# Basics of Concrete Pavement Thickness Design

# Concrete Pavement Design

- Geometrics
- Thickness(es)
- Joints
- Materials

# Concrete Pavement Design

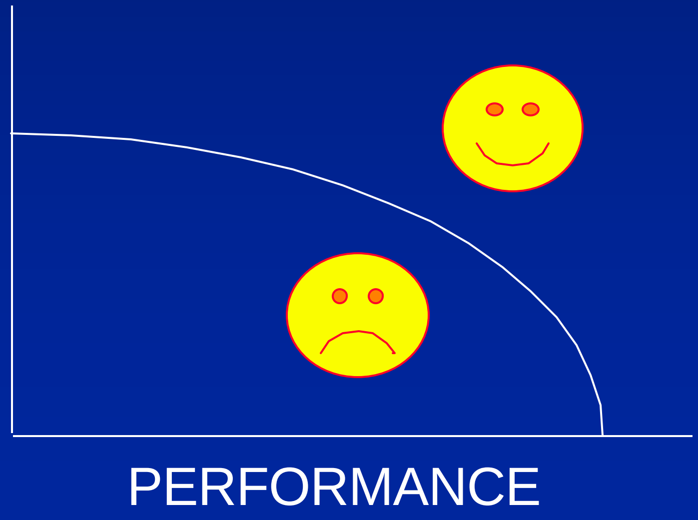
- Geometrics
- Thickness(es)
- Joints
- Materials

**Most Often Influence Cost & Selection of Projects**

# Concrete Pavement Design

- Geometrics
- Thickness(es)
- Joints
- Materials

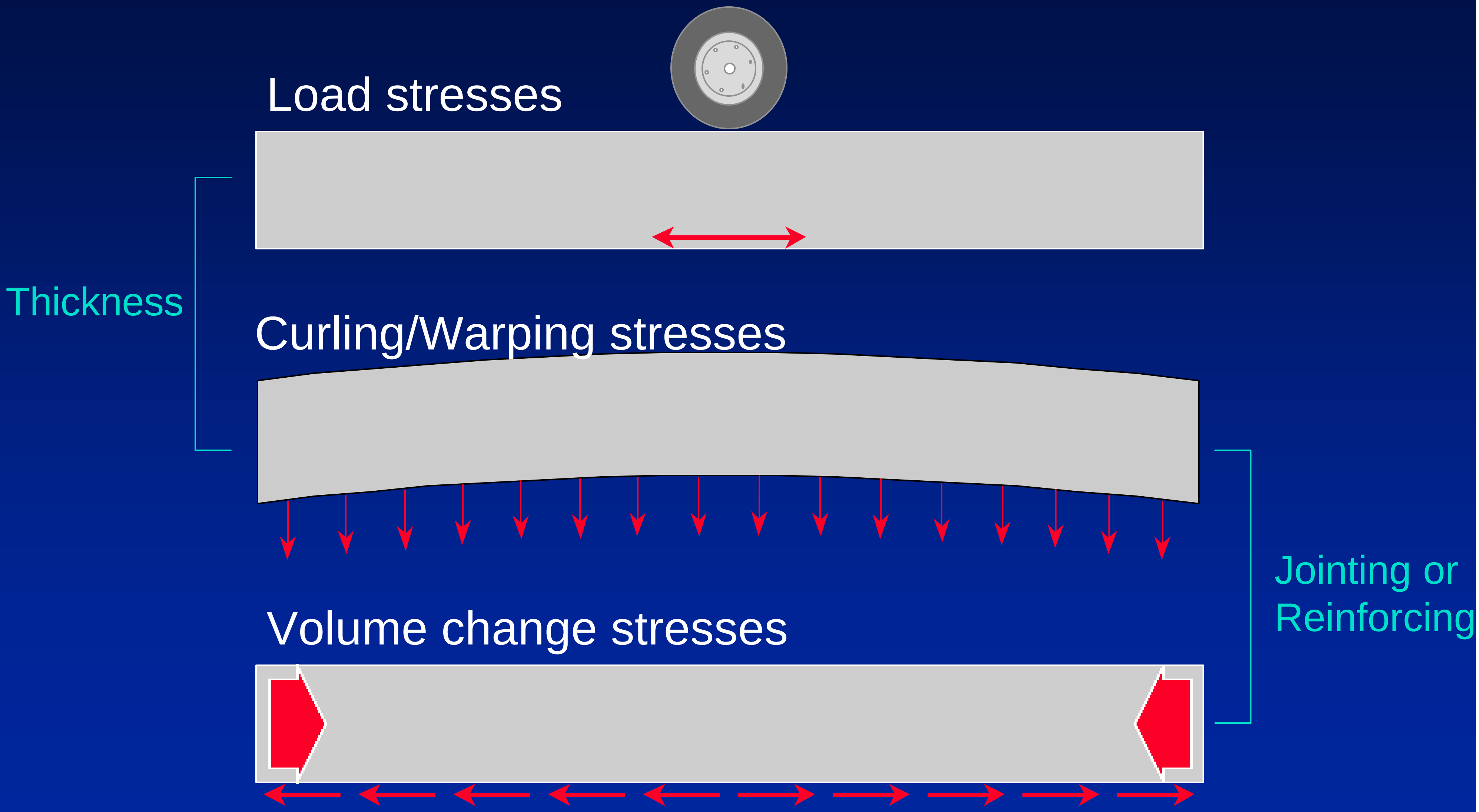
**Most Often Influence Real-world Performance**



