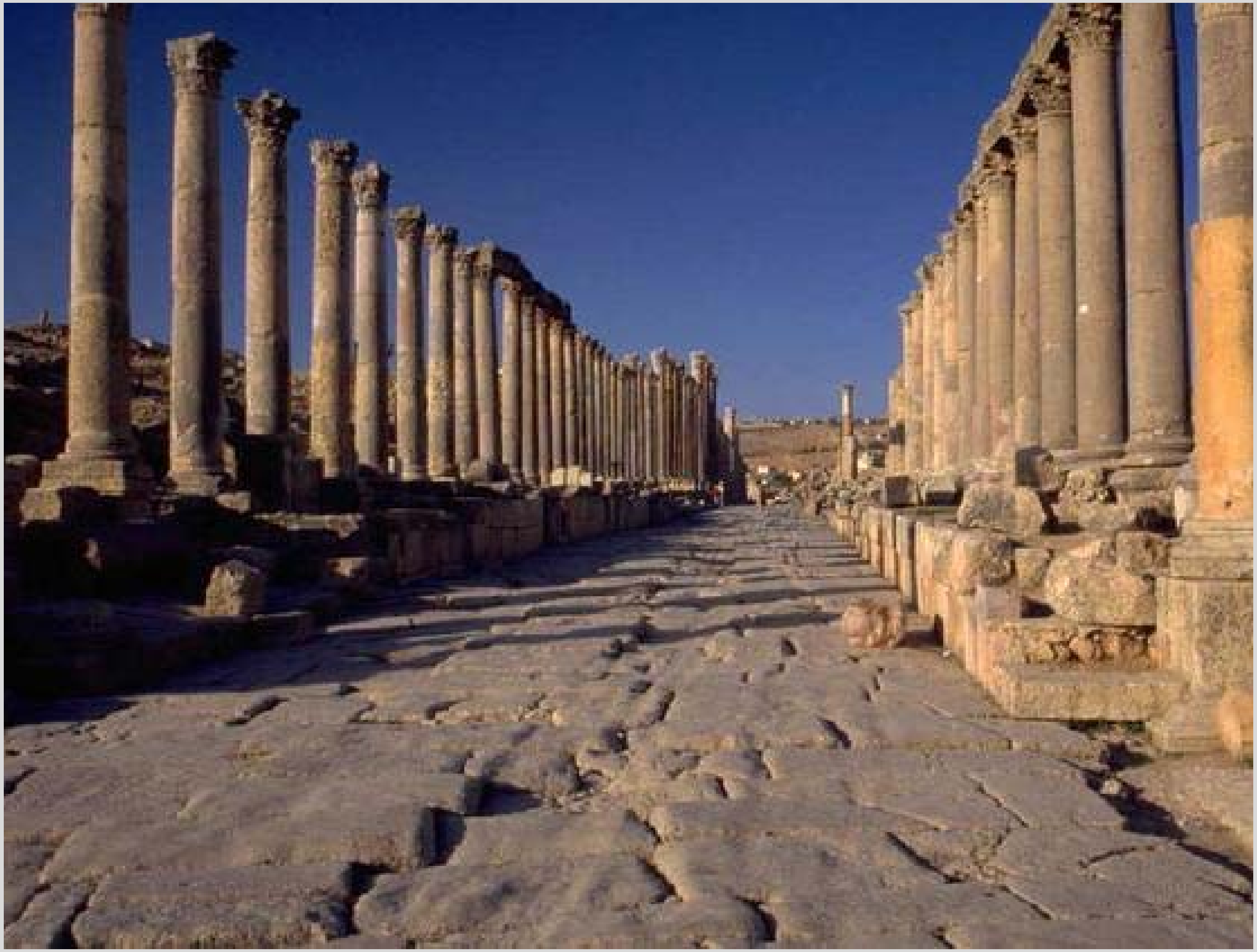
Concrete Pavement Longevity



Concrete Pavement Longevity

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Concrete Pavement Longevity

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Benefits of Longevity

- Less-frequent reconstruction
- Lower consumption of raw materials
  - Cement, aggregates, steel
- Less Congestion

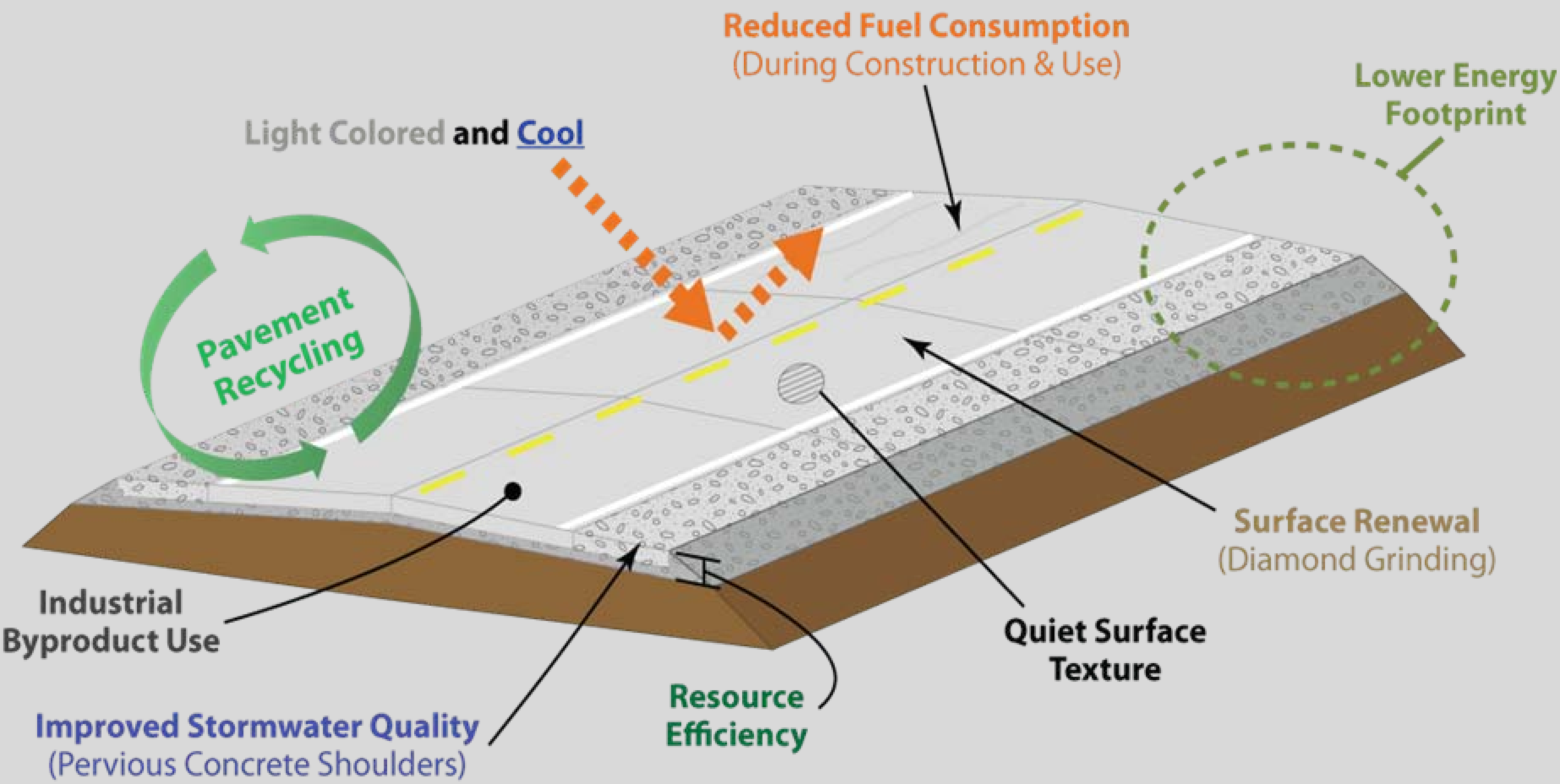
Benefits of Longevity

- Reduction in pollutants
  - Manufacturing, construction, congestion
- Infrequent construction zones
- Real economic benefits…

Raw Materials Savings

- Equivalent Sections
  - 8” HMA on 12” CSBC
  - 10 ½ “ PCCP on 4” CSBC
- Future Overlays
  - 2” mill and fill every 10 – 15 years
- Savings of 2,200 tons/lane mile over 50 years

Sustainable Benefits ***Beyond*** Longevity



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Sustainability and Roadways?

- ACPA Special Report on Green Roadways…
  - Emphasizes **longevity** as the primary opportunity!**!**

Green Roadways

Environmentally and Economically Sustainable Concrete Pavements

concrete pavement research and technology *special report*

Contents

Introduction

The concepts of "sustainability" and "sustainable development" are receiving considerable attention as the causes of global warming and climate change are debated. The World Commission on Environment and Development has defined sustainable development as "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).

In recent years it has been suggested that in order for human activity to meet present needs without compromising the prospects of future generations, we need to carefully balance economic, environmental, and societal demands. This concept is often referred to as the "three pillars of sustainability" or the "triple-bottom-line."

A major focus of this concept involves ensuring that sustainable practices in pavements go hand in hand with economic success. This is indeed true of concrete pavements.

Particularly because of its long life, concrete is an economical, cost-effective pavement solution that consumes minimal materials, energy, and other resources for construction, maintenance, and rehabilitation activities over its lifetime. Beyond longevity, other features of concrete pavement further enhance its sustainability:

- Because of its rigidity, concrete pavement deflects less under vehicle loading, which results in reduced vehicle fuel consumption.
- The construction of concrete pavements consumes less fuel (particularly diesel) during materials production, transportation, and placement than the construction of asphalt pavements.
- Concrete pavements exhibit a lower energy footprint associated with their production, delivery, and maintenance than asphalt pavements do over a 50-year time period.
- Due to its inherent rigidity, concrete pavement requires less subbase aggregate materials for structural support than asphalt pavements.
- Concrete pavement mixtures incorporate industrial byproducts (i.e., fly ash and slag cement), which lowers the disposal needs, reduces the demand on virgin materials, and conserves natural resources.

Figure 1. An example of a green, sustainable concrete pavement; see ACPA's [illegible], "Nall Avenue: A Green Street," for details on the sustainability-related benefits of this project (photo courtesy of The City of Overland Park, Kansas).

ACPA
American Concrete Pavement Association

June 2011

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What are we currently focusing on?

- **Sustainability programs and rating systems have emerged for pavements.**
  - **GreenRoads (rate roadways, not an LCA)**
  - **FHWA Self Evaluation Tool (rating)**
  - **FHWA Sustainable Pavements TWG**
  - **ISI Envision (rating)**
- **Relate to production/construction phases**
- **Little is focused on the long-term use or operational phase of its life-cycle!**

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What should we be doing?

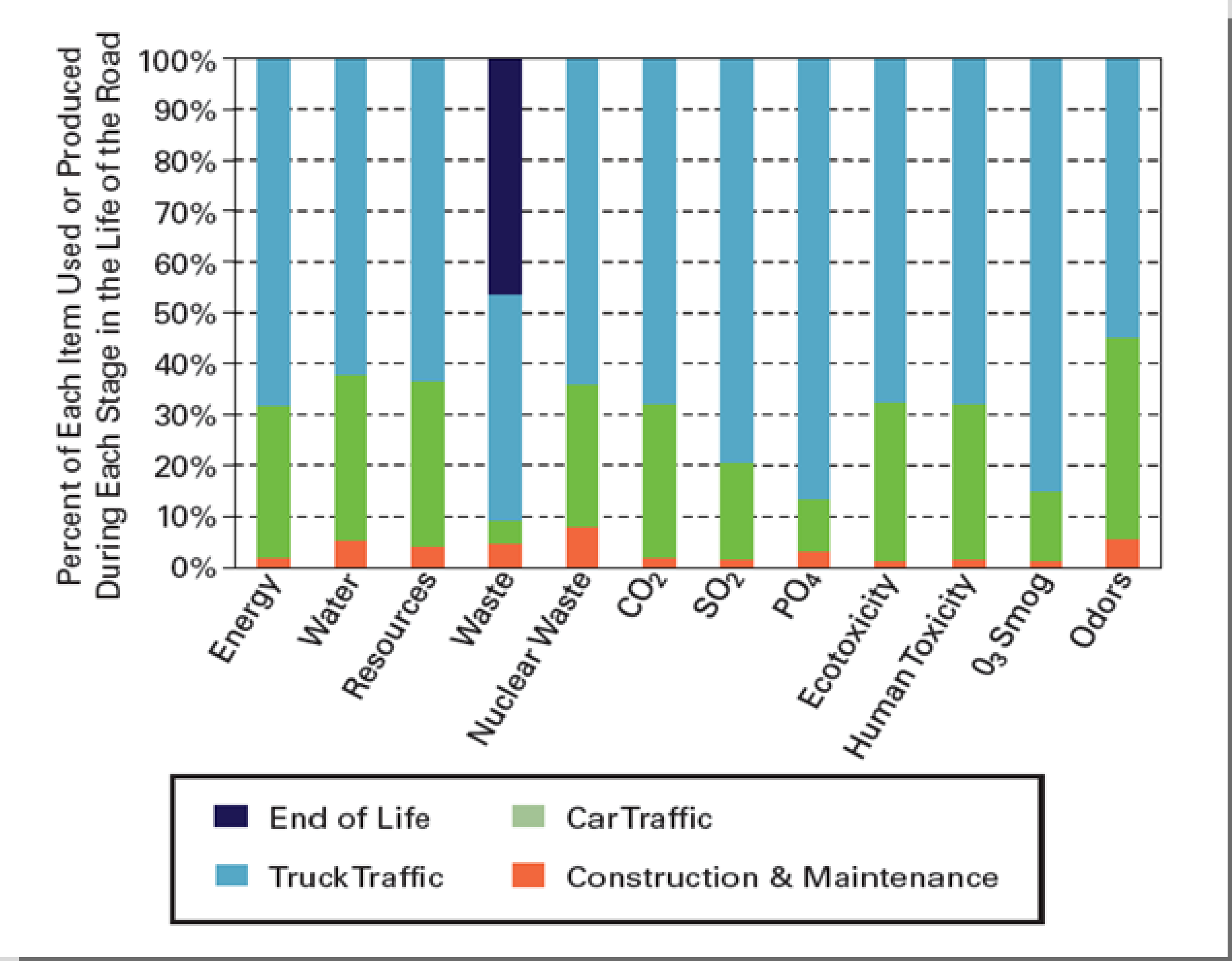
- **Clarification:**

  All the commonly adopted sustainability strategies are important and should be embraced!

- **…though, it is useful to know where we can be most impactful.**
- **Recent comprehensive LCA studies are giving us clues as to where that is...**

What should we be doing?

Ecoprofile of different life cycle stages of a typical road



[Centre d'Energetique de l'Ecole des Mines de Paris]

What should we be doing?

- From this LCA we see:
  - Overall impacts from use-phase dwarfs impacts from ALL other phases of the roadway life cycle
  - From energy perspective… construction and maintenance accounts for less than 2% of the entire energy footprint *[EAPA 2004]*
- Therefore (as an example):
  - Just a **2-3%** improvement in the truck/car portion of the ecoprofile could offset the entire construction and maintenance ecoprofile!

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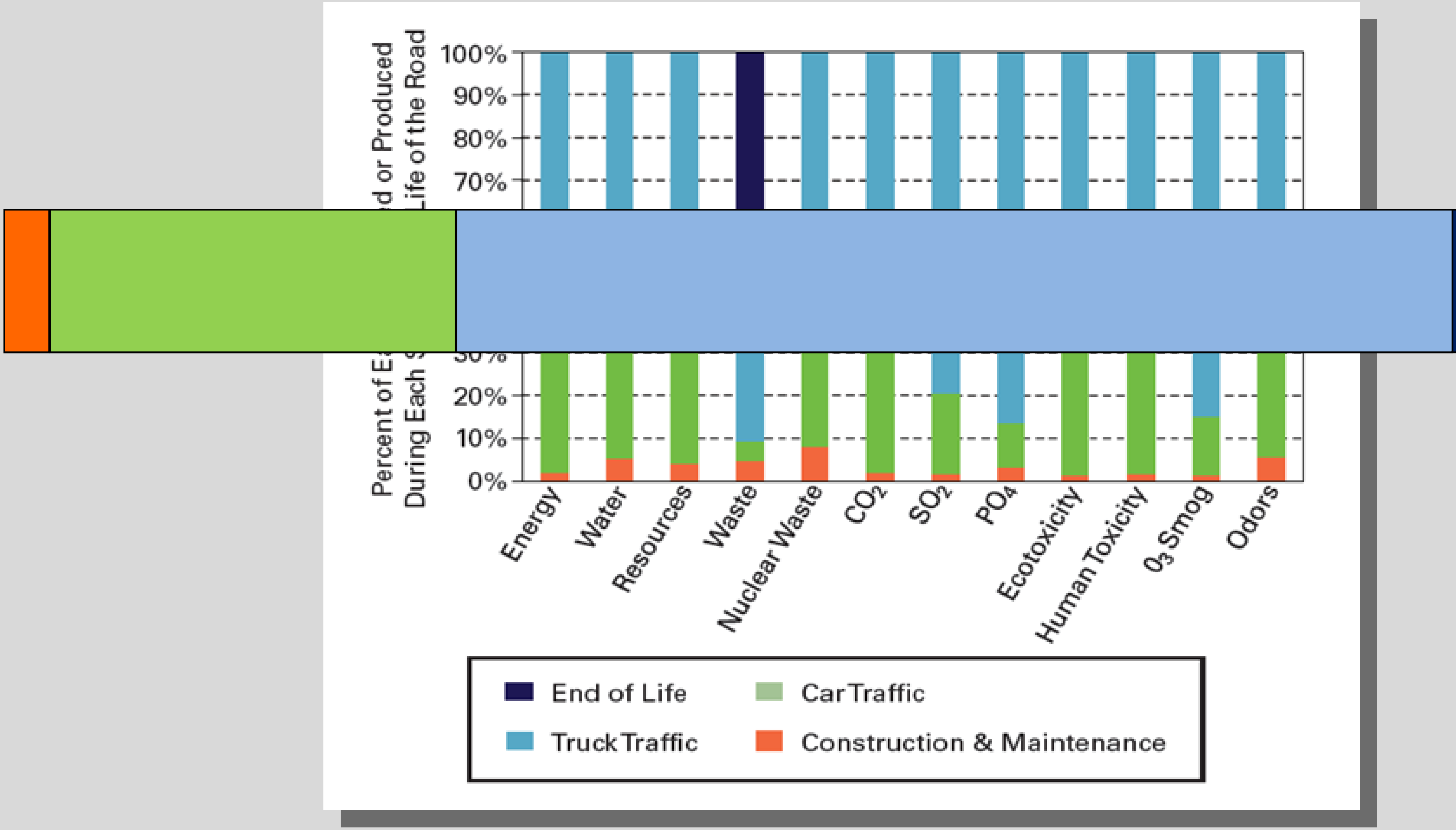
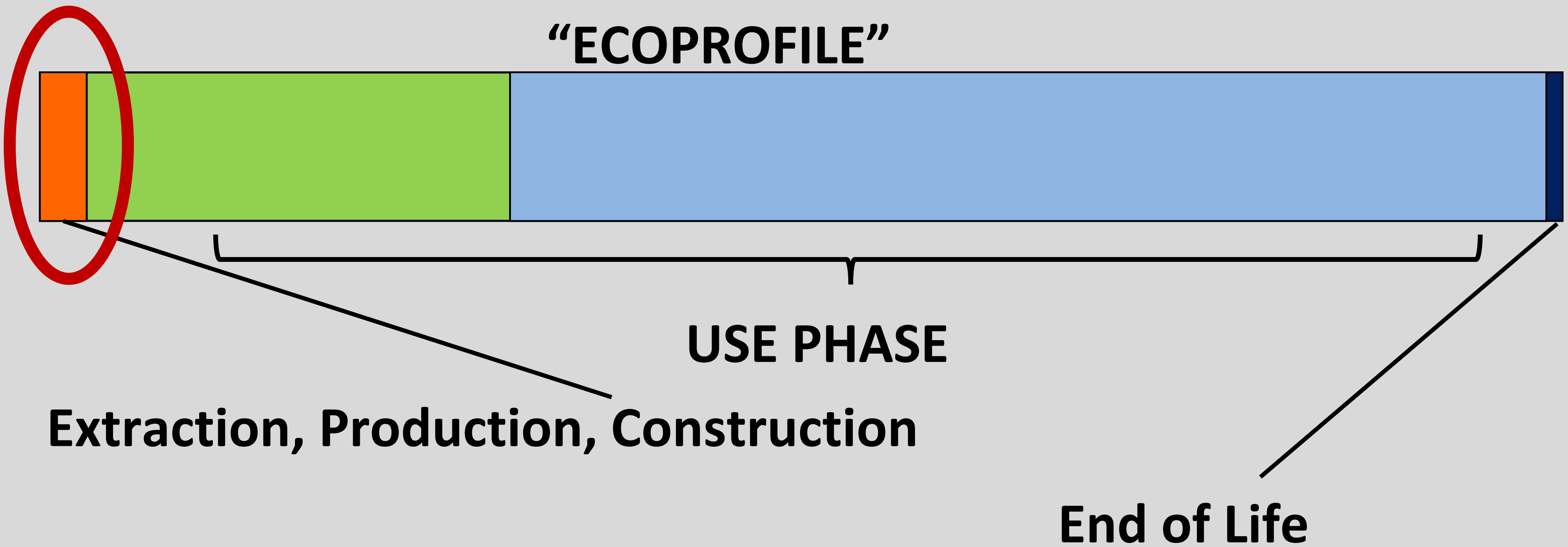
What should we be doing?



[Centre d'Energetique de l'Ecole des Mines de Paris]

What should we be doing?



Where do our "conventional" sustainability tools fit in this ecoprofile?

RCA, RAP, Flyash, Slag, Warm Mix?