# Concrete Pavement Design

| **Design Area** | **Performance Factor** |
|---|---|
| Materials Selection & Proportioning | ASR<br>D-cracking<br>Freeze-Thaw<br>Scaling<br>Skid Resistance |
| Jointing & Subbase | Blow-ups<br>Random cracking<br>Faulting<br>Pumping<br>Spalls |
| Thickness (*Slab*) | Fatigue Cracking |

# Principles of Design



# Thickness Design Procedures

- Empirical Design Procedures
  - Based on observed performance
    - AASHO Road Test
- Mechanistic Design Procedures
  - Based on mathematically calculated pavement responses
    - PCA Design Procedure (PCAPAV)

# PAVEMENT DESIGN

Pavement design is an a priori process.

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.

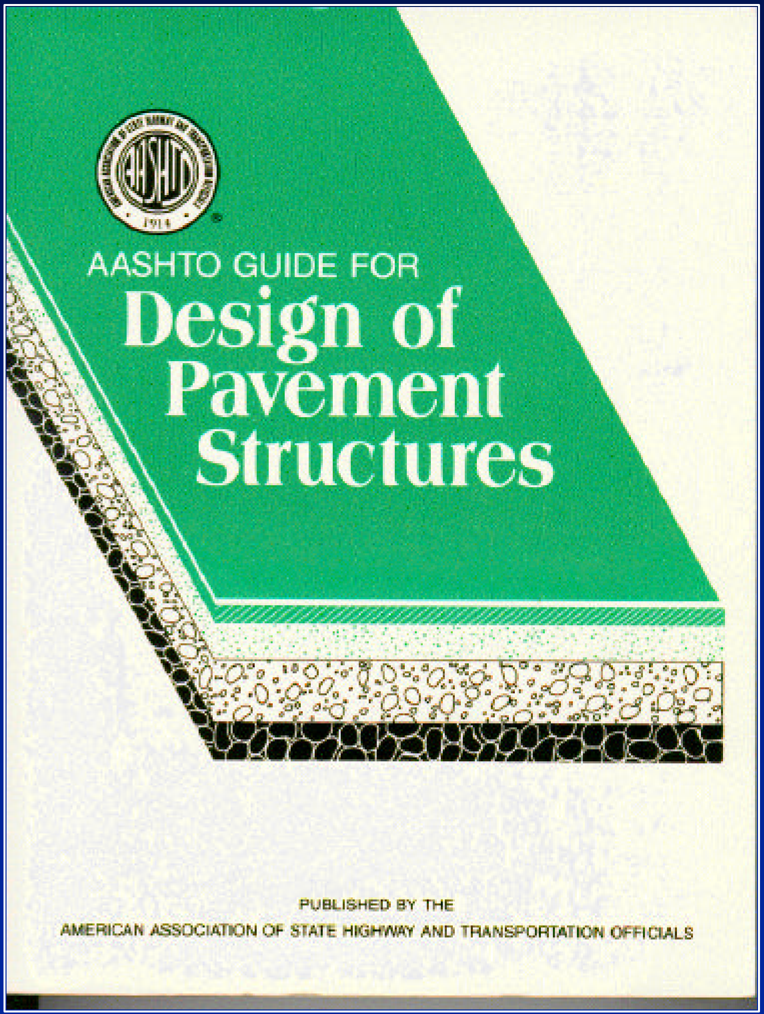
NCHRP 1-26 Phase II Final Report

# Design of Concrete Pavements

- Thickness Design Considerations:
  - Traffic Loads and Traffic Growth
  - Subgrade and Subbases
  - Drainage
  - Concrete Properties
  - Load Transfer
  - Reliability