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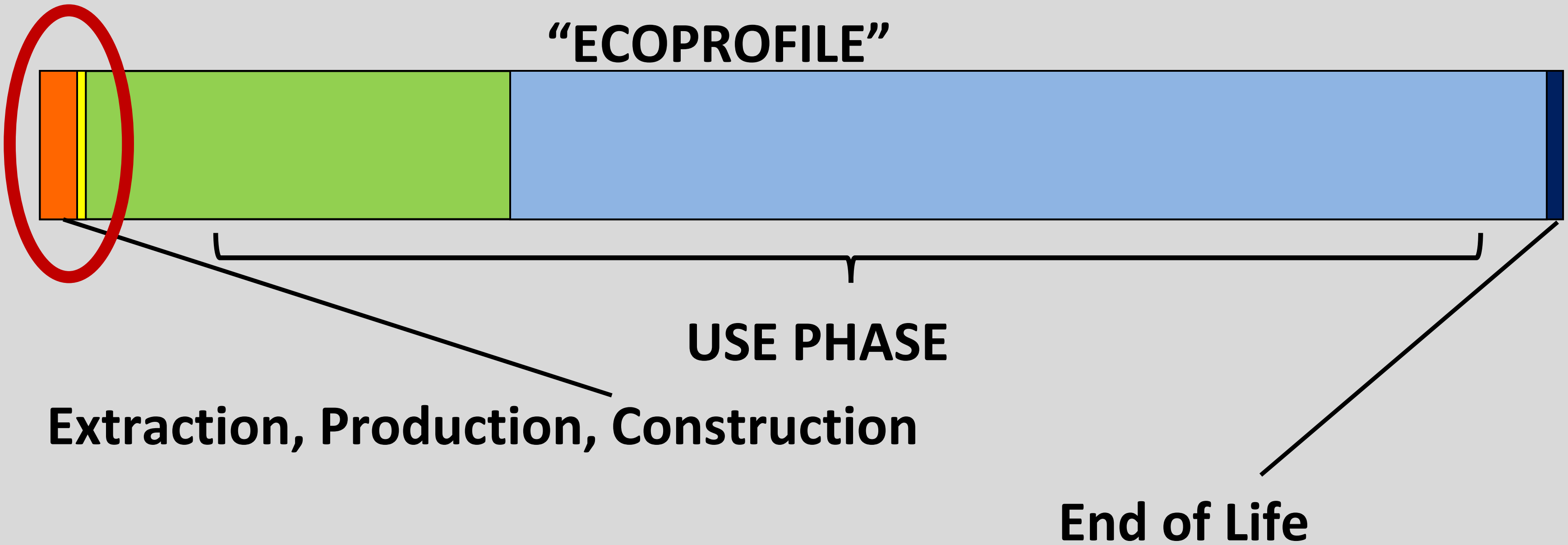
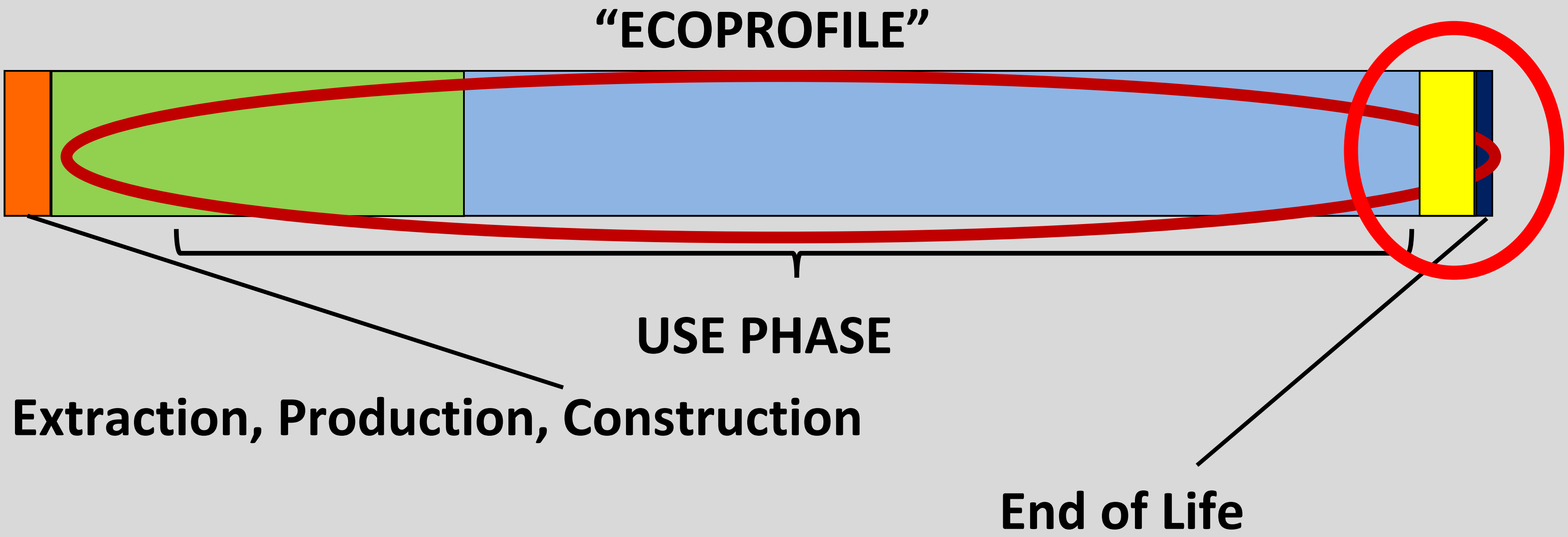
What should we be doing?



SO… if we make a 30% improvement in the production energy footprint …

…that small sliver would be the impact on the entire life-cycle "ecoprofile"!

What should we be doing?



However, what if we can find a way to reduce the use-phase portion by, say 5%?

This yellow area would represent the overall impact…

What should we be doing?

What are these use/operational-phase impacts?

- **Vehicle fuel consumption rates**
  - Pavement rigidity
  - Pavement smoothness
- **Pavement surface reflectivity (albedo)**
  - Urban heat island mitigation
  - Lighting need
  - Global cooling potential

CoolMix!

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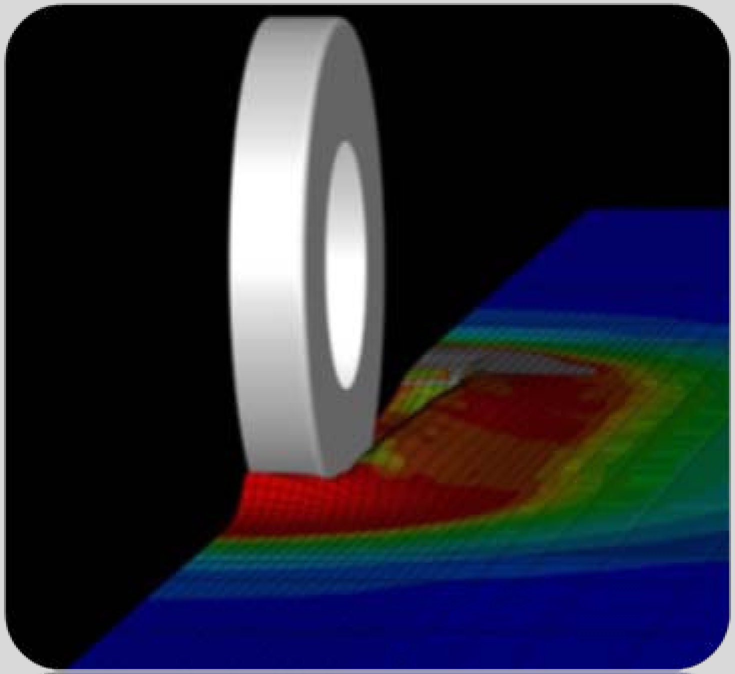
Are we Focusing on the Right Things?



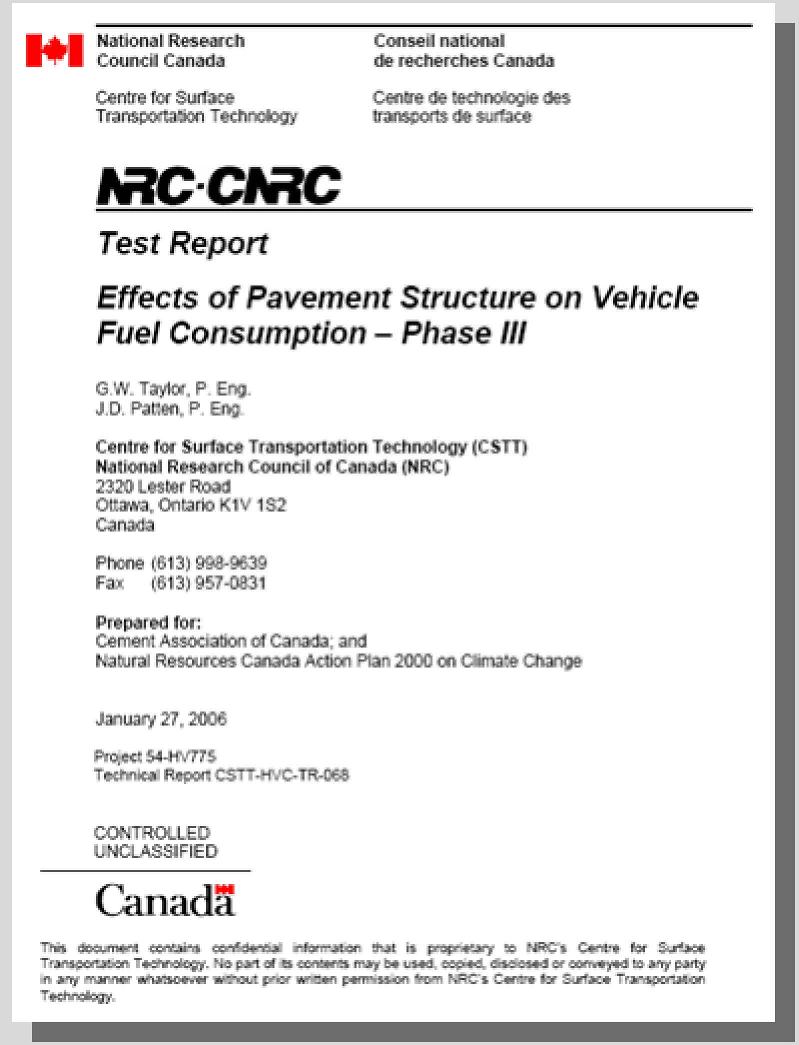
Vehicle Fuel Economy

Vehicle Fuel Economy

- Rigid Surface

  →Lower Deflection

  →**Less Loss**
- In-depth study by *National Research Council Canada*
- Significant fuel consumption reductions for trucks on concrete pavement (**0.8-6.9%**)
- Sweden, UTA, NCHRP, MIT



National Research Council Canada | Conseil national de recherches Canada

Centre for Surface Transportation Technology | Centre de technologie des transports de surface

NRC·CNRC

Test Report

Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III

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Cement Association of Canada; and
Natural Resources Canada Action Plan 2000 on Climate Change

January 27, 2006

Project 54-HV775
Technical Report CSTT-HVC-TR-068

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Vehicle Fuel Economy

- US DOT data
  - US truck fuel consumption billion gallons per year
  - With just a 3% improvement on roughly 50% of the network, savings would amount to…

    … approx **585 million gallons of diesel/yr**

    (13.5 billion lbs CO_2 eq. and $2.3 billion)
  - Additional savings from lighter vans, cars, etc.

Vehicle Fuel Economy

- Smoothness – smooth roads are fuel efficient roads.
  - Should **specify** and **construct** smooth concrete pavements
  - FHWA reported a **4.5%** improvement in fuel economy (trucks) with smoothness (IRI) improving from 152in/mile to 76in/mile ('00).
  - Ongoing work as well at MIT and NCHRP.
  - Applies not just to new pavements – must maintain smoothness. Pavement renewal!

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Are we Focusing on the Right Things?

Surface Reflectivity

NORTHWEST CHAPTER

Surface Reflectivity - Lighting

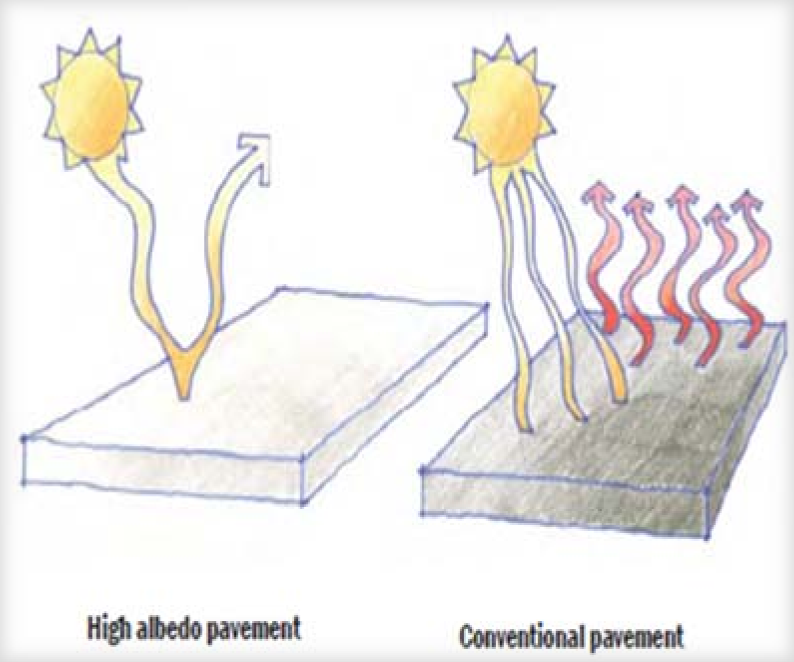
Enhanced Nighttime Visibility:

- Improved pedestrian and vehicle safety
- Reduced lighting & energy requirement:
  - Fewer fixtures/watts
  - Up to 33% reduction
  - AASHTO - 40% lower
  - Huge budget impact!

Surface Reflectivity

Urban Heat Island Mitigation:

- Urban areas up to 9°F warmer due to UHI resulting in greater energy use and resulting pollution
- PCCP is an effective mitigation strategy
  - – lower city temperatures
  - – lower cooling costs
  - – reduce smog formation
- Pot. energy savings $2B in US alone*(LBNL'08)*



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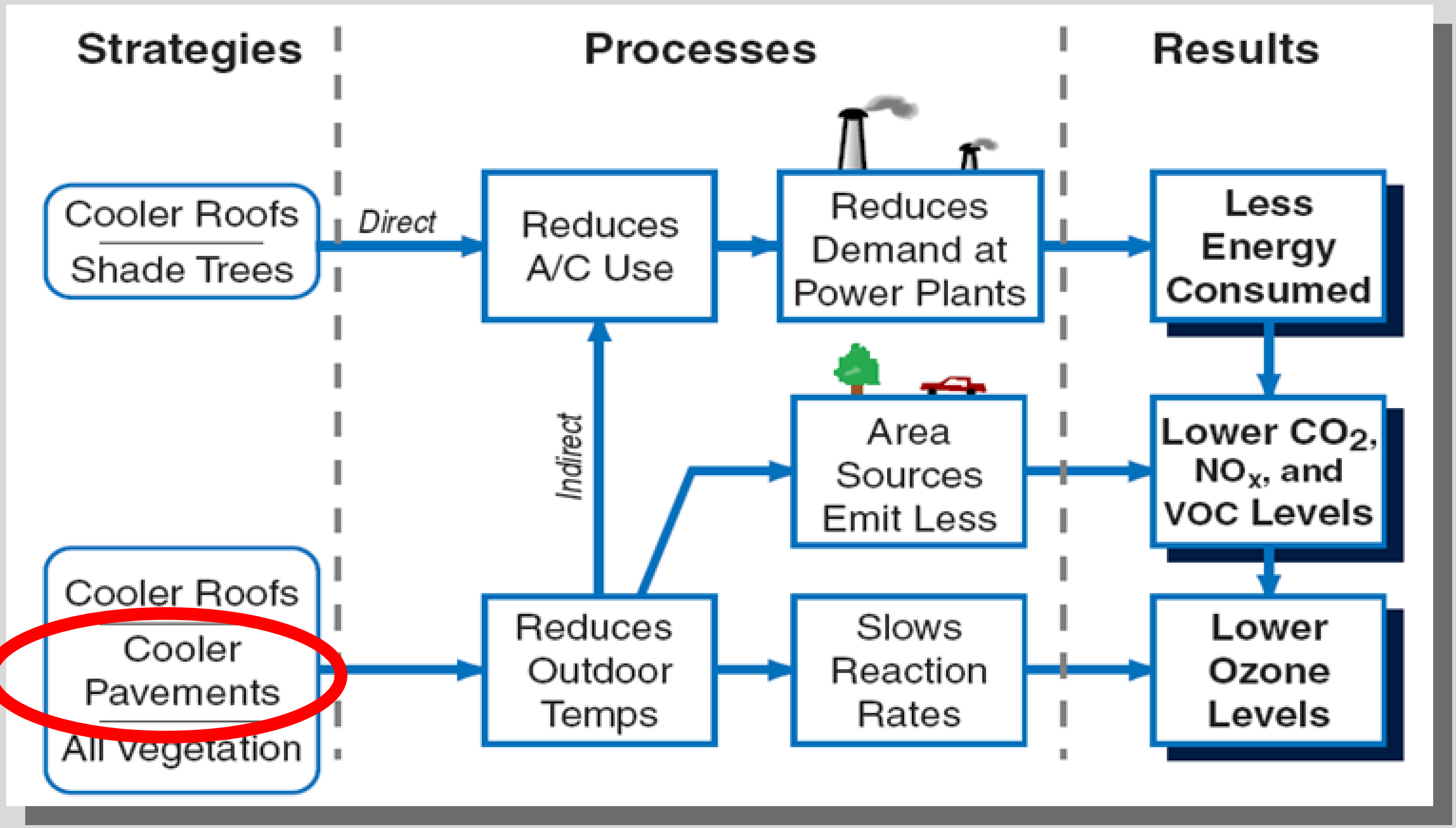
Surface Reflectivity

- 5th CA Climate Change Conference (*LBNL and CEC*)



Surface Reflectivity

- Concept is that earth is not a closed system

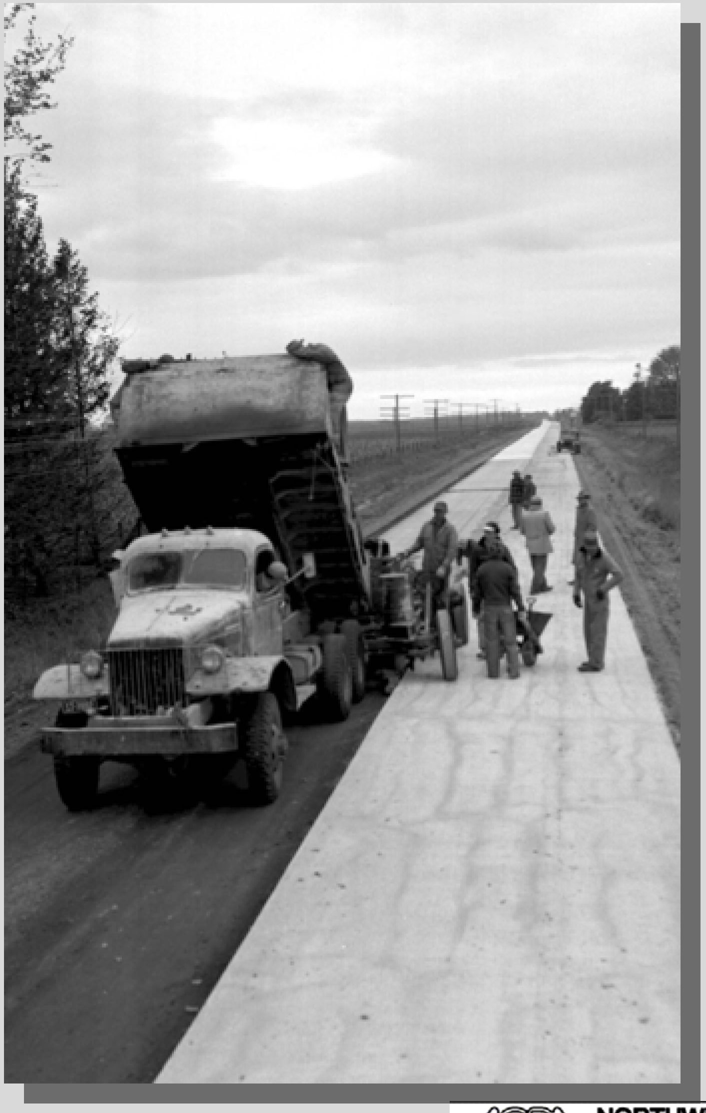
- Reflective materials on earth's surface (snow, ice, concrete) return more of sun's energy back into space – reducing temperatures
- This amounts to the equivalent of CO_2 reduction (offset)

Global Cooling

- Cities 1% of global land area
- 60% cities=roofs/pavements
- Cool roofs and pavements (concrete) can increase urban albedo by 0.1, and in turn induce negative radiative forcing….
- If implemented in 100 largest cities in world, this can offset **44Gt** of emitted CO_2 ($1.1 trillion at $25/ton) – proposal to UN considered.

Pavement Engineering

- ***…the art of molding materials we do not wholly understand into shapes we cannot precisely analyze so as to withstand forces we cannot assess in such a way that the community at large has no reason to suspect our ignorance.***



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Thickness Design

- The new pavement will be built in the future, on subgrades often not yet exposed or accessible, using materials not yet manufactured from sources not yet identified, by a contractor who submitted the successful "low dollar" bid, employing unidentified personnel and procedures under climatic conditions that are frequently less than ideal.
- Measure with a micrometer, mark with a grease pencil and cut with an axe… we design to 100th of an inch, round up to nearest ½” and then contractor overbuilds thickness and uses materials with higher than necessary strength to ensure pay.
- How many concrete pavements fail because of thickness?

Mechanistic Design

- A purely scientific approach
- Relies on mechanics of structural behavior to loading
- Requires knowledge of fundamental material properties
- Requires knowing (precisely) the geometric properties of the structure

Empirical Design

- Based on results of experiments or experience
- Requires many observations to establish links between design variables and performance
- Does not require establishing a scientific basis for observed relationships

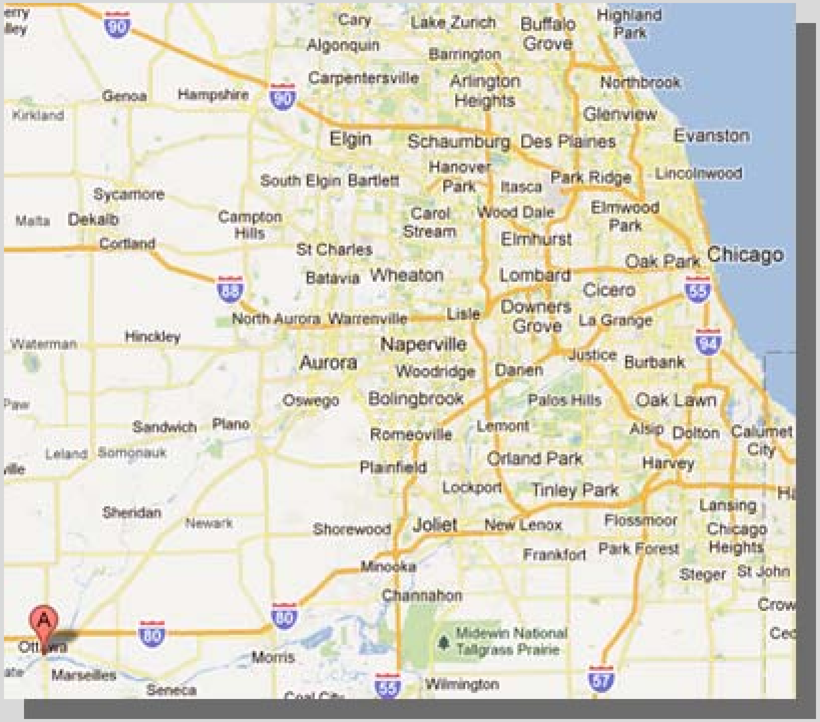
$$Cracking = loads + environment + material + this + that$$

Introduction to the WinPAS Design Procedure

The AASH(T)O Road Test

AASHO Road Test

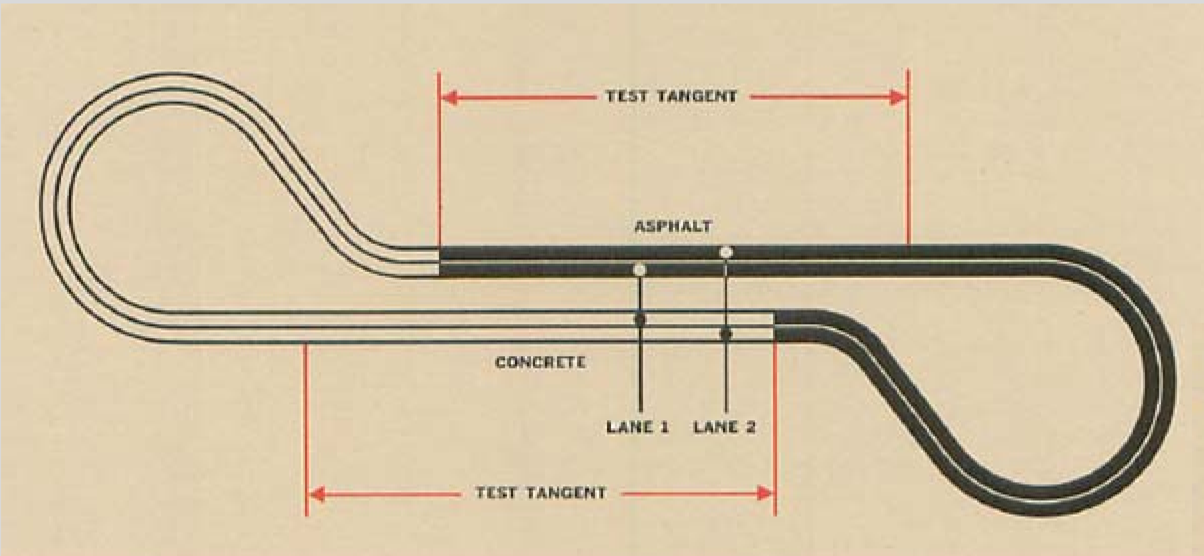
Conceived and sponsored by the American Association of State Highway Officials to study the performance of pavement structures of known thickness under moving loads of known magnitude and frequency.