# AASHTO Design Procedures

AASHTO Guide for Design of Pavement Structures - 1993



# 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
- Include both Rigid and Flexible Designs
- Include a wide range of axle loads and pavement cross-sections

# AASHO Test Layout

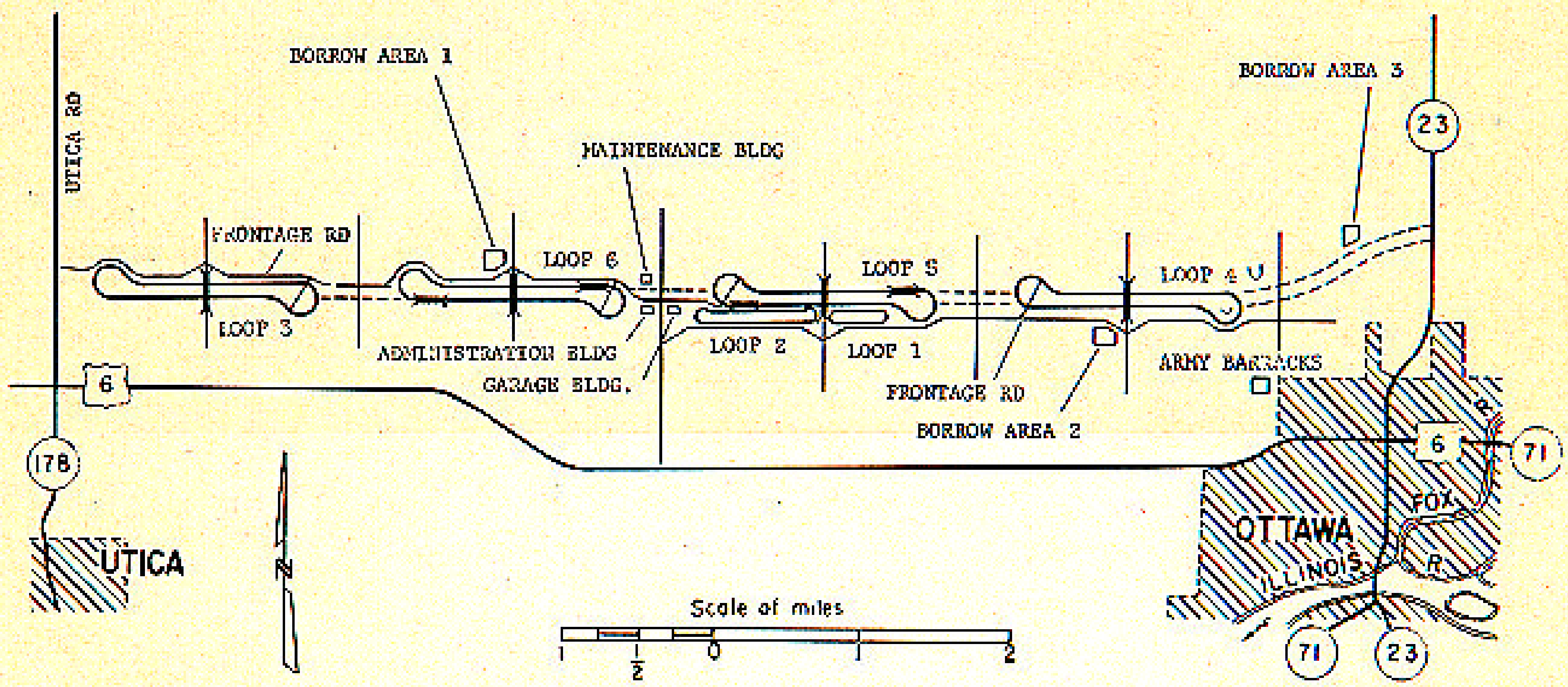
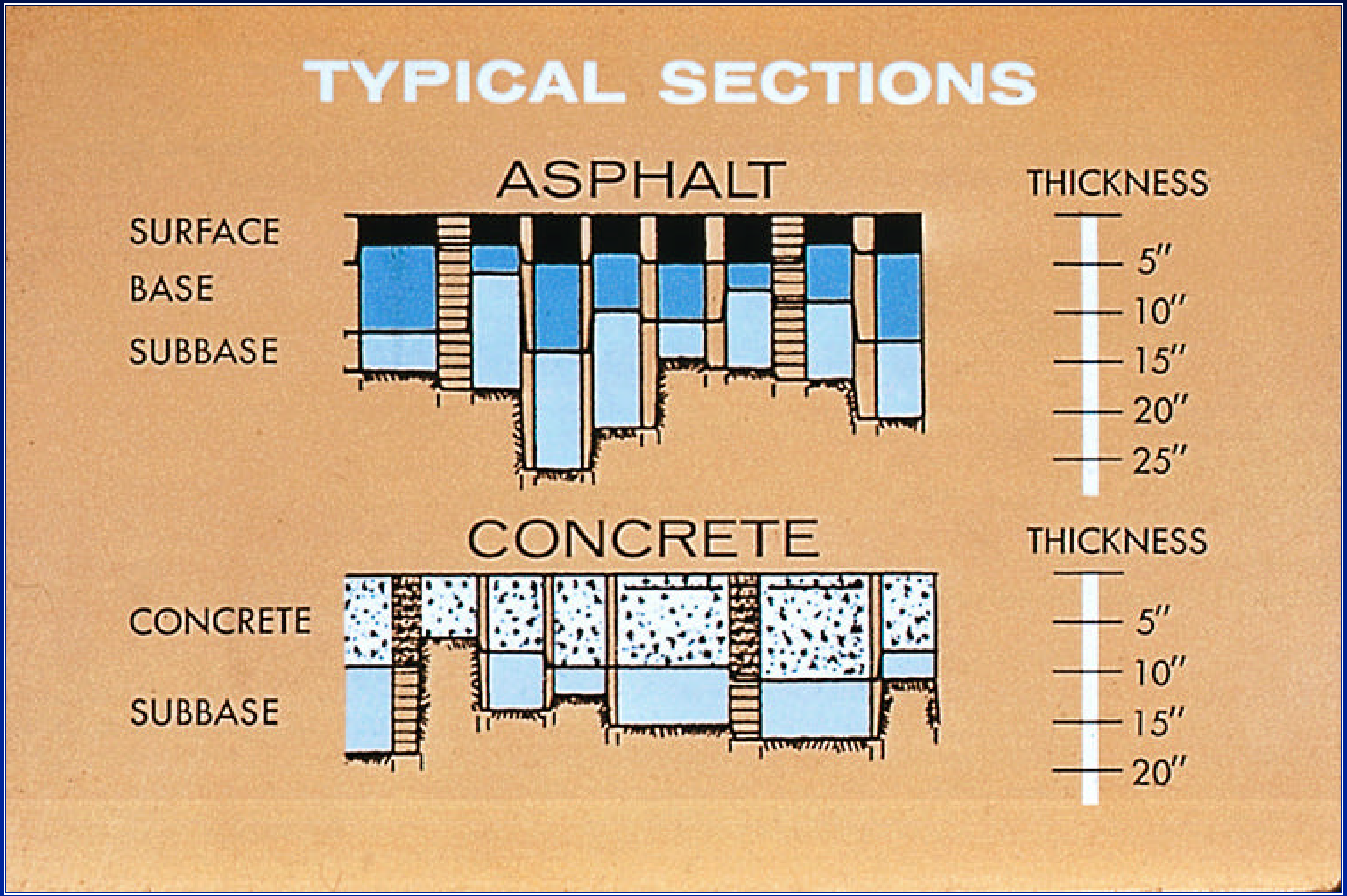



Figure 11. Map of AASHO Road Test.