AASHO Road Test (1958-1960)

- Third Large Scale Road Test
  - Maryland Road Test (1950-51)
    Rigid Pavements Only
  - WASHO Road Test (1952-54)
    Flexible Pavements only
- Included both concrete and asphalt designs
- Included a wide range of axle loads and pavement cross-sections

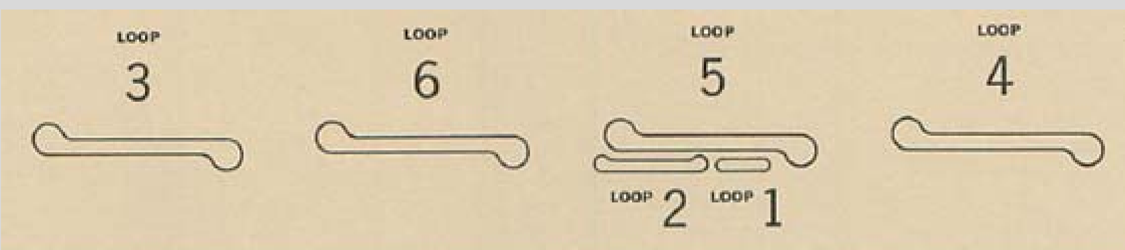
Typical AASHO Loop Layout

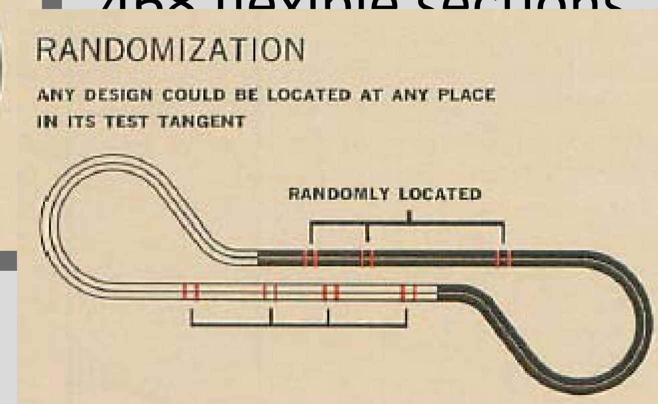


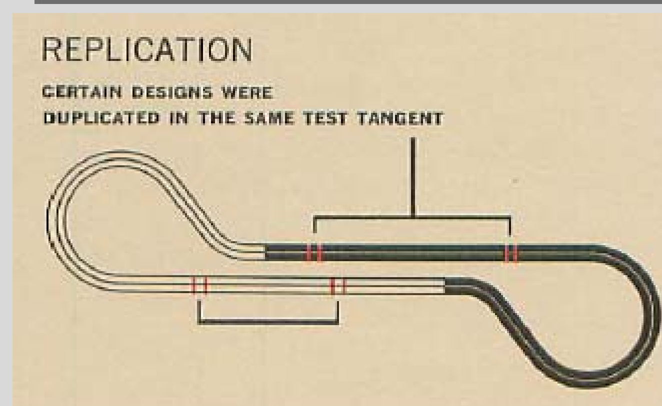
Test Tangent = 6,800 ft

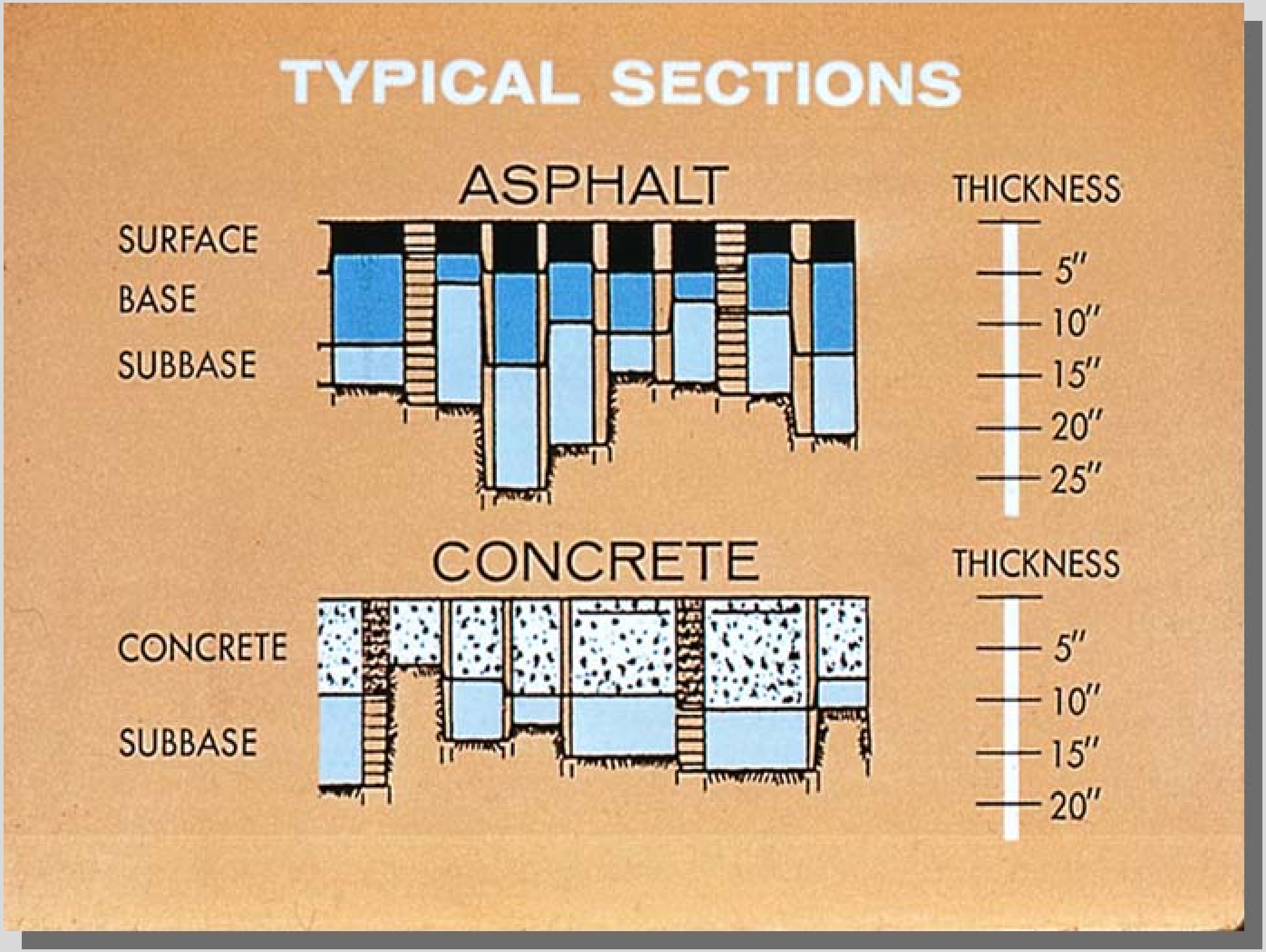
368 rigid sections

468 flexible sections









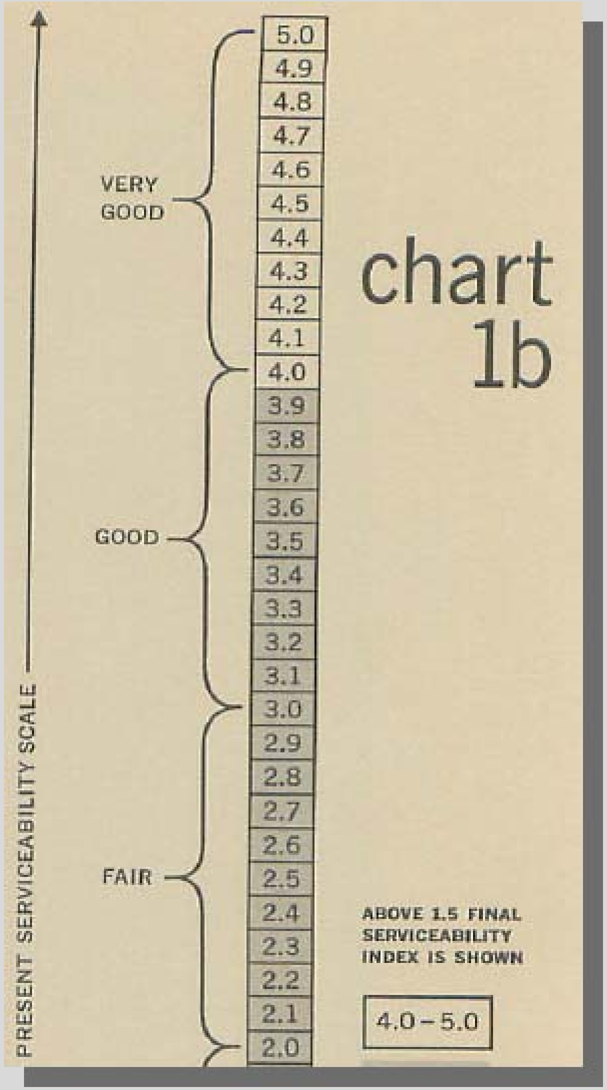
Subgrade = Clay Soil

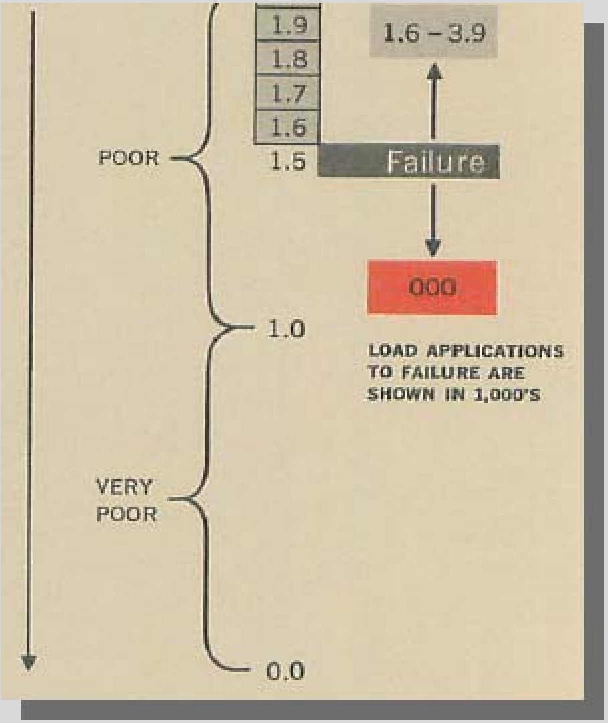
AASHO Test Traffic

Max Single Axle

Max Tandem Axle

Performance Metric





Some AASHO Results – Loop 2

Concrete thickness	Lane	Subbase 0" Plain	Subbase 0" Reinforced	Subbase 3" Plain	Subbase 3" Reinforced	Subbase 6" Plain	Subbase 6" Reinforced
2½"	LANE 1	4.3	4.2	4.4	4.2	4.4	4.4
2½"	LANE 2	555	469	2.2	840	3.1	3.8
3½"		4.2	4.4	4.0	4.1	4.2	4.5
3½"		3.7	4.1	4.0	4.1	4.0	4.6
3½"					4.5		
3½"					4.2		
5"		4.1	4.3	3.9	4.6	4.1	4.3
5"		4.1	4.5	4.1	4.6	4.0	4.3
5"				3.5			
5"				3.6			

ALL SECTIONS IN SECOND ROW ARE REPLICATES

0.0 — SERVICEABILITY INDEX AT END OF TEST

000 — LOAD APPLICATIONS TO FAILURE (1,000'S)

LOOP 2 CONCRETE

…1,114,000 load applications to end

Some AASHO Results – Loop 2

2
CHART 2

ASPHALT

LANE 1 →
LANE 2 →

ASPHALT SURFACE THICKNESS	Lane	BASE 0" / SUBBASE 0"	BASE 0" / SUBBASE 4"	BASE 3" / SUBBASE 0"	BASE 3" / SUBBASE 4"	BASE 6" / SUBBASE 0"	BASE 6" / SUBBASE 4"
1"	LANE 1	52	80	552	2.5	2.8	3.2
	LANE 2	2	2	70	73	106	570
2"		645	1.7	3.8	3.5	3.4	3.6
		74	87	250	582	3.5	3.2
				2.4	3.3	3.7	3.3
				120	1.8	2.5	2.6
3"		3.0	3.3	3.8	3.8	3.6	3.9
		104	106	710	2.7	3.1	3.6

ALL SECTIONS IN SECOND ROW ARE REPLICATES

0.0 — SERVICEABILITY INDEX AT END OF TEST

000 — LOAD APPLICATIONS TO FAILURE (1,000'S)

Some AASHO Results – Loop 4

Concrete thickness \ Subbase	3" Plain	3" Reinforced	6" Plain	6" Reinforced	9" Plain	9" Reinforced
5"	716 343	415 304	353 328	325 175	291 289	592 408
6½"	3.8 687	3.8 2.6 3.6 793	4.4 3.4 4.3 1000	3.4 796	3.0 722	1.8 1036
8"	4.4 4.1 4.5 4.2	3.9 4.0	4.4 4.2	4.4 4.4 3.9 3.8	4.3 4.1	4.3 4.2
9½"	4.2 4.0	4.0 4.0	4.5 4.2	4.5 4.3	4.1 4.2	4.8 4.6

18,000 18,000 LANE 1

32,000 32,000 LANE 2

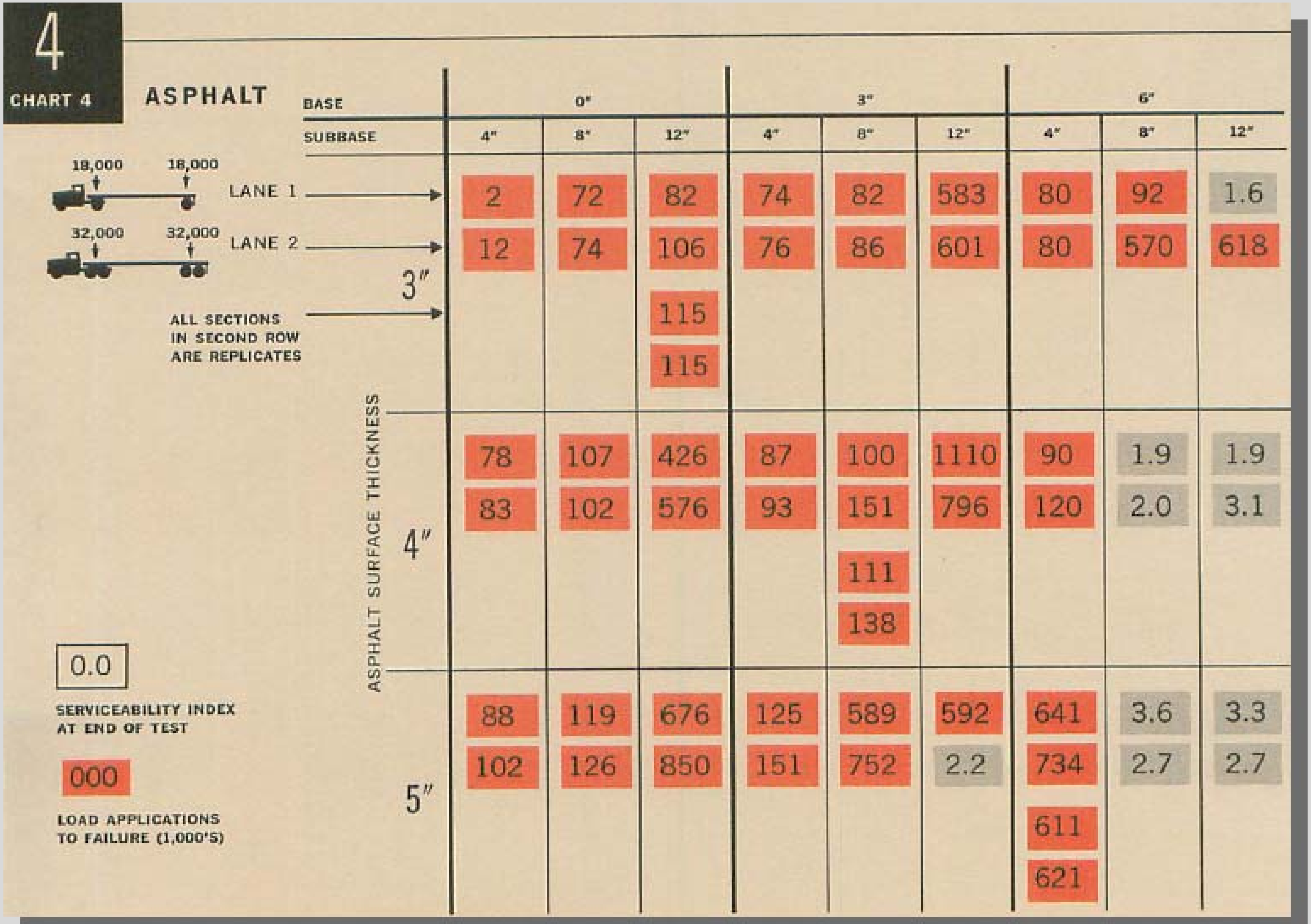
ALL SECTIONS IN SECOND ROW ARE REPLICATES

0.0 SERVICEABILITY INDEX AT END OF TEST

000 LOAD APPLICATIONS TO FAILURE (1,000'S)

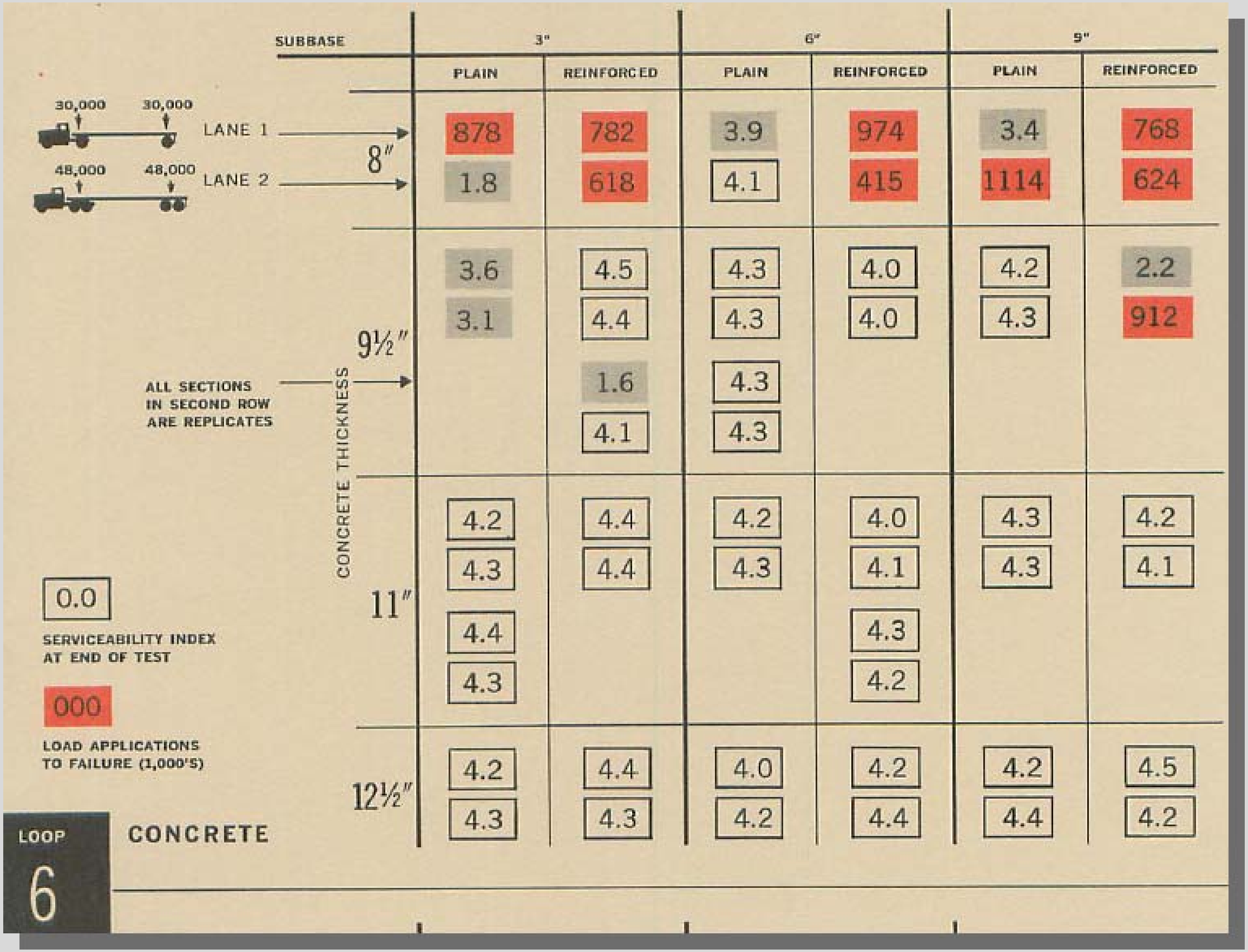
LOOP 4 CONCRETE

Some AASHO Results – Loop 4



Asphalt surface thickness	Row	Base 0", Subbase 4"	Base 0", Subbase 8"	Base 0", Subbase 12"	Base 3", Subbase 4"	Base 3", Subbase 8"	Base 3", Subbase 12"	Base 6", Subbase 4"	Base 6", Subbase 8"	Base 6", Subbase 12"
3"	Lane 1	2	72	82	74	82	583	80	92	1.6
3"	Lane 2	12	74	106	76	86	601	80	570	618
3"	Replicate			115						
3"	Replicate			115						
4"	Lane 1	78	107	426	87	100	1110	90	1.9	1.9
4"	Lane 2	83	102	576	93	151	796	120	2.0	3.1
4"	Replicate					111				
4"	Replicate					138				
5"	Lane 1	88	119	676	125	589	592	641	3.6	3.3
5"	Lane 2	102	126	850	151	752	2.2	734	2.7	2.7
5"	Replicate							611		
5"	Replicate							621		

Some AASHO Results – Loop 6



SUBBASE		3"		6"		9"	
Concrete thickness		PLAIN	REINFORCED	PLAIN	REINFORCED	PLAIN	REINFORCED
8"	Lane 1	878	782	3.9	974	3.4	768
	Lane 2	1.8	618	4.1	415	1114	624
9½"	Lane 1	3.6	4.5	4.3	4.0	4.2	2.2
	Lane 2	3.1	4.4	4.3	4.0	4.3	912
	Lane 1		1.6	4.3			
	Lane 2		4.1	4.3			
11"	Lane 1	4.2	4.4	4.2	4.0	4.3	4.2
	Lane 2	4.3	4.4	4.3	4.1	4.3	4.1
	Lane 1	4.4			4.3		
	Lane 2	4.3			4.2		
12½"	Lane 1	4.2	4.4	4.0	4.2	4.2	4.5
	Lane 2	4.3	4.3	4.2	4.4	4.4	4.2

Some AASHO Results – Loop 6

6

CHART 6 **ASPHALT**

Asphalt surface thickness	Row	Base 3" / Subbase 8"	Base 3" / Subbase 12"	Base 3" / Subbase 16"	Base 6" / Subbase 8"	Base 6" / Subbase 12"	Base 6" / Subbase 16"	Base 9" / Subbase 8"	Base 9" / Subbase 12"	Base 9" / Subbase 16"
4"	Lane 1	72	373	134	82	83	552	82	353	2.0
4"	Lane 2	80	573	621	373	100	621	242	737	3.2
4"	Replicates			91						
4"	Replicates			104						
5"	Lane 1	78	101	573	100	634	1.8	595	719	3.3
5"	Lane 2	103	419	652	105	595	809	624	722	3.5
5"	Replicates					411				
5"	Replicates					618				
6"	Lane 1	141	113	627	106	1.6	3.2	624	2.8	2.7
6"	Lane 2	579	485	2.4	250	3.0	3.9	2.6	2.6	3.6
6"	Replicates							2.1		
6"	Replicates							1.7		

LANE 1: 30,000 – 30,000

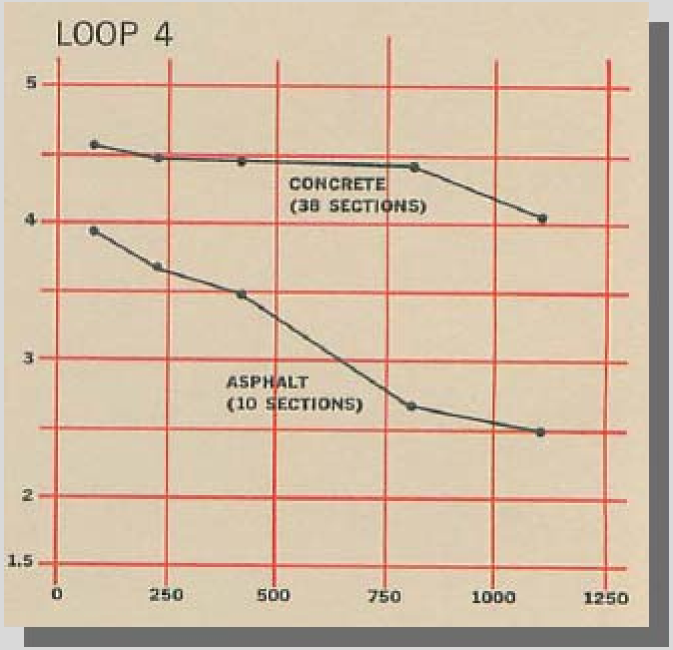
LANE 2: 48,000 – 48,000

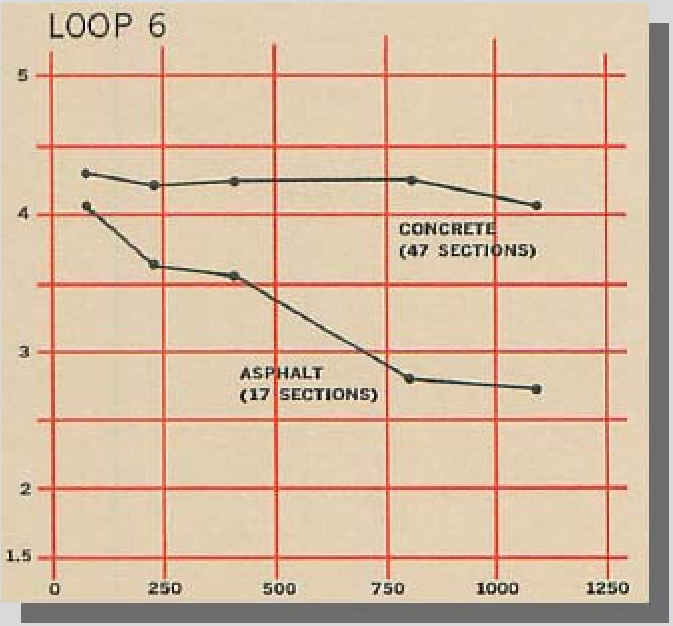
ALL SECTIONS IN SECOND ROW ARE REPLICATES

0.0 — SERVICEABILITY INDEX AT END OF TEST

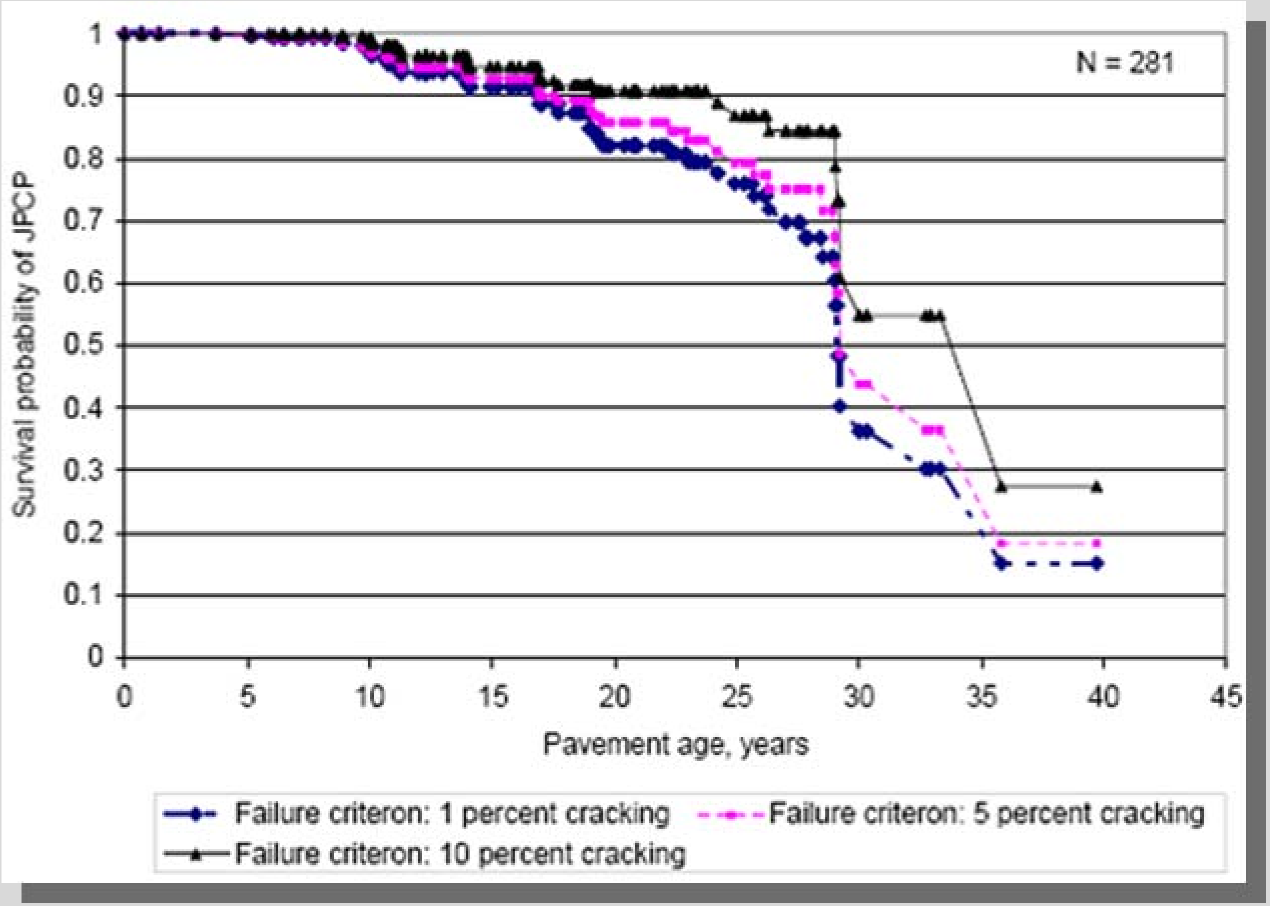
000 — LOAD APPLICATIONS TO FAILURE (1,000'S)

Some AASHO Results – Average Serviceability of Surviving Sections





LTTP JPCP Survival Curve

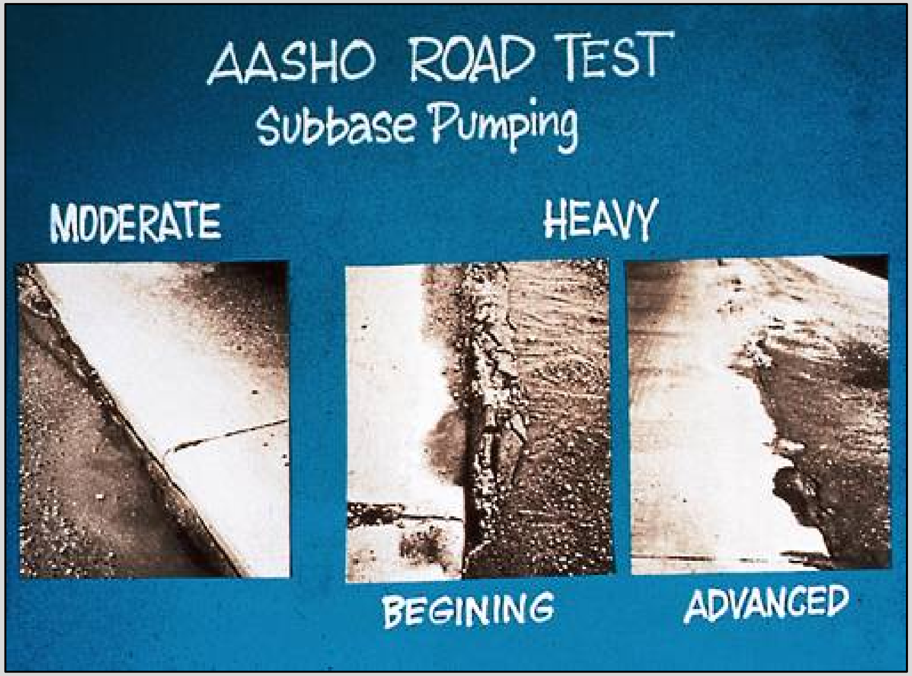


FHWA-HRT-07-019, Advanced Quality Systems: Guidelines for Establishing and Maintaining Construction Quality Databases, 2006
http://www.fhwa.dot.gov/pavement/concrete/pubs/07019/chapt5.cfm

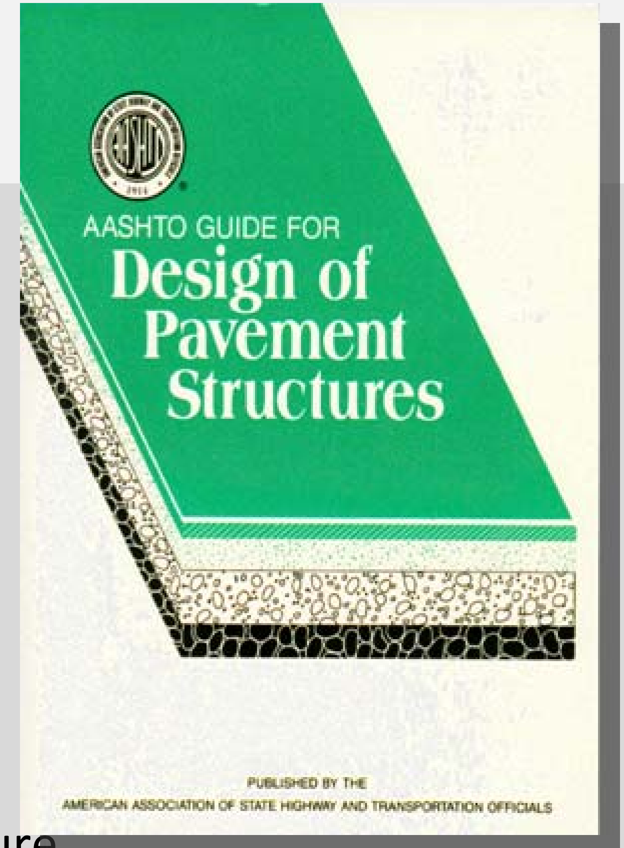
AASHO Road Test Performance

The primary mode of concrete pavement failure at the road test was loss of support in the poor clay soil.

All cracking of concrete pavements at the AASHO road test was preceded by the pumping of material from underneath the slab.



Improved designs (dowel, subbase, geotex, etc.) have solved this problem!



Introduction to the WinPAS Design Procedure

The AASHTO Pavement Design Method

ACPA NORTHWEST CHAPTER

AASHTO Design Procedures & Changes

1961-62	AASHO Interim Guide for the Design of Rigid and Flexible Pavements
1972	AASHTO Interim Guide for the Design of Pavement Structures – Consolidate + update
1981	Revised Chapter III on Portland Cement Concrete Pavement Design – Minor revisions
1986	Guide for the Design of Pavement Structures - Major revisions to subgrade support; added overlays, reliability, LCCA, pavement management
1993	Revised Overlay Design Procedures – Addressed deficiencies in 86 overlay design; basis of **WinPAS**
2010	DARWin-ME^{TM} – Mechanistic principles added

ACPA NORTHWEST CHAPTER

1986-93 Rigid Pavement Design Equation

$$\log(ESALs) = Z_R * s_o + 7.35 * \log(D+1) - 0.06 + \frac{\log\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624*10^{7}}{(D+1)^{8.46}}}$$

$$+(4.22-0.32p_t)*\log\left[\frac{S'_c * C_d * \left[D^{0.75}-1.132\right]}{215.63 * J * \left[D^{0.75} - \frac{18.42}{(E_c/k)^{0.25}}\right]}\right]$$

Standard Normal Deviate (Z_R)

Overall Standard Deviation (s_o)

Depth (D)

Change in Serviceability (ΔPSI)

Terminal Serviceability (p_t)

Modulus of Rupture (S'_c)

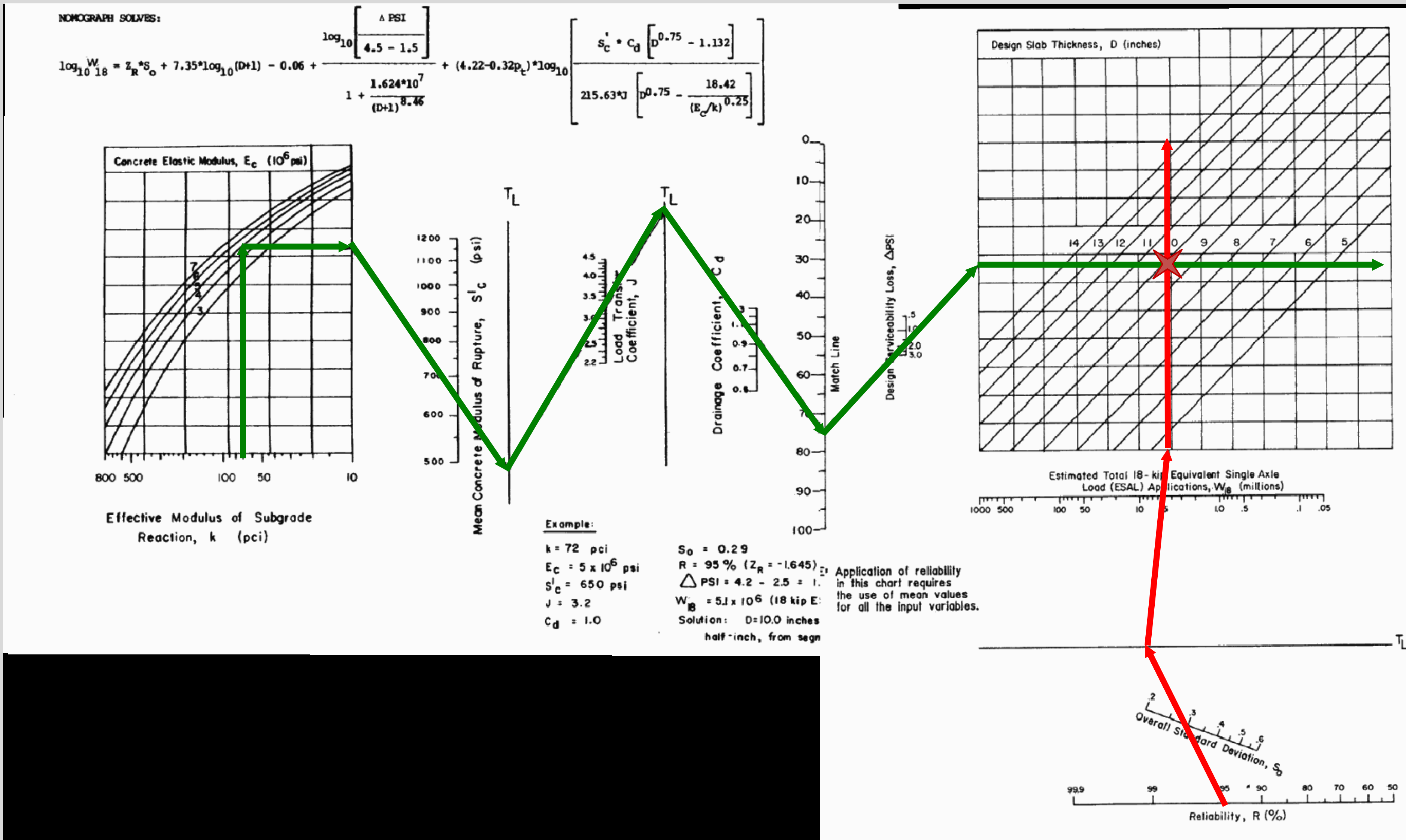
Drainage Coefficient (C_d)

Load Transfer (J)

Modulus of Elasticity (E_c)

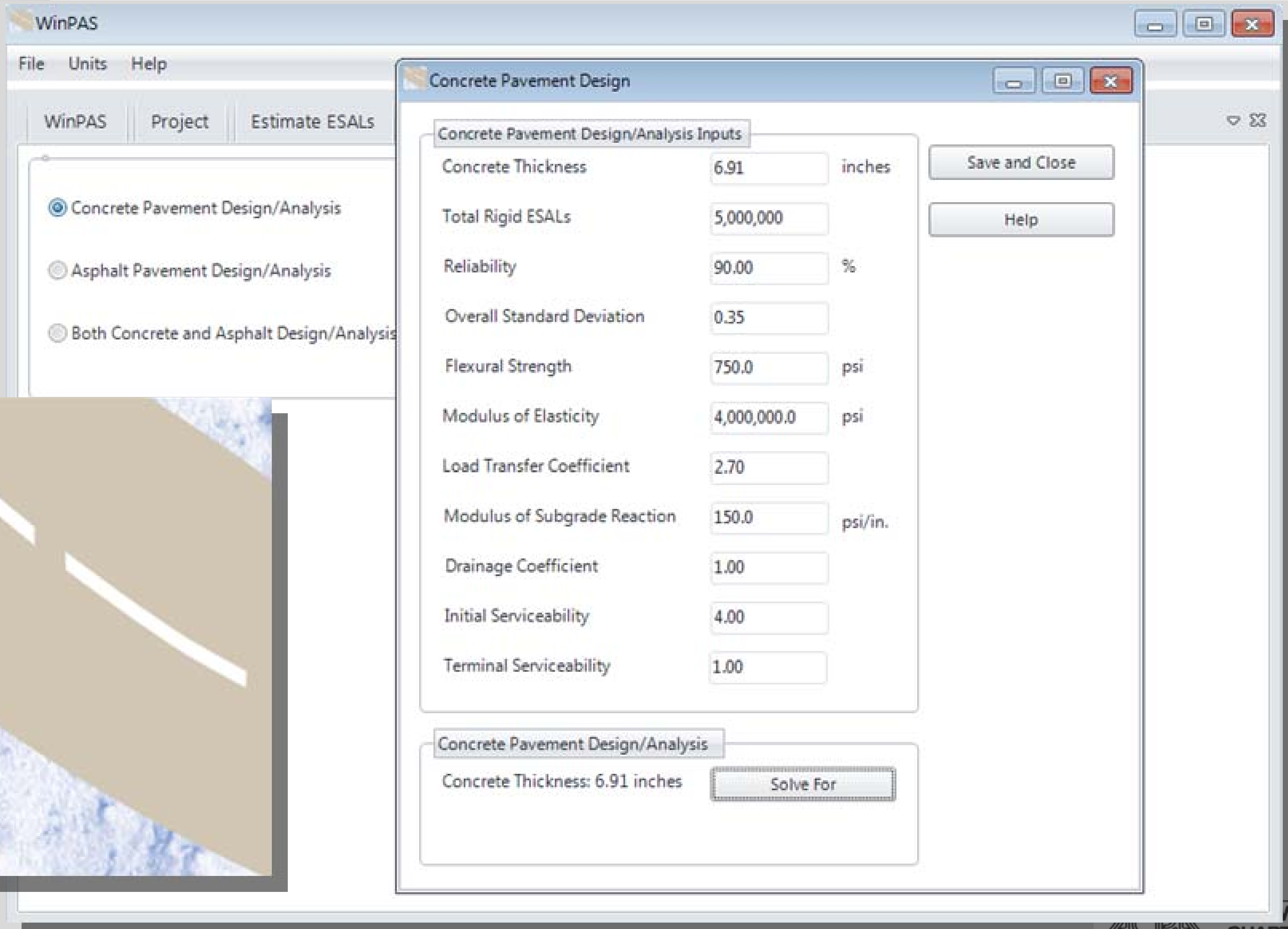
Modulus of Subgrade Reaction (k)

Rigid Design Nomograph

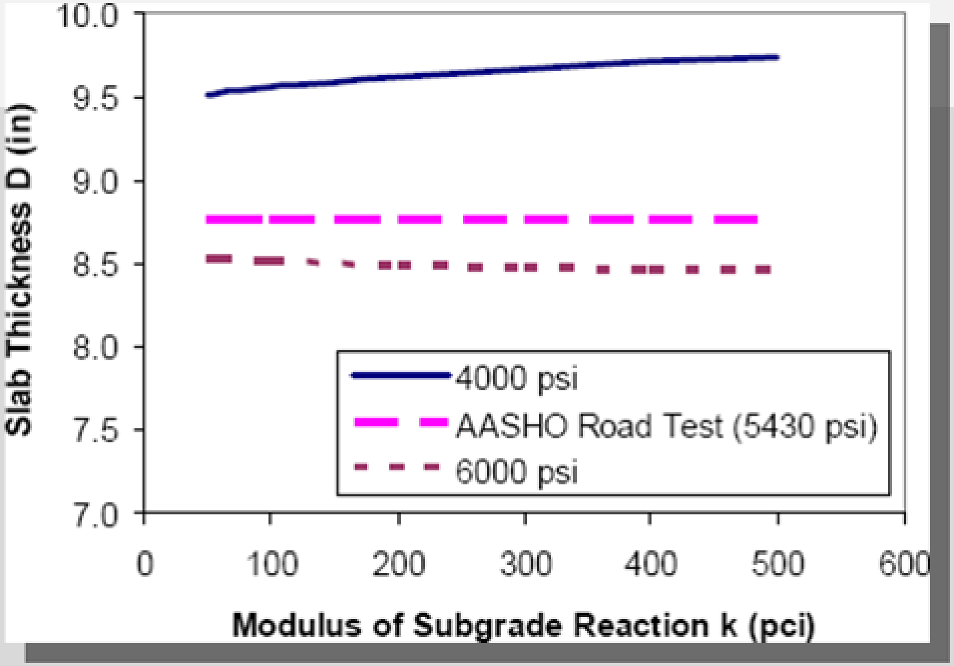


NORTHWEST CHAPTER

WinPAS Makes it Easy



WEST CHAPTER



Introduction to the WinPAS Design Procedure

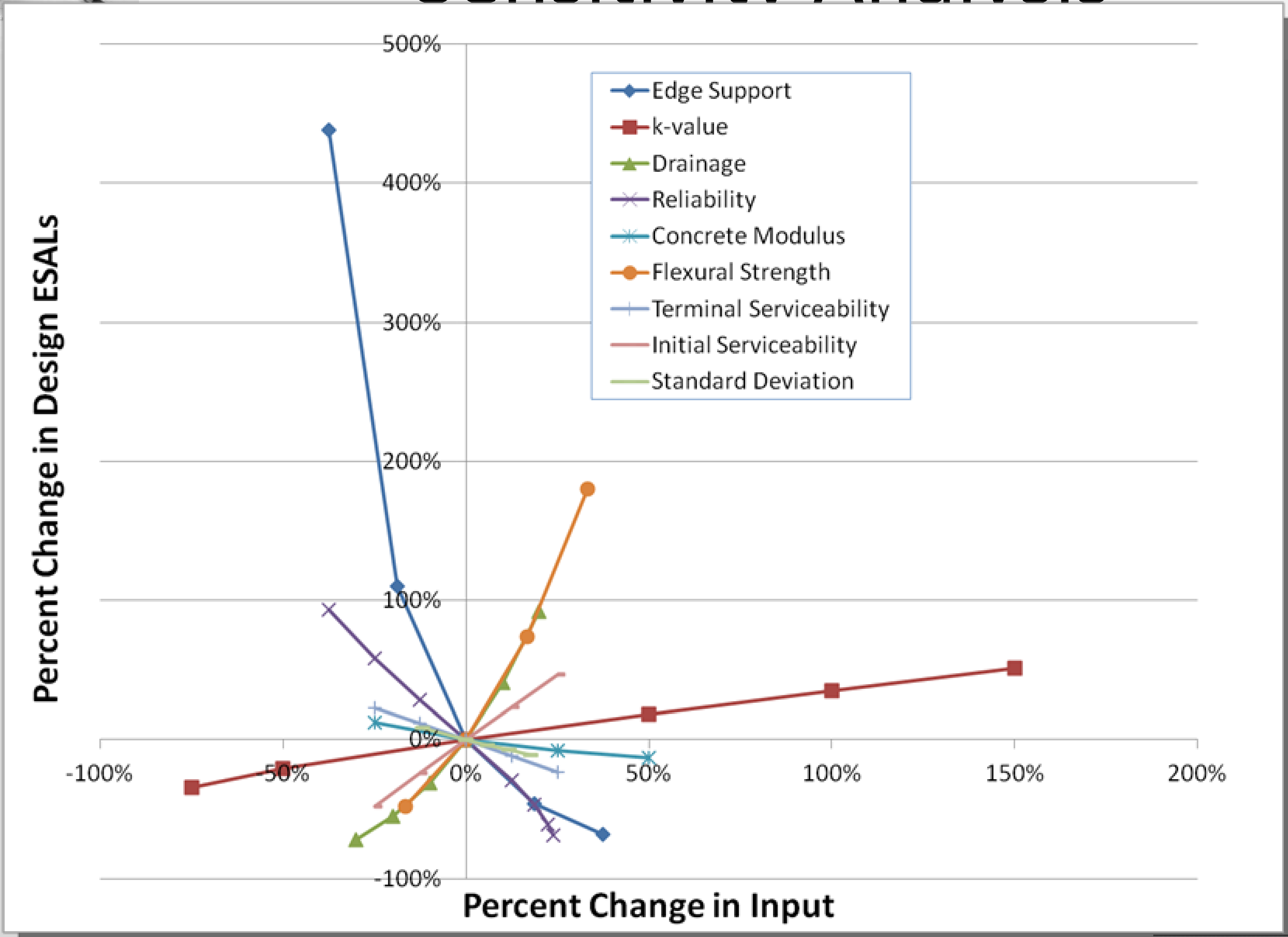
AASHTO 93 Sensitivity

1986-93 RIGID PAVEMENT DESIGN

Factors Affecting Rigid Pavements

- Thickness
- Serviceability (p_o, p_t)
- Traffic (ESALs, E-18s)
- Load Transfer (J)
- Concrete Properties (S'_c, E_c)
- Subgrade Strength (k, LS)
- Drainage (C_d)
- Reliability (R, s_o)

Sensitivity Analysis



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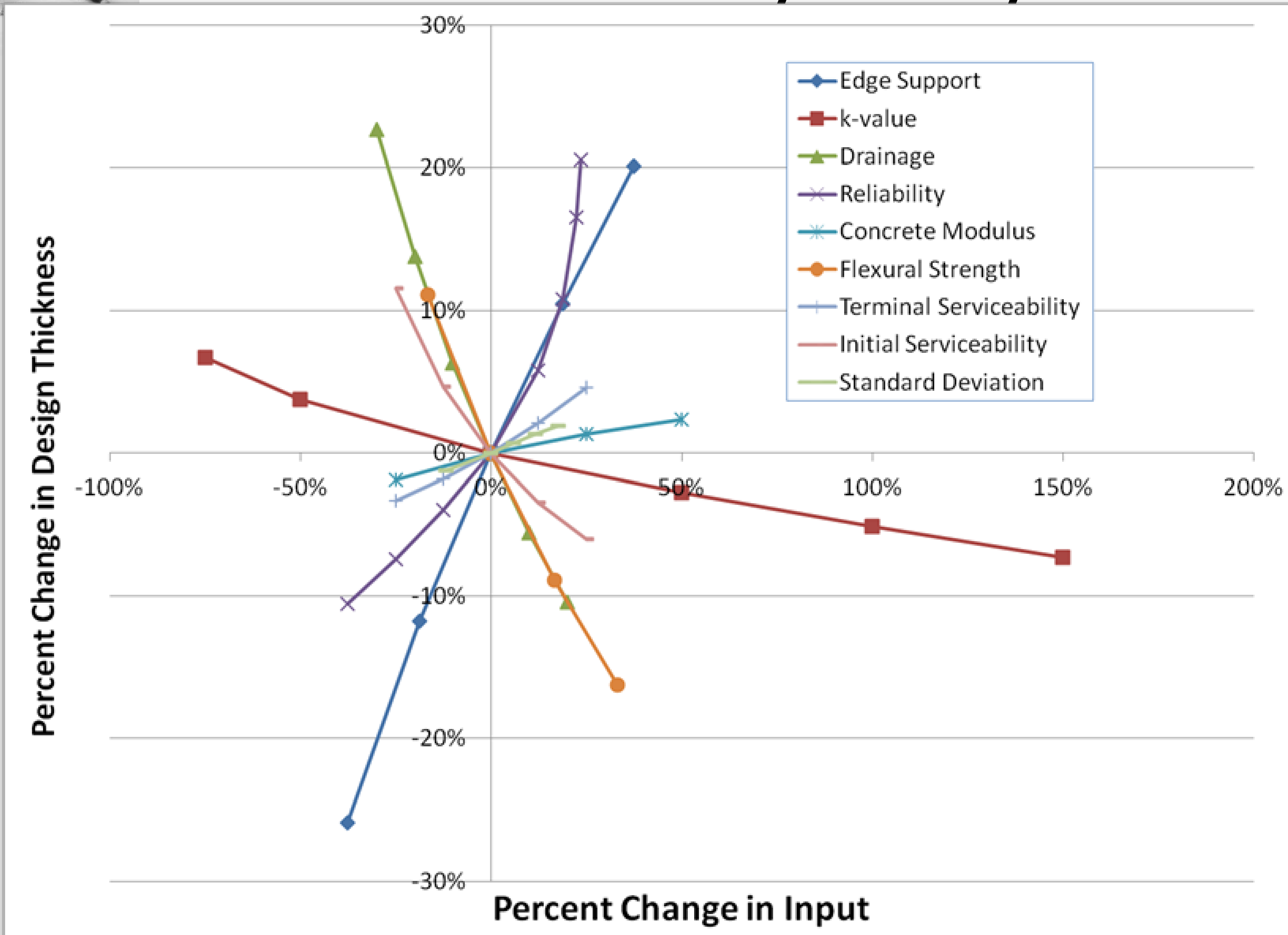
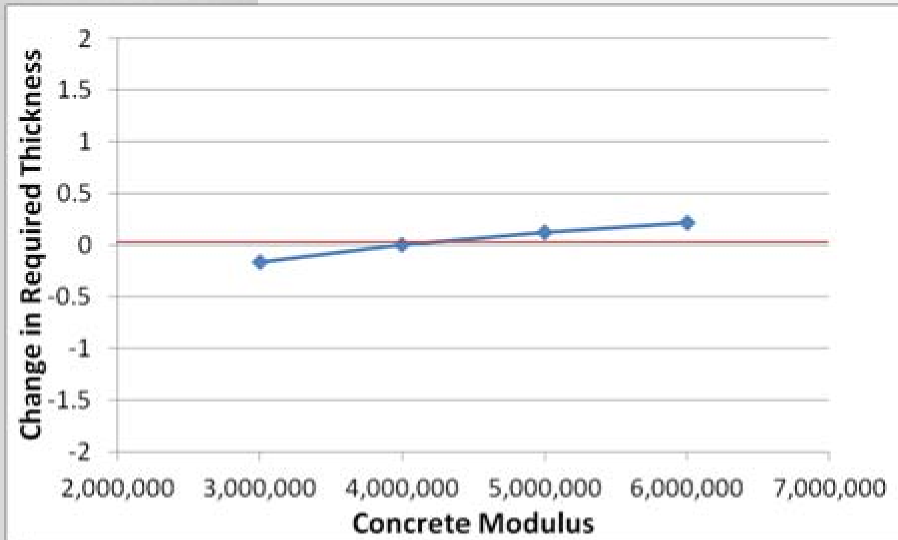
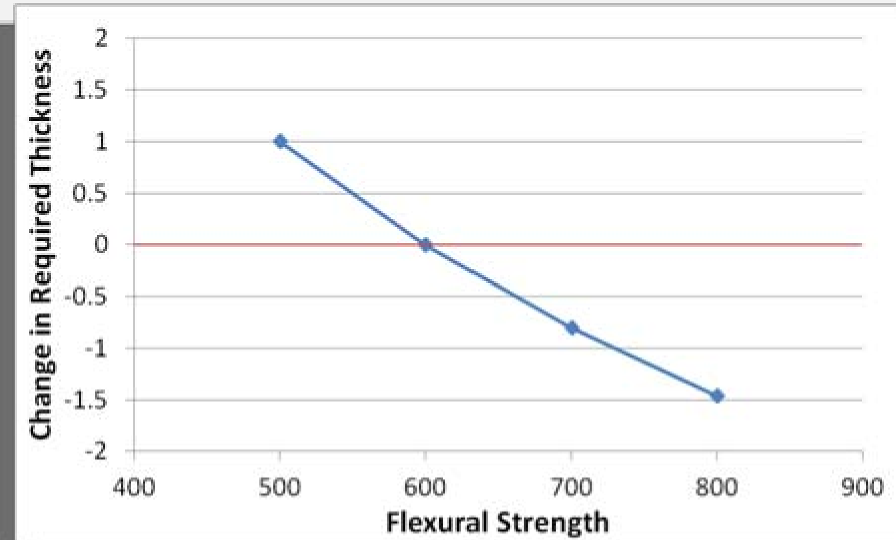
Sensitivity Analysis

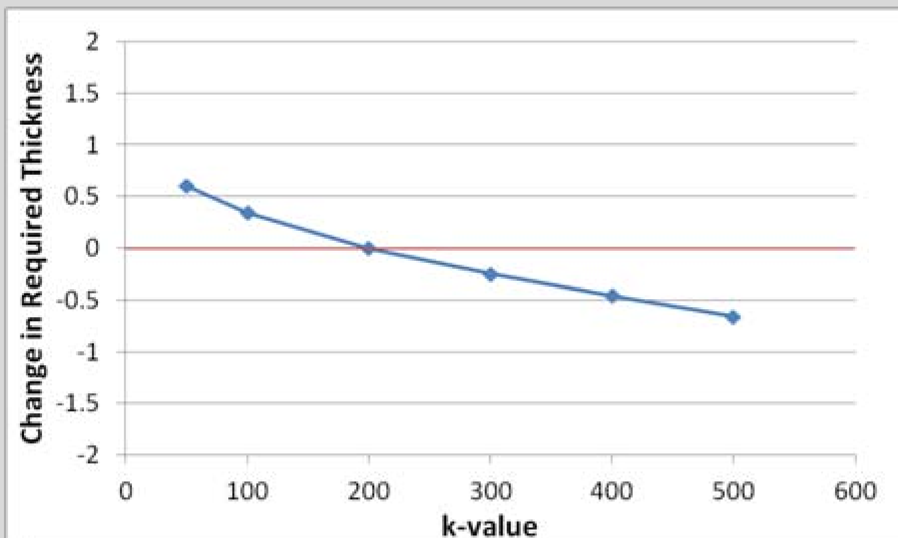


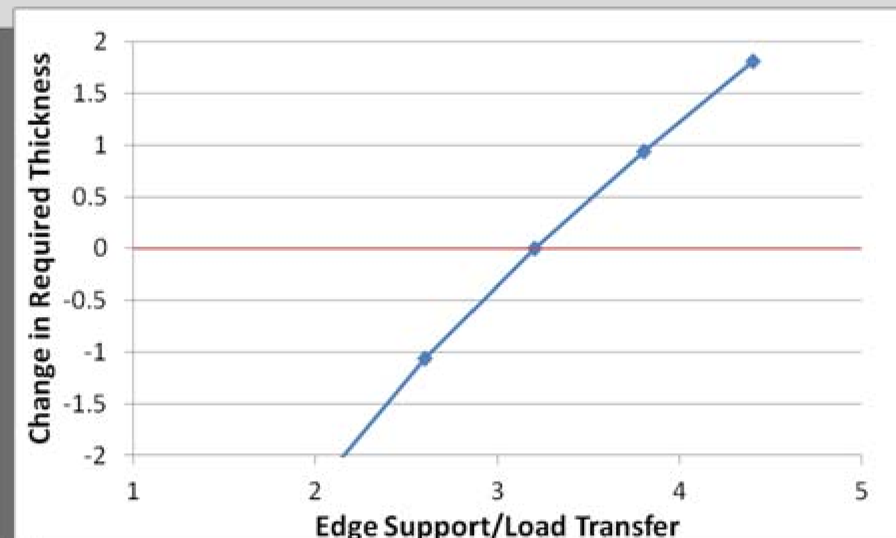
NORTHWEST CHAPTER

Sensitivity Analysis



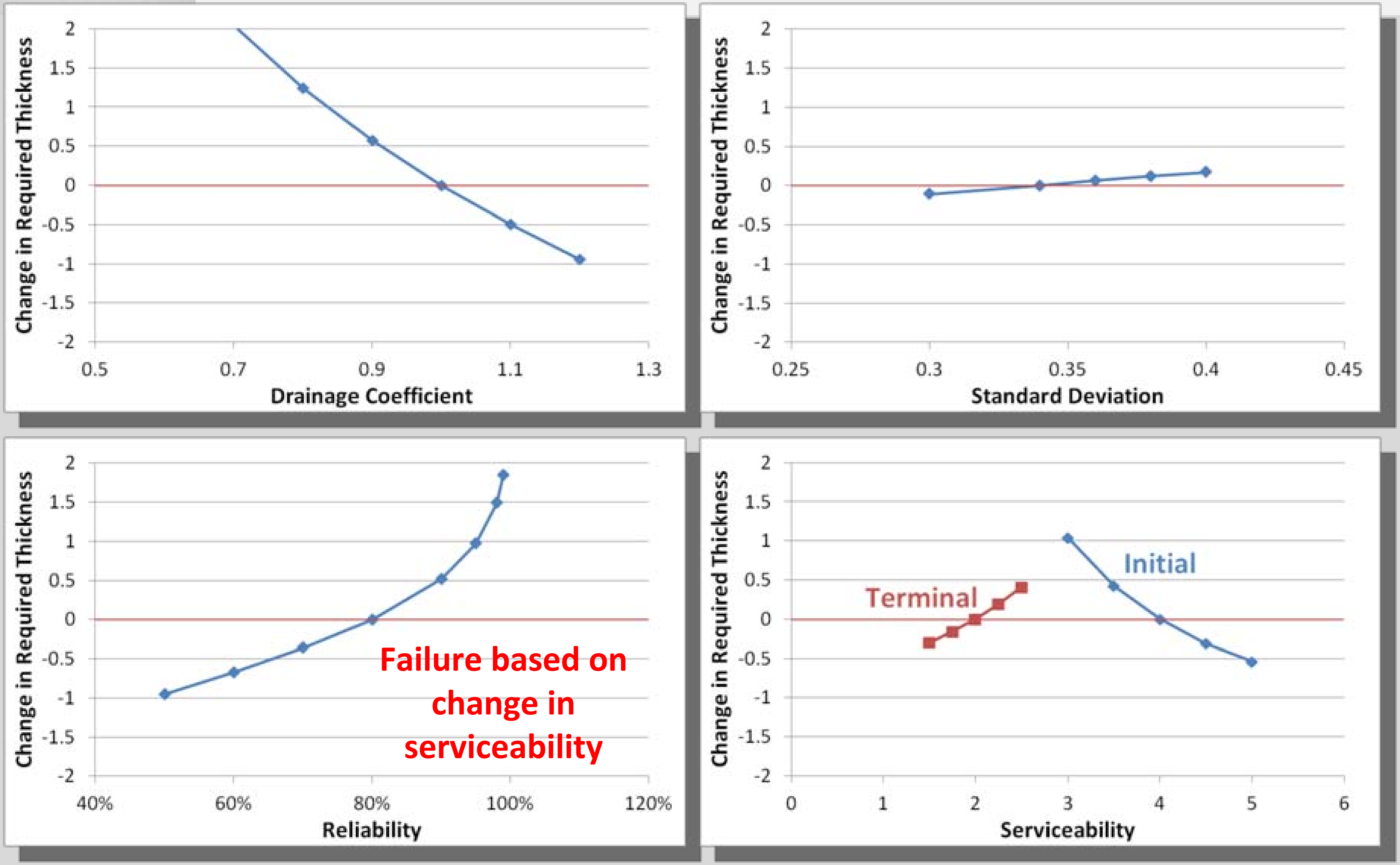






ACPA NORTHWEST CHAPTER

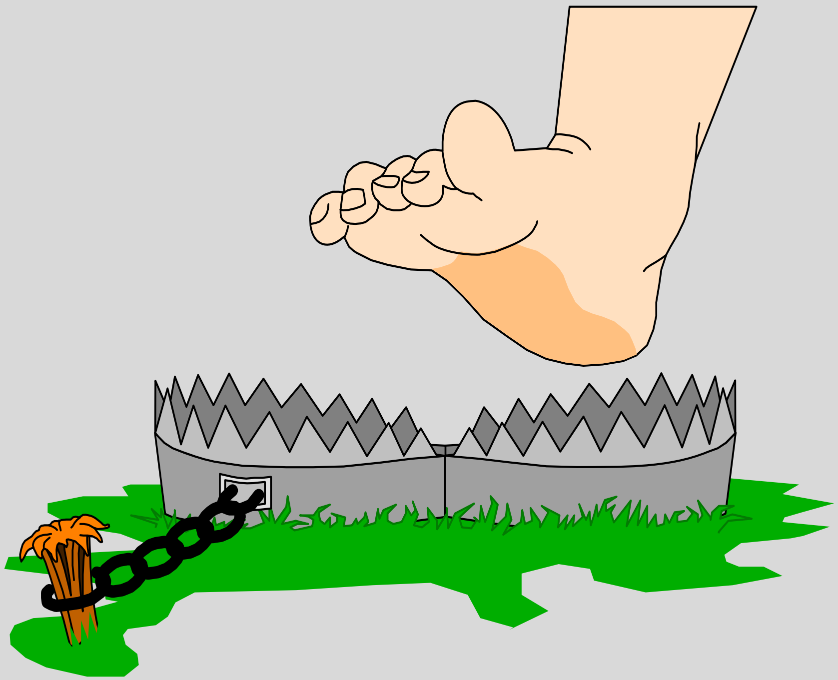
Sensitivity Analysis



Introduction to the WinPAS Design Procedure

A Few Things to Watch

AASHTO DESIGN
Beware of Bear Traps



BEAR TRAPS

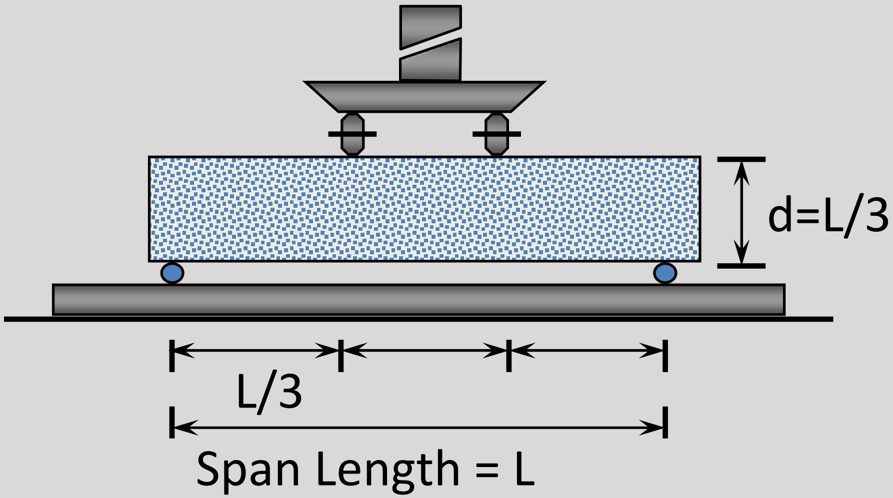
- Over conservative inputs
- Nonsensical inputs
- Poor relationships
- Fudge factors

Assigning improper values can create over-conservative designs… junk in = junk out

Concrete Strength

Use average, in-field strength for design (not min specified)

Third-point Loading



If specify minimum flexural strength at 28-day of 550 psi & allow 10% of beams to fall below minimum:

STEP 1

Estimate SDEV:

9% for typical ready mix.

SDEV = 550 * 0.09 = 50 psi

STEP 2

$$S'c_{design} = S'c_{minimum} + z * SDEV$$

$$S'c_{design} = 550 + 1.282 * 50$$

$$S'c_{design} = 614 \text{ psi}$$

ACPA NORTHWEST CHAPTER

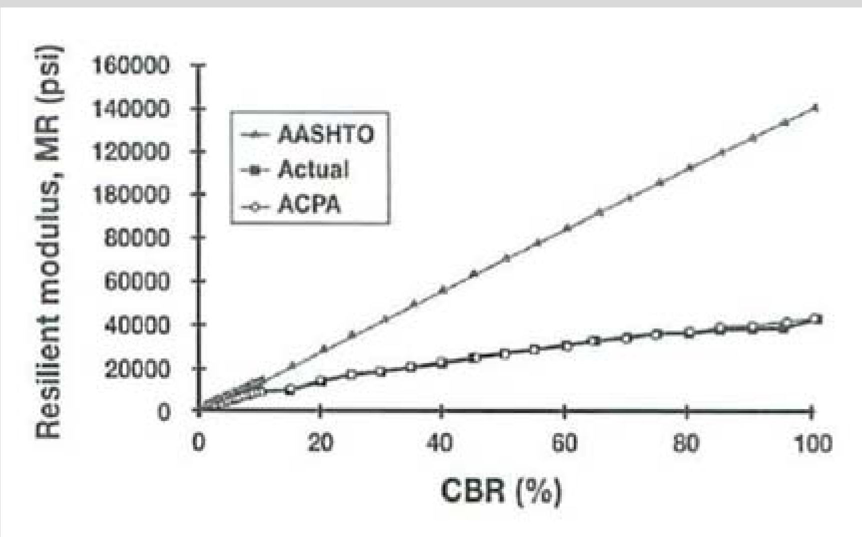
Subgrade Soil Relationships

Be careful when using the AASHTO subgrade soil relationships

M_R = 1,500 * CBR

M_R = 1,000 + 500 * R

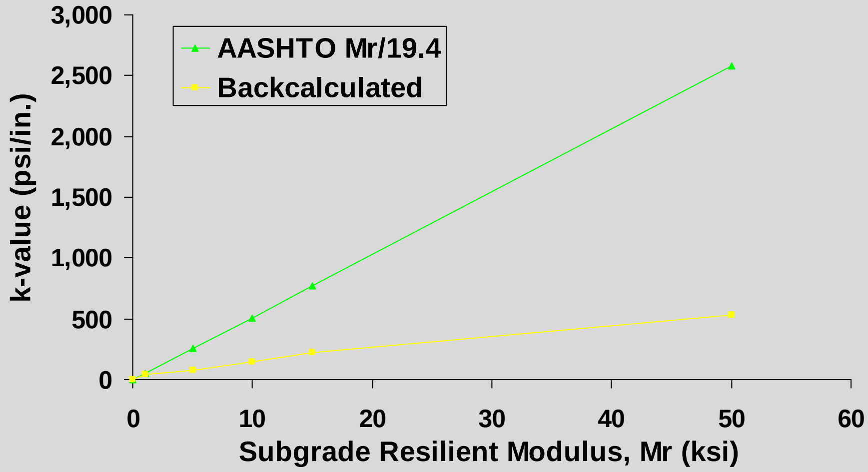
These relationships given in the guide between M_R and CBR and R-values over estimates actual M_R values.



NORTHWEST CHAPTER

k-Value Determination

The relationships between k and MR (base - no base) give inconsistent results



For Example,

Assume M_R = 12,000 psi

with no-base

k = M_R /19.4 = 619 psi/in

with 6 in. granular base

k = 574 psi/in

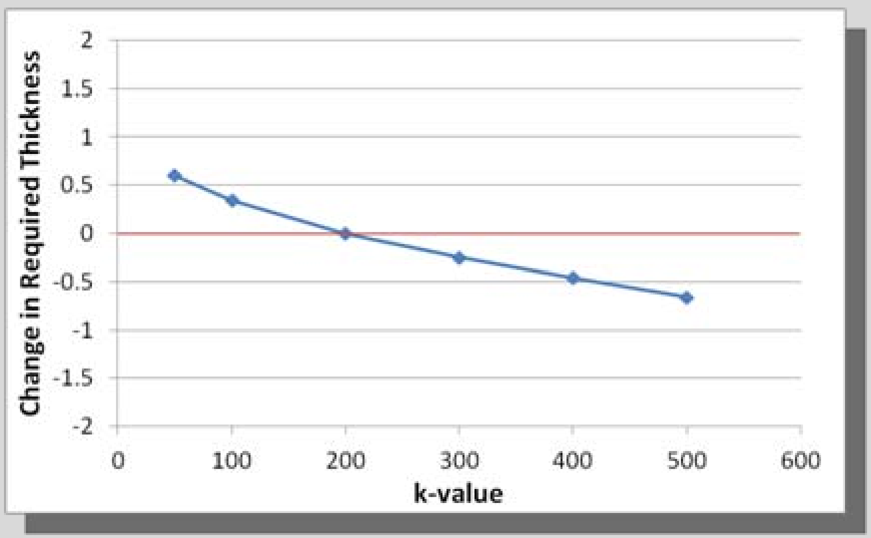
As the M_R value increases, the difference becomes greater.

Neither value is very realistic. Historical values are 150-250 psi/in.

ACPA NORTHWEST CHAPTER

k-Value Determination

Don't get hung up on k-value as a designer



Natural subgrade ≈ 100 psi/in.

Granular subbase ≈ 150 psi/in.

Asphalt-treated subbase ≈ 300 psi/in.

Cement-treated subbase ≈ 500 psi/in.

Extra effort to test and collect detailed k-value info likely not worth the cost… concentrate on other inputs!

ACPA NORTHWEST CHAPTER

Loss of Support

Use Loss of Support = 0

(otherwise your using a huge fudge factor)

LL.2 LOSS OF SUPPORT

A theoretical attempt is made to evaluate the effects of the loss of support on pavement performance. This factor essentially defines the size of the area of pavement slab which experiences a complete loss of support due to erosion. Based on experience

All cracking of rigid pavements at the AASHO road test were preceded by the pumping of material from underneath the slab.

The primary mode of failure at the road test was loss of support in the poor clay soil.

Therefore, AASHTO design equations already account for support loss.

Subgrade Strength

Start with the in-situ subgrade soil (not a stabilized soil)

If designing a roadway on a clay soil that you intend to lime stabilize 6 in.:

<u>FIRST:</u> Determine k and Mr for clay:

-typical clay; k = 100 psi/in

-Mr = k * 19.4 = 1,940 psi

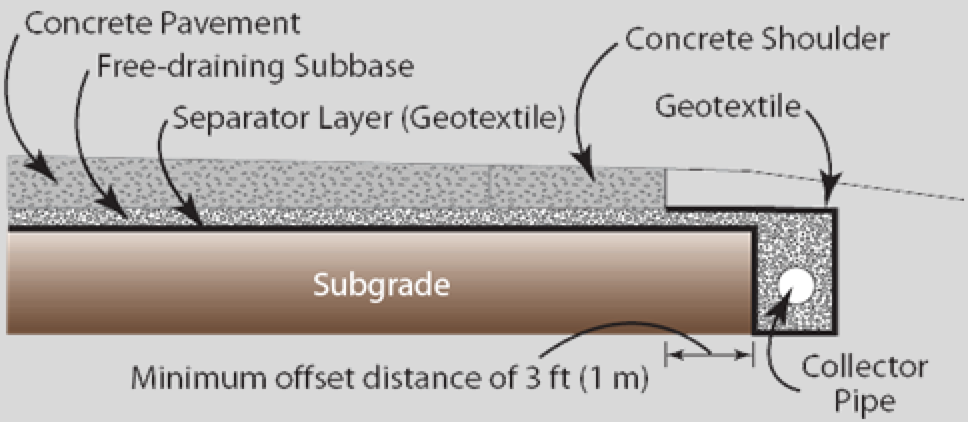
<u>Second</u>: Determine $k_{composite}$ starting with k = 100 & add 6-inch layer w/ typical E for lime soil (30,000 psi).

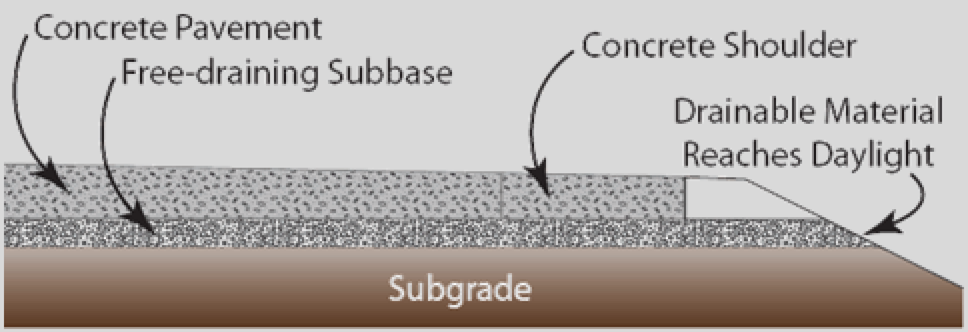
$k_{composite}$ = 131 psi/in

ACPA NORTHWEST CHAPTER

Drainage

Use drainage coeff > 1.0 (otherwise using a huge fudge factor)





The subgrade soil at the AASHO road test was a very poorly draining clay soil.

Therefore the AASHTO design equations already account for a poor drainage condition.

Modern open-graded bases and more free-draining soils are design options which can be modeled with C_d > 1.0

Reliability

Never compare designs at different reliabilities (reliability = factor of safety)

Reliability (R)	Z_R standard normal deviate
50	-0.000
75	-0.674
90	-1.282
95	-1.645
99	-2.327

Another way to think about reliability is to consider that at 90% reliability, only 10% of the pavement will have "failed" by the end of the design period.

If you are comparing a new concrete section to a new asphalt section use the same reliability for each.

No need for conservatism in other inputs! Use best in-place guess!

If evaluating pavement, use reliability of 50%.

Total ESALs

Never compare rigid and flexible ESALs

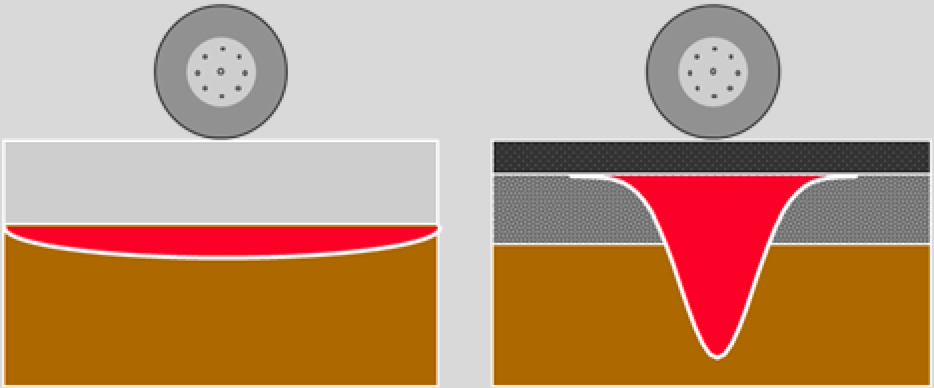
Because pavement responses are different, the load equivalency factors (LEFs) are different. When multiplying the traffic by the different equivalencies, you get different ESALs

34,000 lbs.

34,000 lbs.

Load appliles 12,000 lbs. to the subgrade.

pressure = 5 psi



Load appliles 24,000 lbs. to the subgrade.

pressure = 30 psi

Concrete ESAL
1.87

Bituminous ESAL
1.10

ACPA NORTHWEST CHAPTER

Example

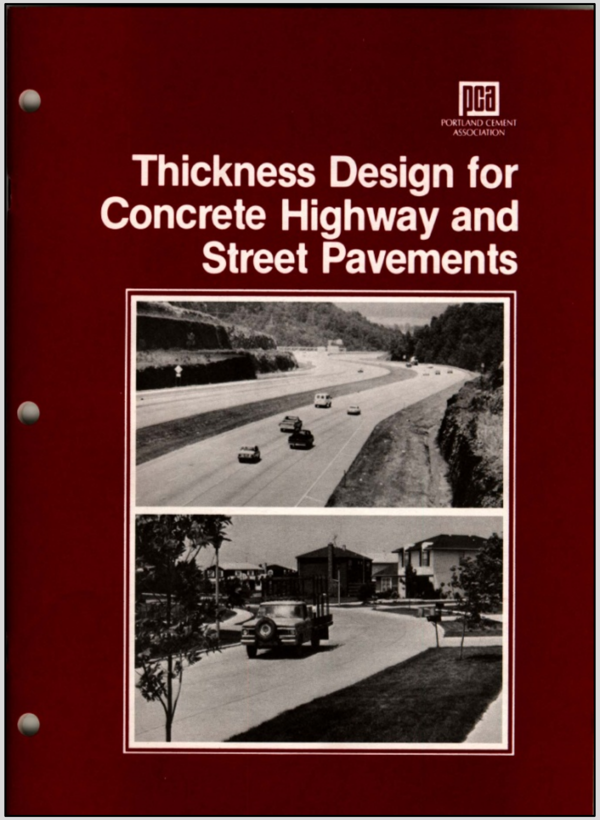
WinPAS

StreetPave Thickness Design Procedure

- Mechanistically based pavement design procedure
- Based on the PCA's pavement thickness design methodology
- Assesses adequacy of concrete thickness using both fatigue and erosion criteria

Background / Timeline

- PCA's thickness design methodology originally published in 1933 by Frank Sheets, updated in 1951, again in 1966
- Latest update was 1984 (EB109P)
- Developed *PCAPAV* program to do iterative thickness design with PC, latest version 1990



PCAPAV Mechanistic Concepts

- Fatigue Analysis
  - Stress determination originally based on Westergaard analysis
  - Modified based on Pickett and Ray's work in 1951
  - Equations developed based on JSLAB analysis
  - MATS program used to account for subgrade extending beyond slab edges
  - Based on edge load
  - Calculates cumulative damage for each class of loads

PCAPAV Mechanistic Concepts

- Erosion Analysis
  - Primary mode of failure at AASHO was loss of support
  - Calculates corner deflections and pressure on foundation
  - Poor correlation w/ AASHO
  - Modified to use power function for better correlation: (deflection x pressure)/radius of relative stiffness
  - Correlated w/ AASHO, WI, MN, ND, GA, CA

Background / Timeline

- ACPA / PCA merged in 1993; ACPA takes control of all PCA products, software, publications pertaining to concrete pavements for roads, streets, airports
- ACPA published “Design of Concrete Pavement for City Streets” (IS184P) in 1992; thicknesses based on PCA
- ACPA formed a Technical Task Force in 2004 to investigate design procedure changes

ACPA NORTHWEST CHAPTER

Background / Timeline

- ACPA funded research in 2004 to improve the PCA design method to include:
  - Reliability
  - Tridem axle configurations

Objectives

- ACPA commissioned study to:
  - – Expand, improve, and broaden the current PCA fatigue model by:
    - Including reliability as a user input
    - Replacing PCA models with a single model
  - – Calibrate the enhanced PCA fatigue model with additional fatigue data from recently completed studies

Final PCC Fatigue Model

$$\log N_f = \left[\frac{-SR^{-10.24} \log(1-p)}{0.0112} \right]^{0.217}$$

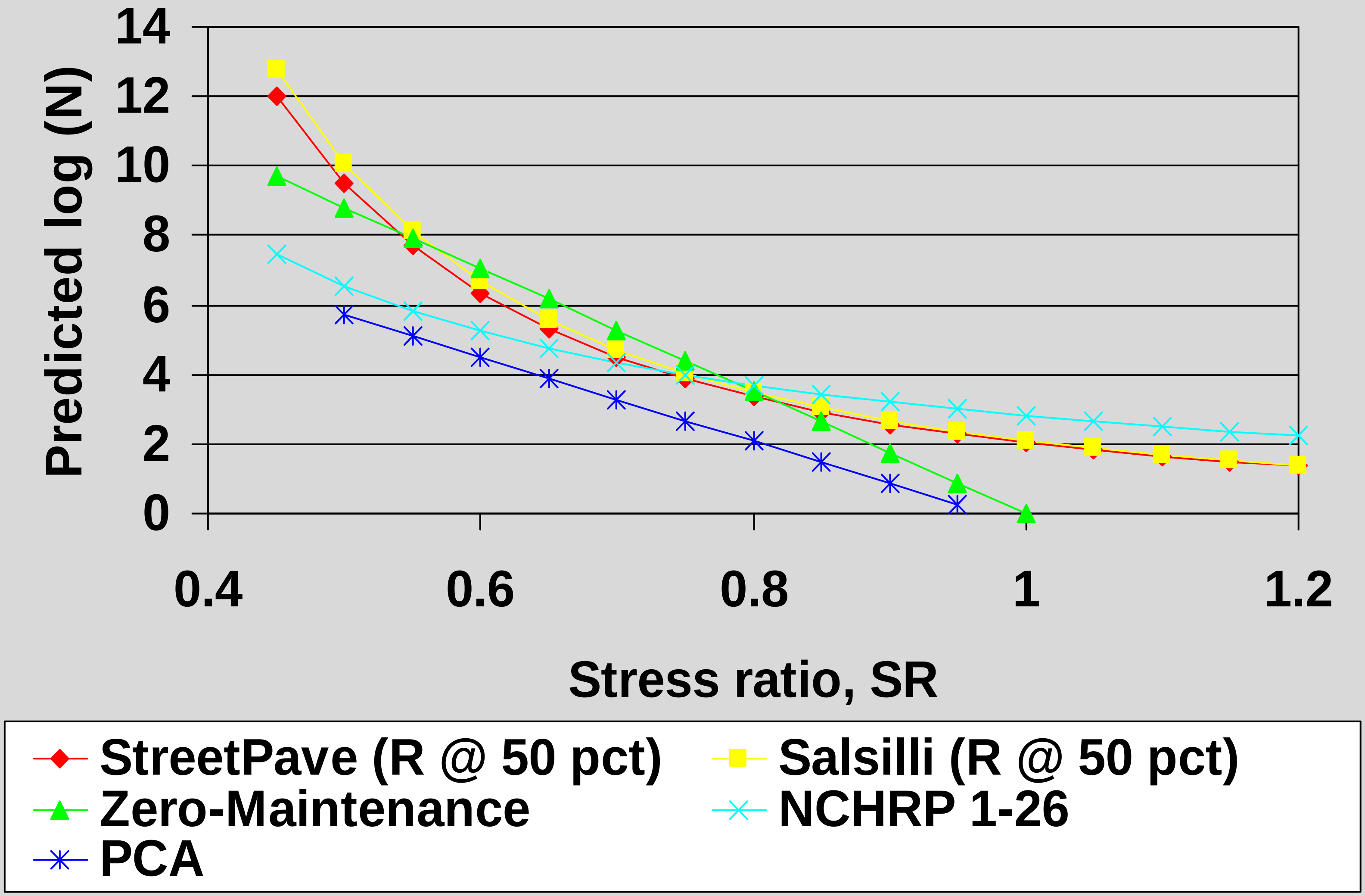
Model Statistics

N = 87

R^2 = 91 percent

RMSE = 0.31 (log N)

Model Comparison

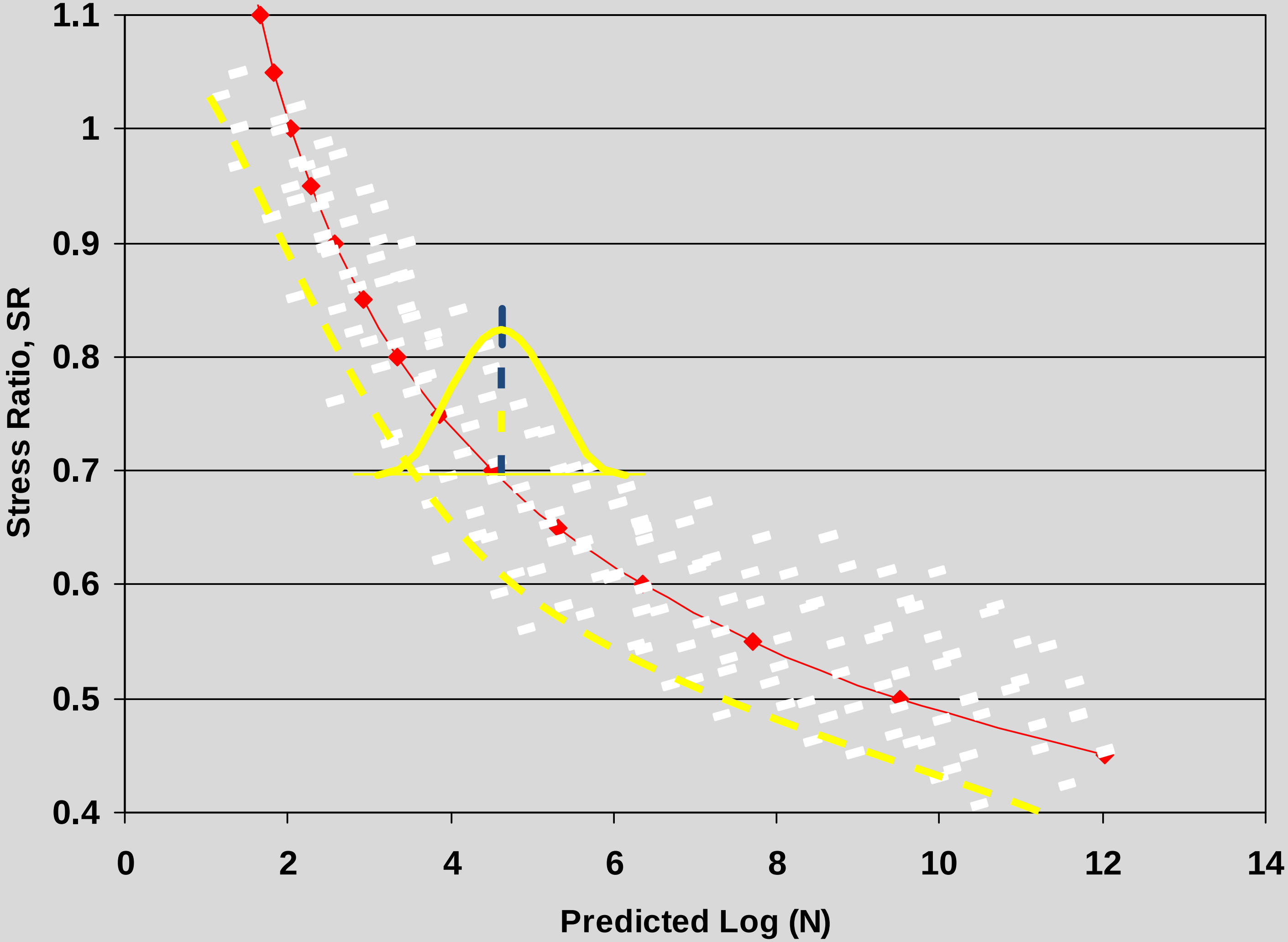


ARA Model Was Tweaked to Add a Cracking Component

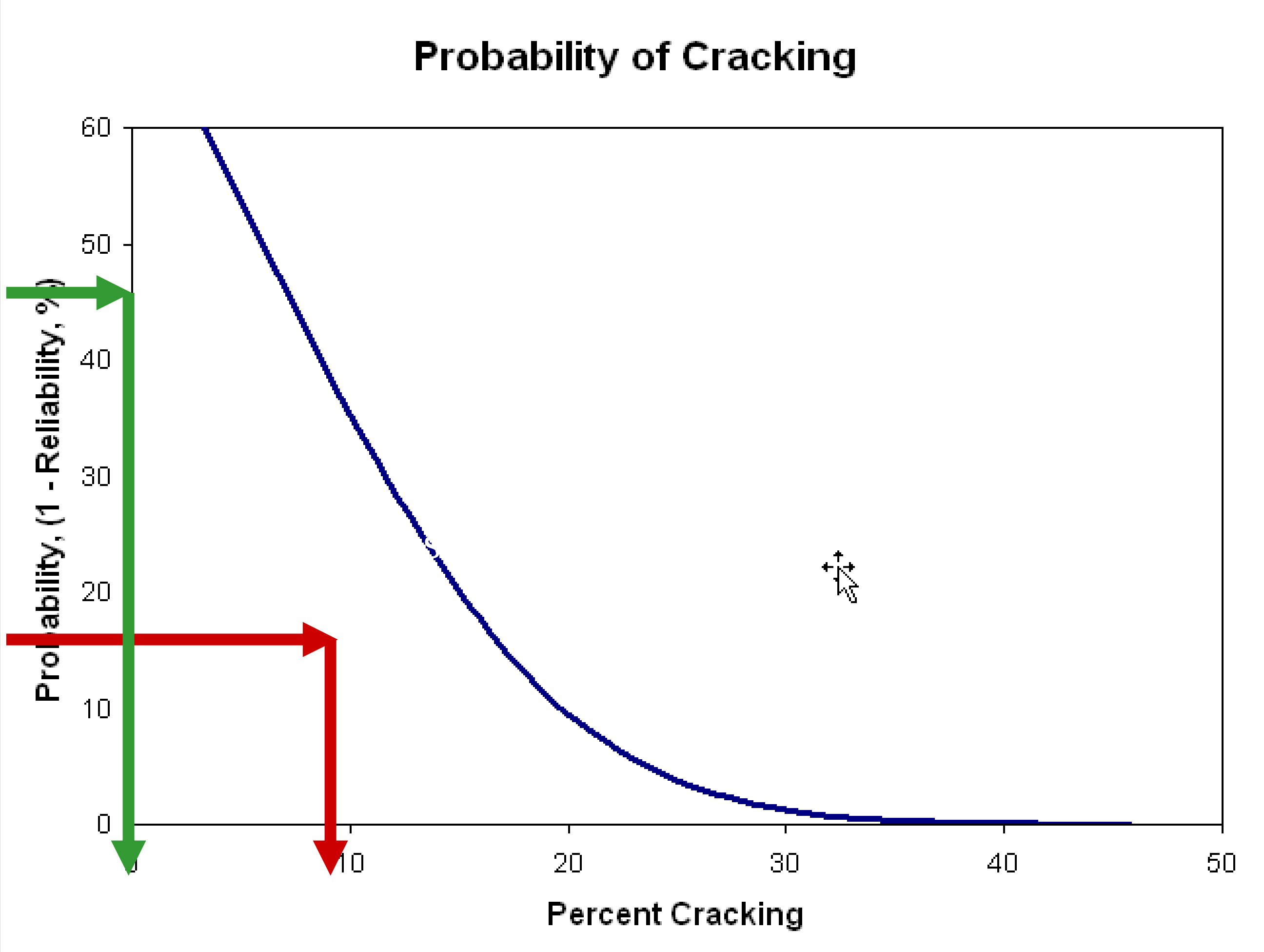
- Based on compound probability
- In a universe of data...

$$\log N_f = \left[\frac{-SR^{-10.24} \log\left(1 - p\left(\frac{C\%}{0.50}\right)\right)}{0.0112} \right]^{0.217}$$

What Do the Equations Really Tell Us?



Percent Allowable Cracking is a Consideration



Thickness Design for Streets

Basic Factors You Need

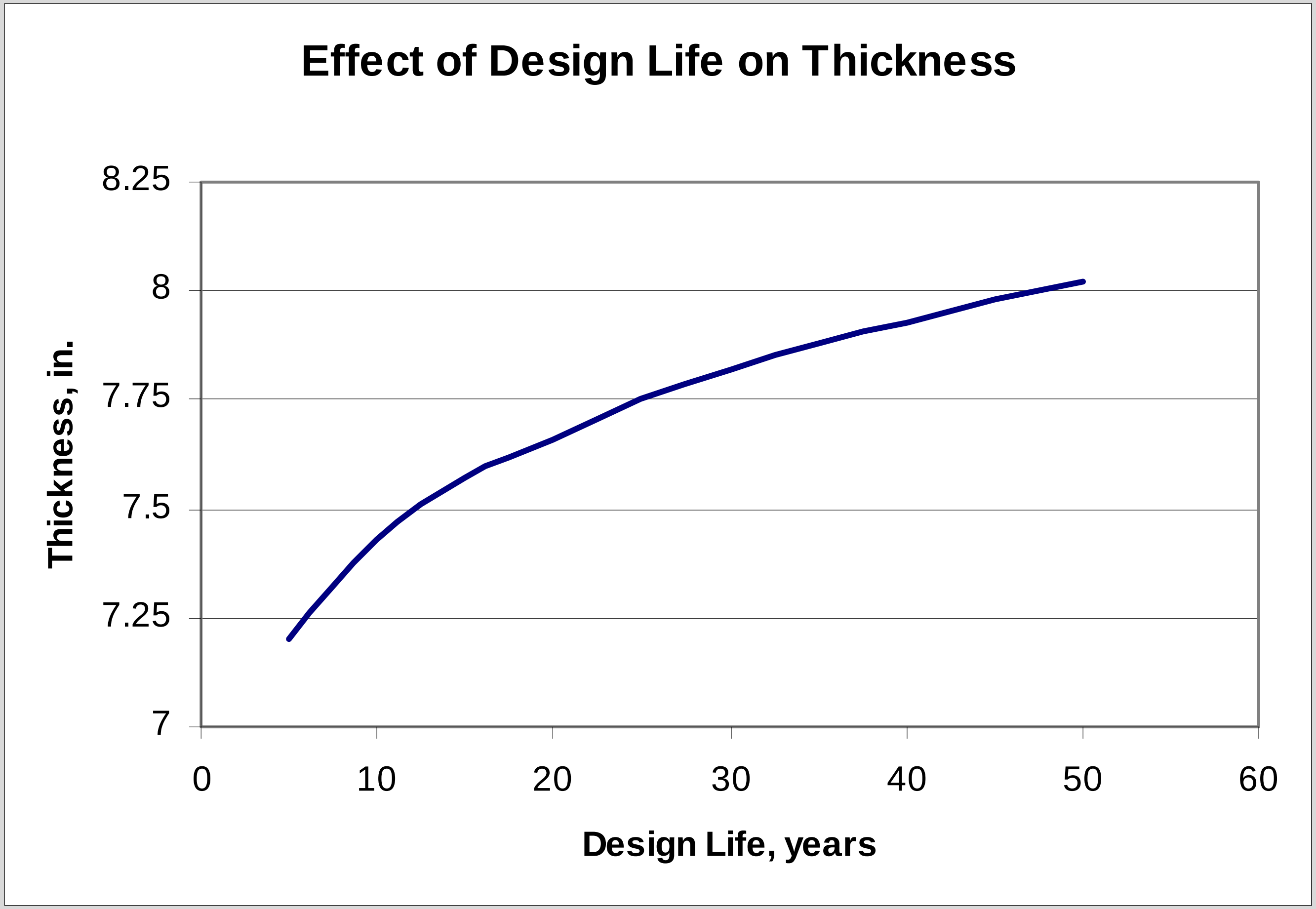
- Design Life
- Traffic
- Subgrade
- Concrete Strength
- Slab/Joint Design
- Reliability

ACPA NORTHWEST CHAPTER

Design Life

- 20 to 35 years is commonly used
- Shorter or longer design period may be economically justified in some cases
  - High performance concrete pavements
  - Long-life pavements
  - A special haul road to be used for only a few years
  - Cross-overs
  - Temporary lanes

Design Life

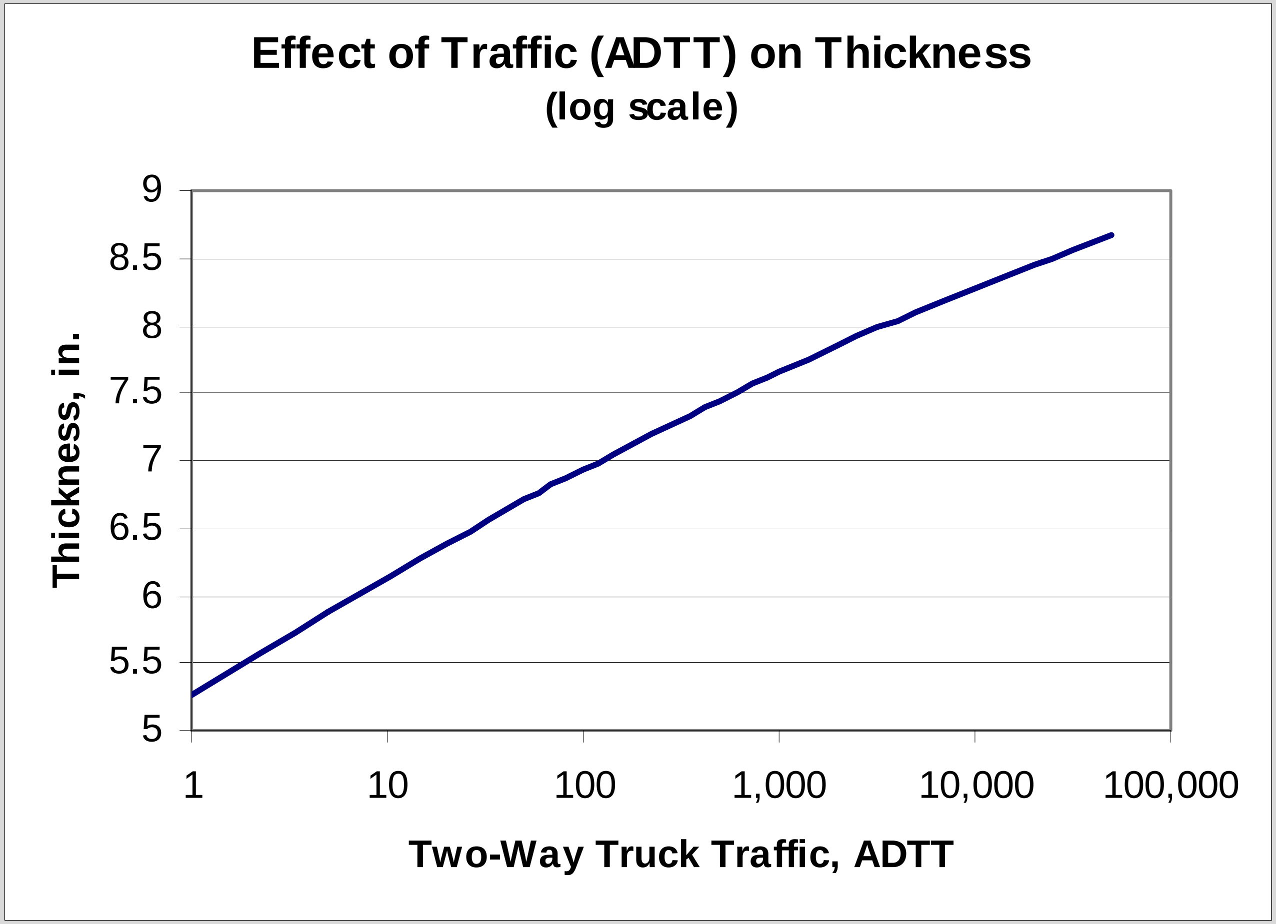


Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, MR=600, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

Traffic

- Numbers & weights of heavy axle loads expected during the design life
- ADT (average daily traffic in both directions)
- ADTT (average daily truck traffic in both directions)
  - Includes only trucks with six tires or more
  - Does not include panel and pickup trucks and other four-tire vehicles

Traffic



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ACPA NORTHWEST CHAPTER

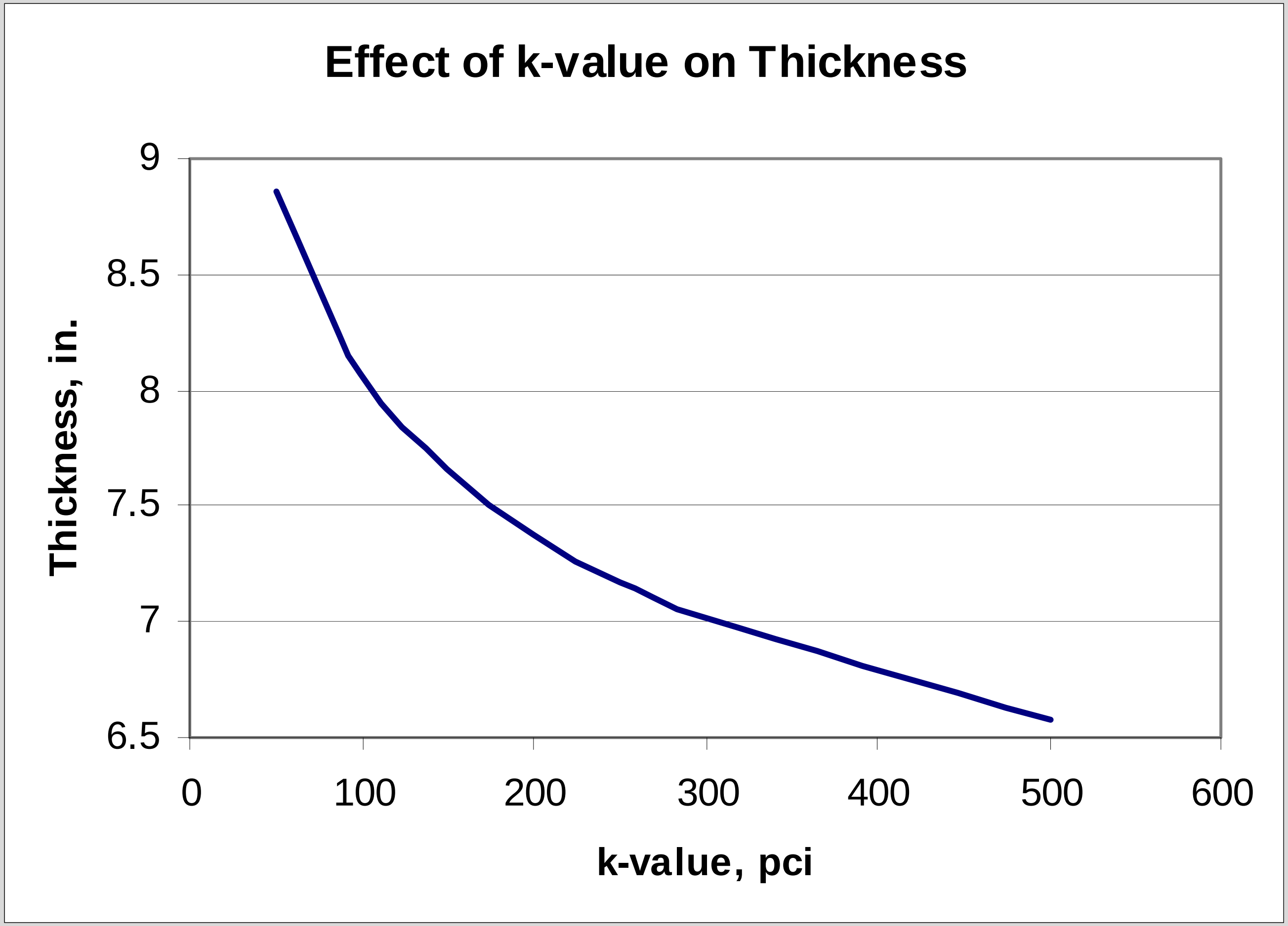
Subgrade Properties

- Plate-load test is rarely performed
  - Time-consuming & expensive
- Estimate k-value by correlation to other tests
  - e.g. California Bearing Ratio (CBR) or R-value tests
- Stabilized subbases increase k-value substantially

Approximate Soil Support Values

Type	Amount of Support	Historical k-values (pci)	CBR (ASTM D1183)	R (ASTM D2844)
Fine-grained with high amounts of silt/clay	Low	75-120	2.5 - 3.5	10-22
Sand and sand-gravel with moderate silt/clay	Medium	130-170	4.5 - 7.5	29-41
Sand and sand-gravel with little or no silt/clay	High	180-220	8.5 - 12	45-52

Soil Support



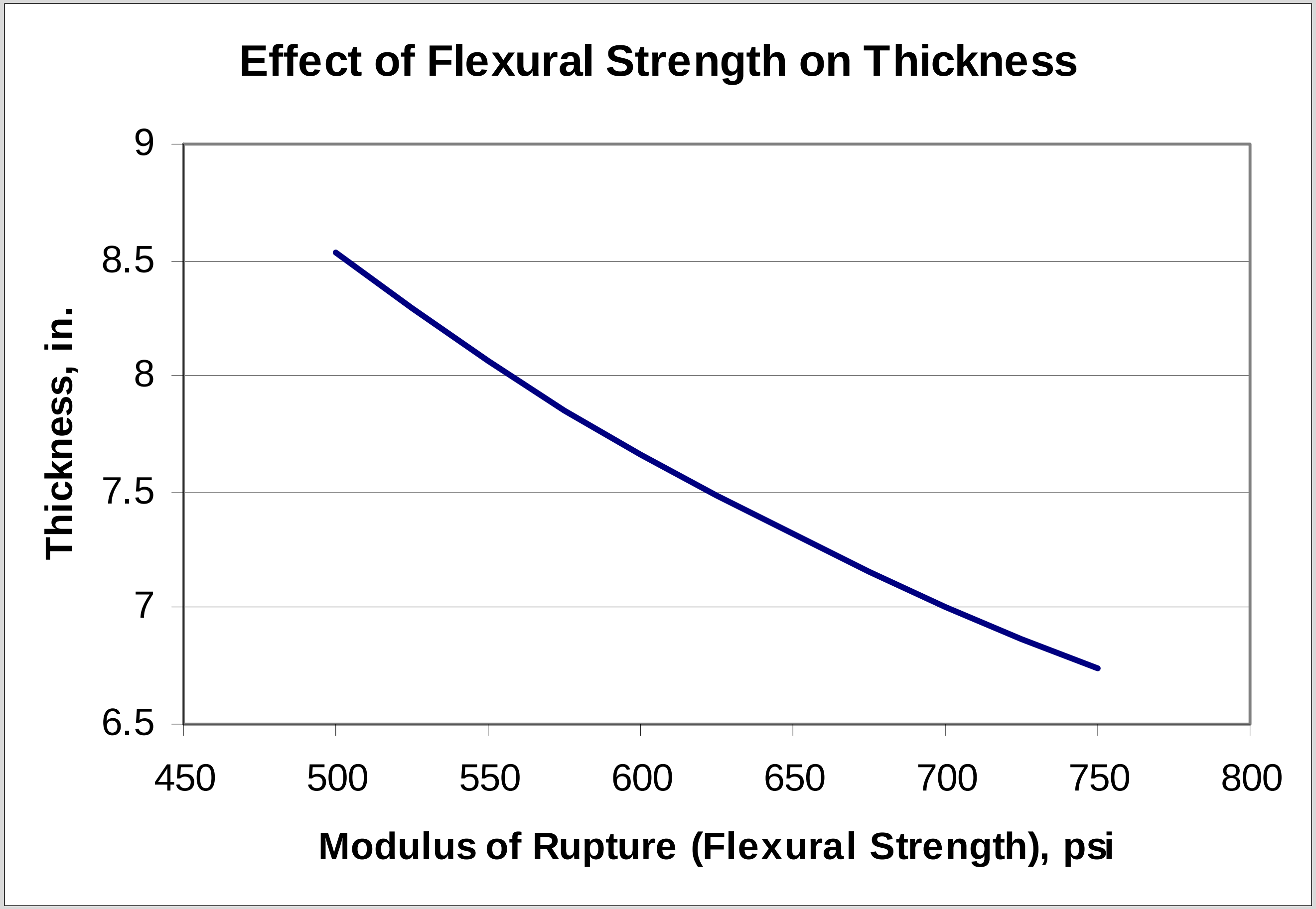
Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, MR=600, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

Concrete Properties

Compressive Strength, psi	Flexural Strength, psi	Design Thickness, inches
3000	450 – 550 (500)	9.0 (8.53)
4000	510 – 630 (600)	8.0 (7.66)
5000	570 – 710 (700)	7.0 (7.01)

Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

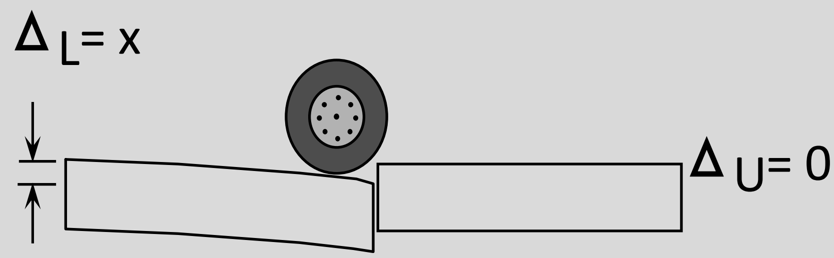
Flexural Strength



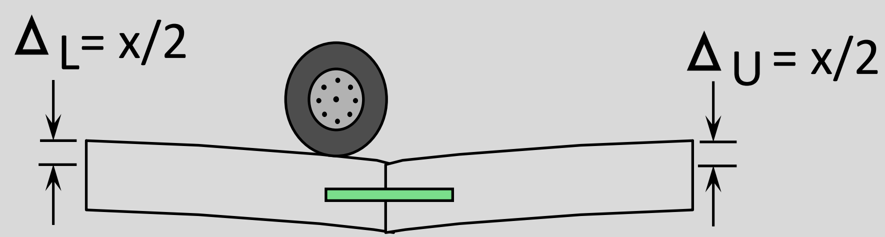
Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, MR=600, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

Load Transfer

- A slab’s ability to share its load with neighboring slabs
  - Dowels
  - Aggregate Interlock
  - Concrete Shoulders
    - Tied concrete, curb & gutter, and widened lane are assumed to have same effect.



Poor Load Transfer



Good Load Transfer

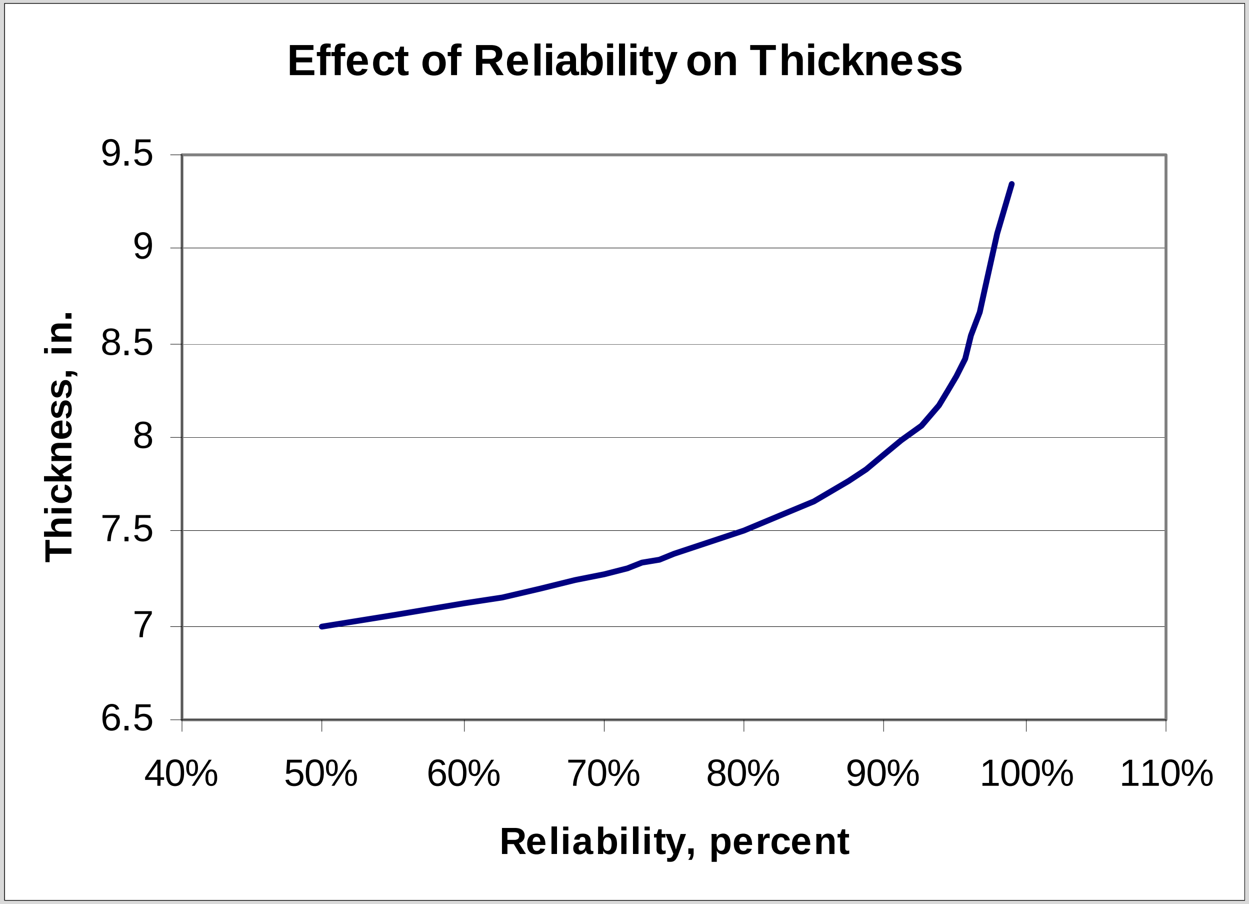
Reliability

- Factor of safety
- A measure of how likely the design will fail due to fatigue
- Can be used to estimate the amount of pavement repair required at the end of design period/life

Functional Classification of Roadway	Recommended Reliability	
	Urban	Rural
Interstates, Freeways, and Tollways	85 - 99	80 - 99
Principal Arterials	80 - 99	75 - 95
Collectors	80 - 99	75 -95
Local Roads	50 - 80	50 - 80

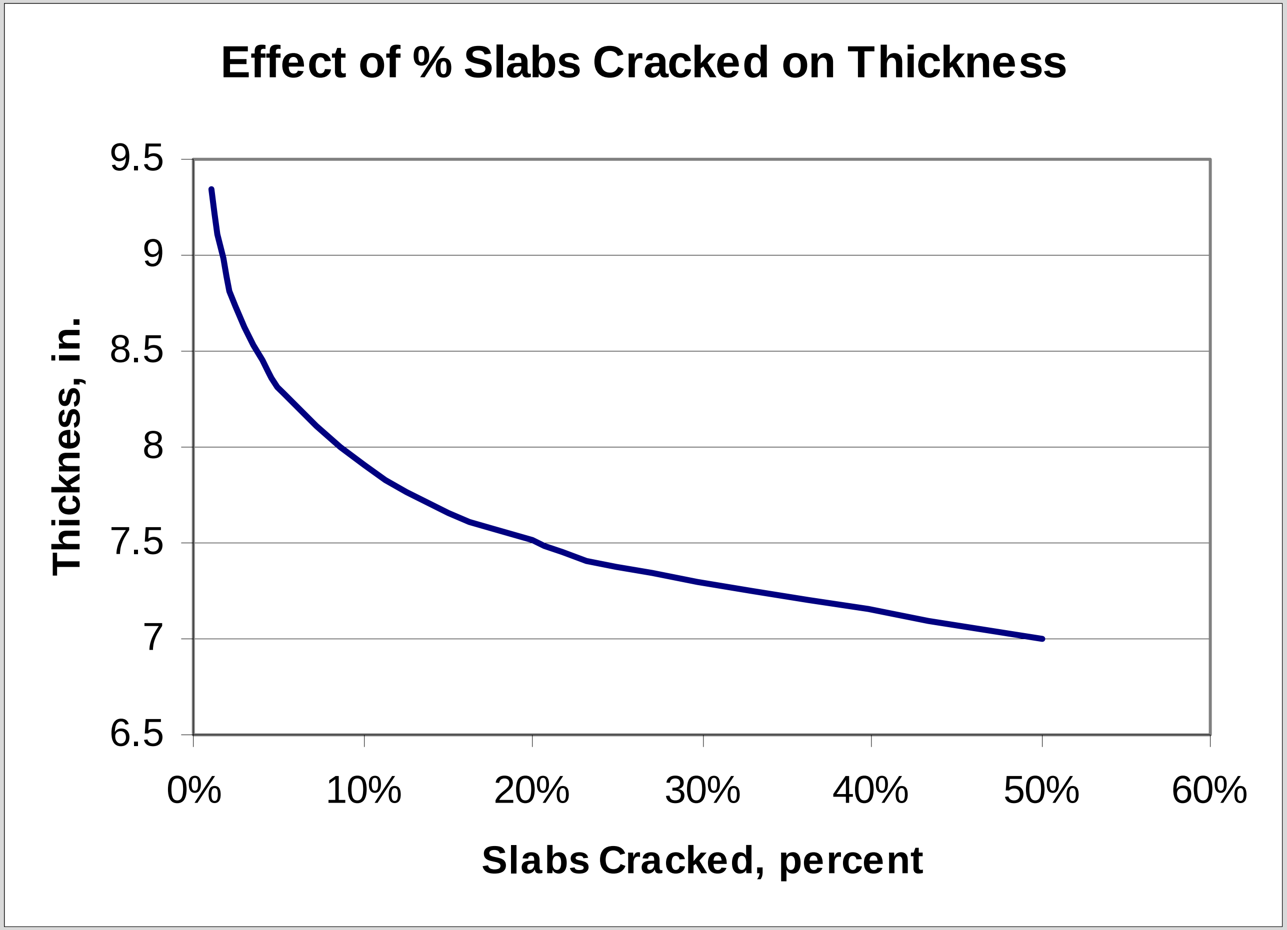
ACPA NORTHWEST CHAPTER

Reliability



Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, MR=600, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

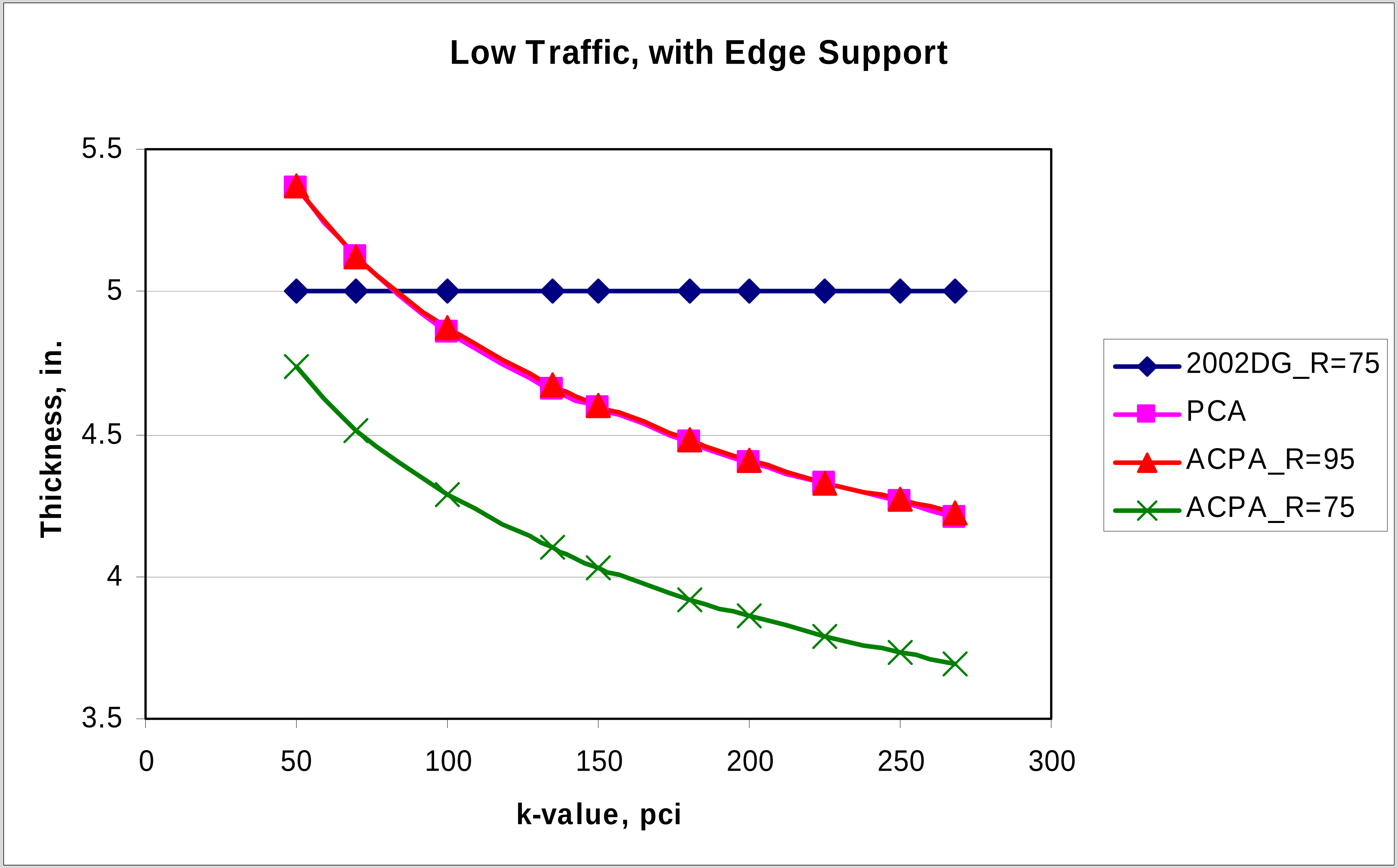
Cracked Slabs



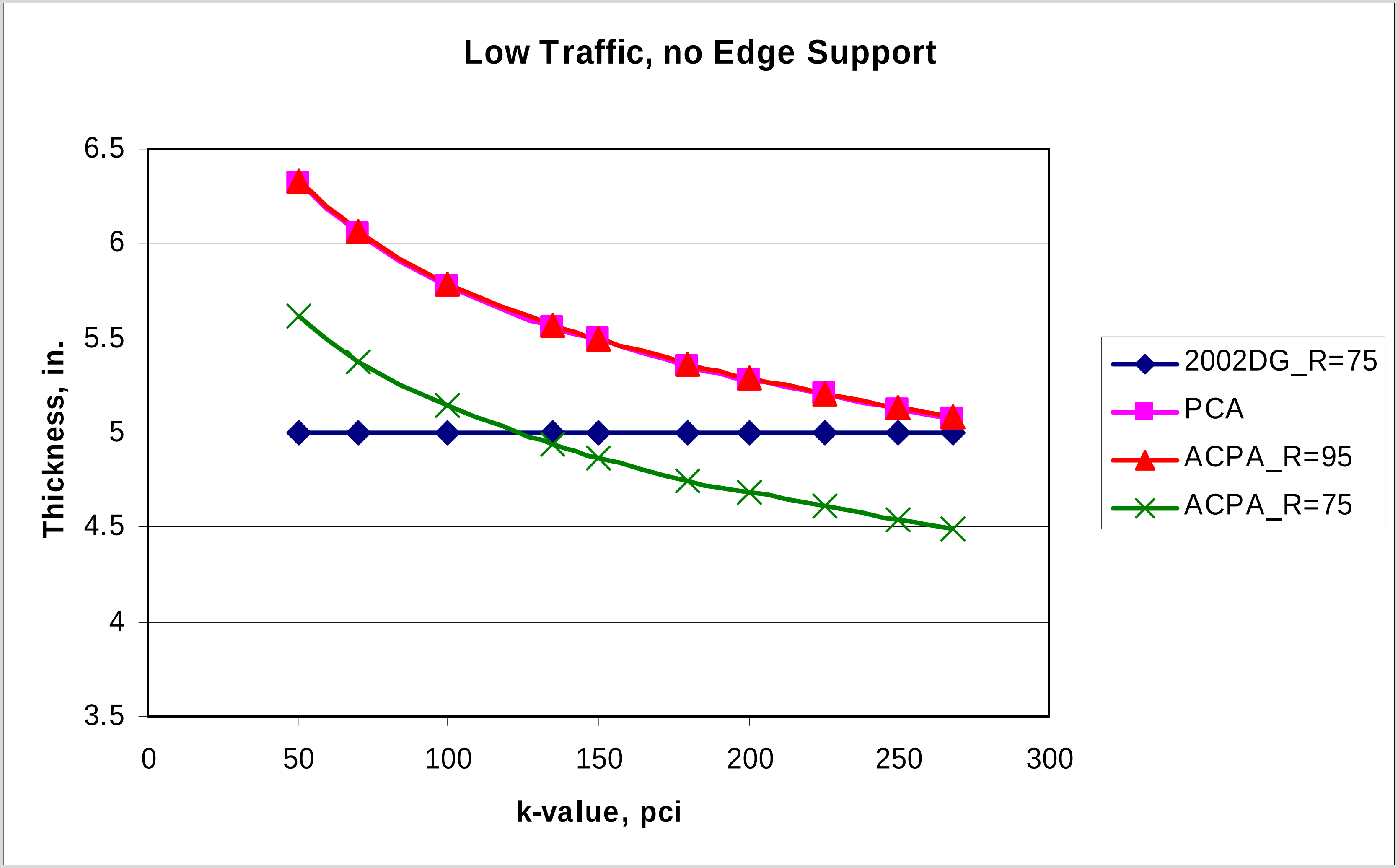
Design Life = 20 yrs, Traffic Category = Major Arterial, ADTT = 1000, 2% Growth, k = 150, MR=600, E=4 mill psi, LT=Yes, ES=Yes, R = 85%, Cracking = 15%

Comparison with MEPDG

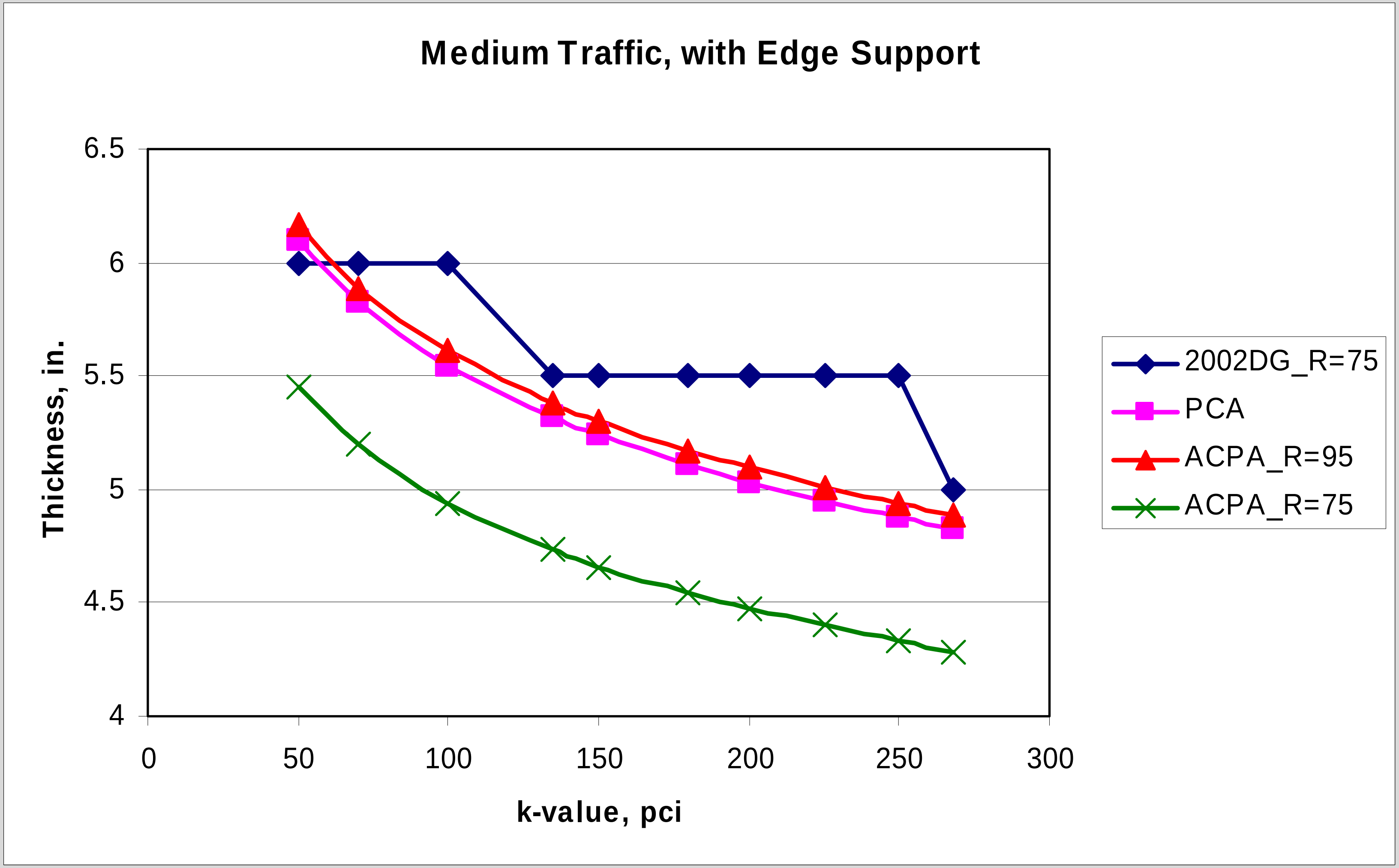
Low Traffic, w/ Edge Support



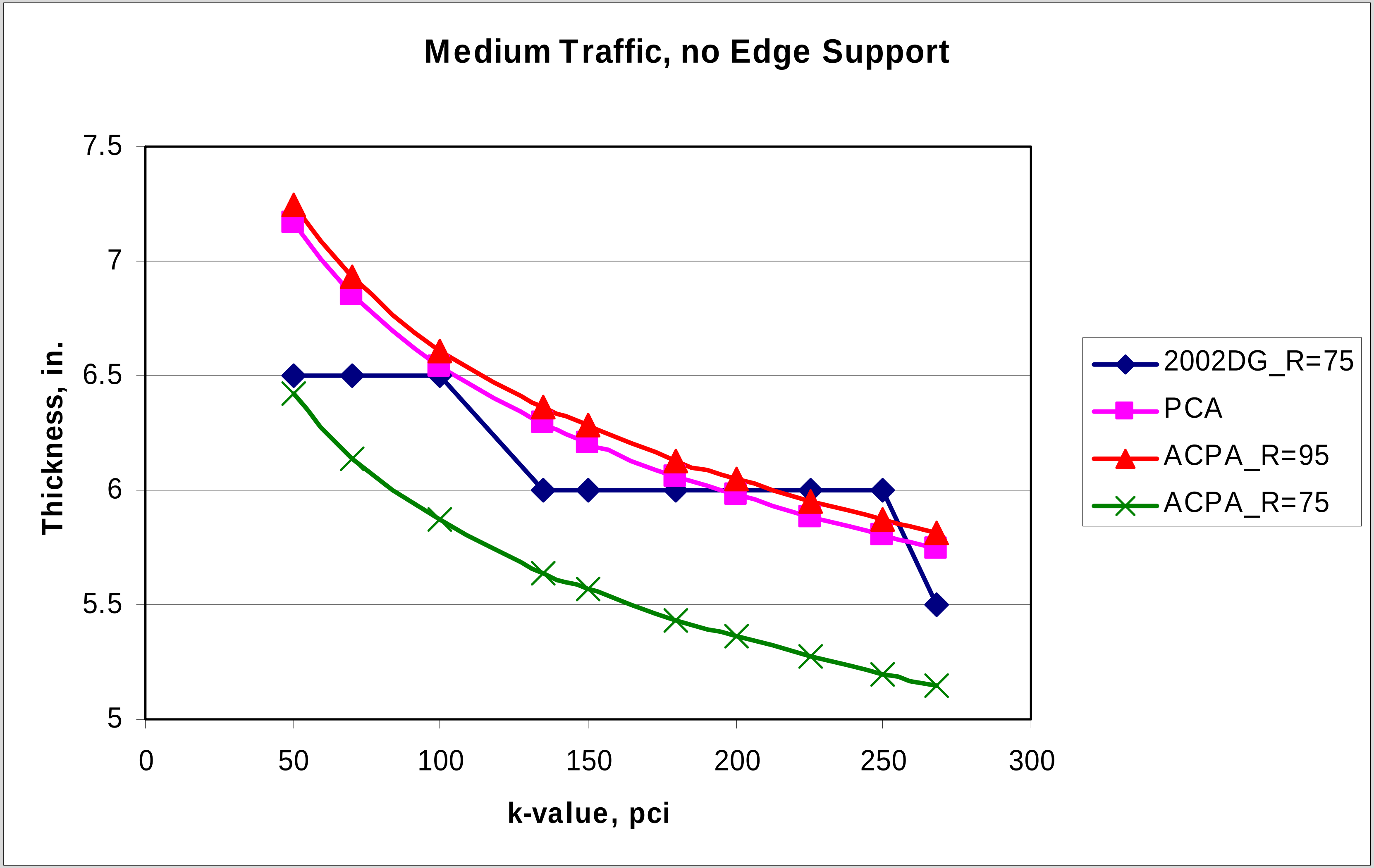
Low Traffic, no Edge Support



Medium Traffic, w/ Edge Support

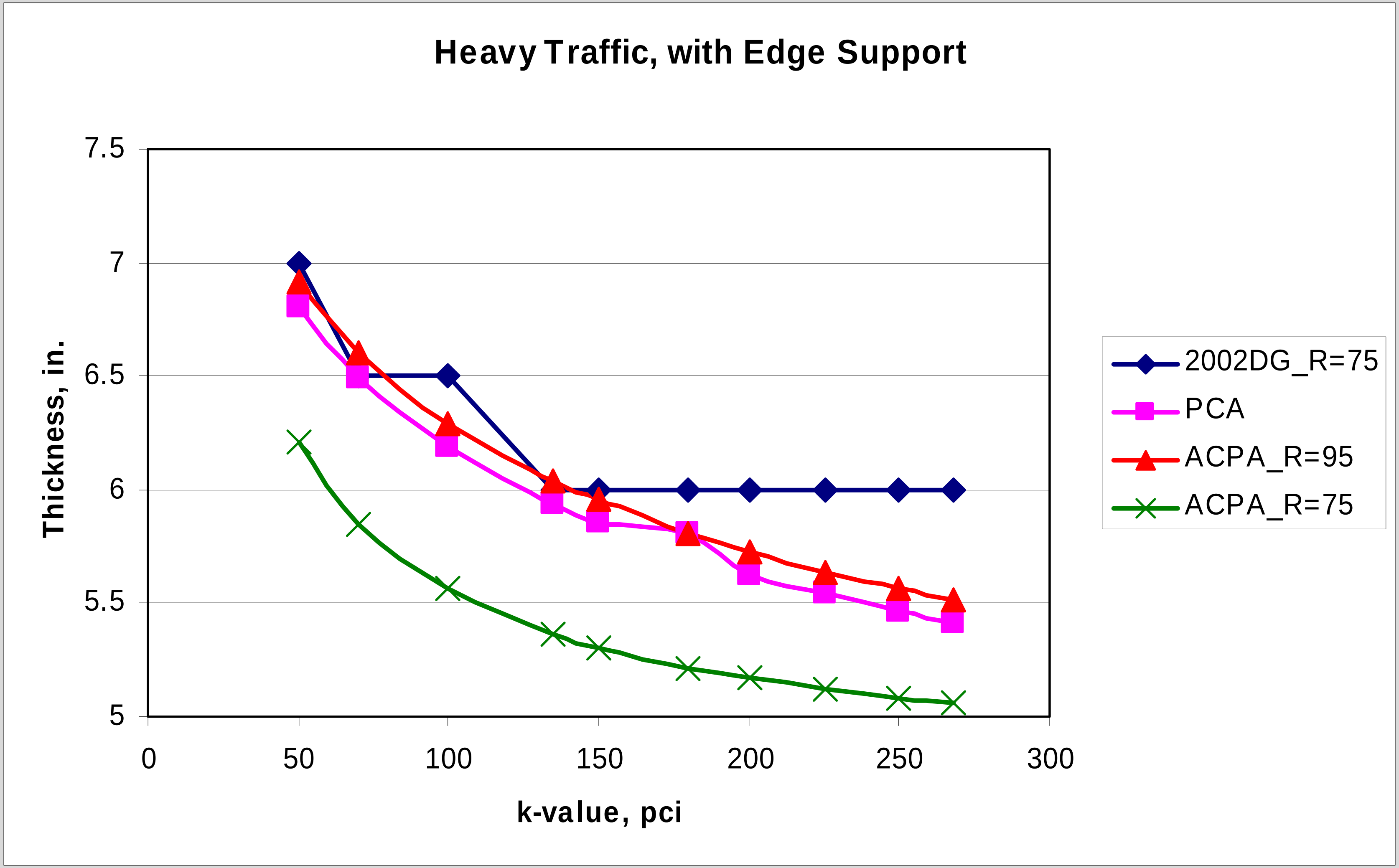


Medium Traffic, no Edge Support

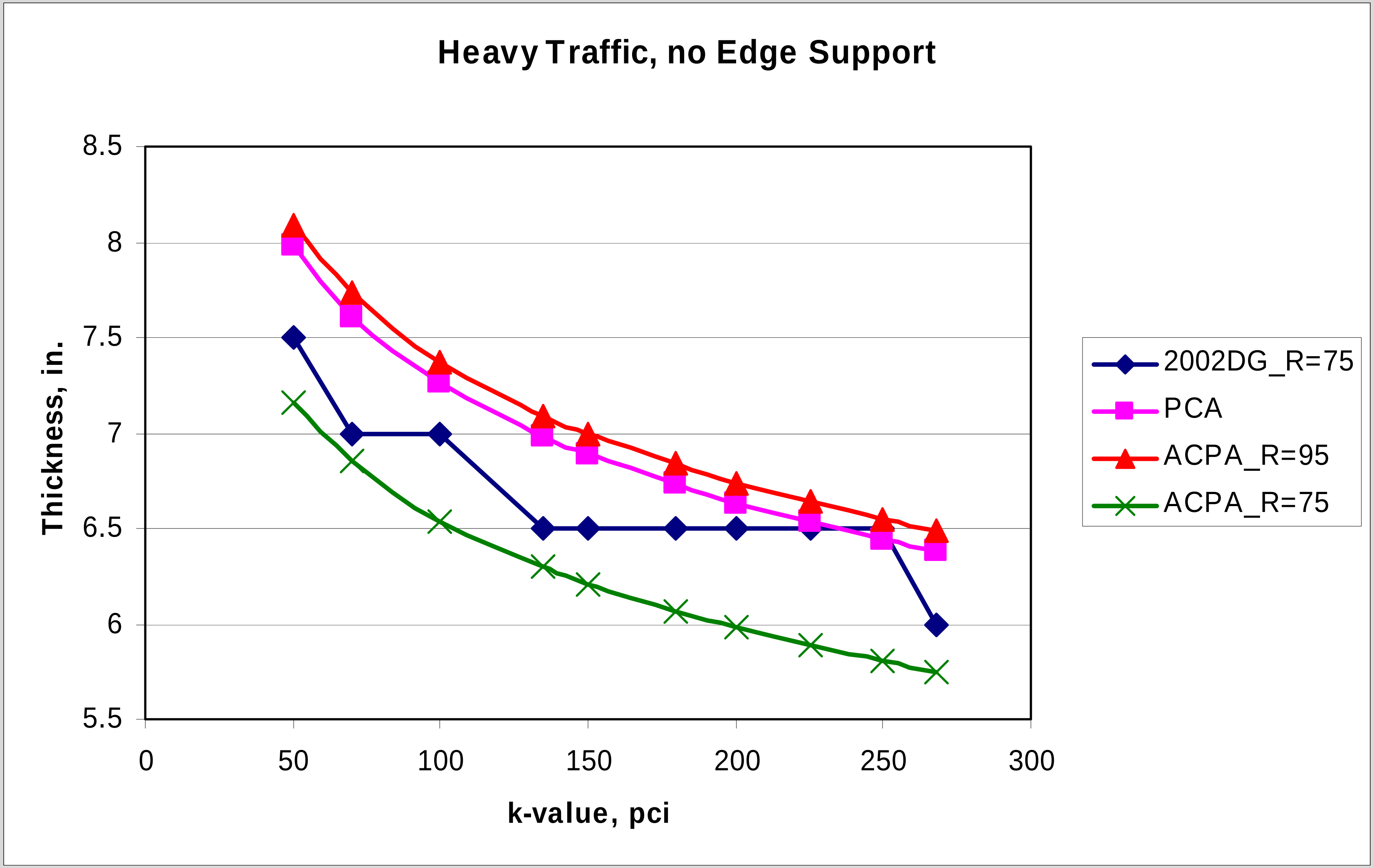


ACPA NORTHWEST CHAPTER

Heavy Traffic, w/ Edge Support



Heavy Traffic, no Edge Support



EXAMPLE

Street Pave

QUESTIONS?

NORTHWEST CHAPTER