# AASHO Test Layout




368 rigid test sections     468 flexible test sections

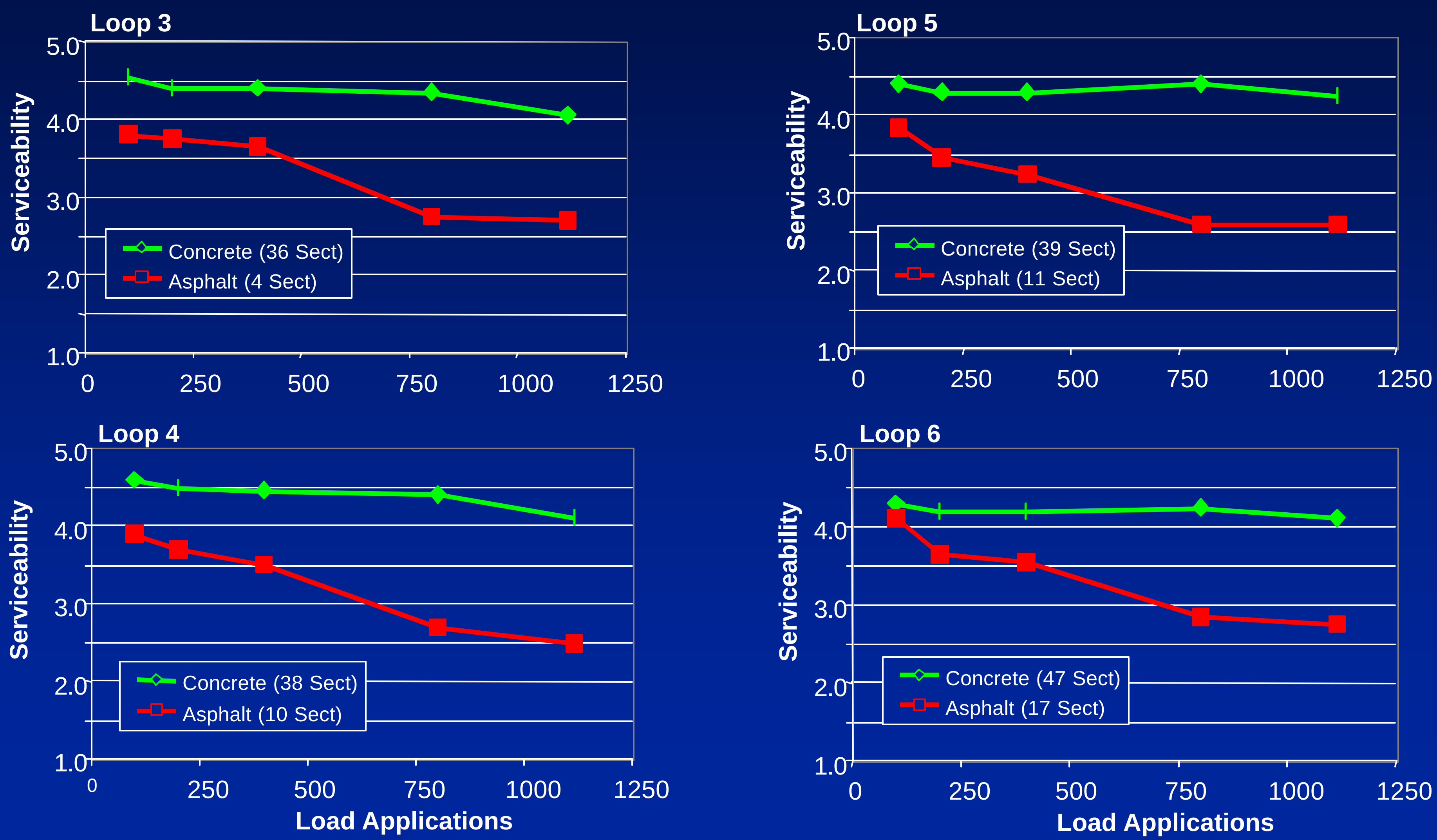
# AASHO Test Traffic

Max Single Axle

Max Tandem Axle

# AASHO Road Test Performance

## Surviving Sections



# 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 - 1972** |
| 1981 | Revised Chapter III on Portland Cement Concrete Pavement Design |
| **1986** | **Guide for the Design of Pavement Structures** |
| **1993** | **Revised Overlay Design Procedures** |
| 1998 | Revised Portland Cement Concrete Pavement Design |

# 1986-93 Rigid Pavement Design Equation

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

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

Standard Normal Deviate ($Z_R$)

Overall Standard Deviation ($s_o$)

Depth ($D$)

Change in Serviceability ($\Delta PSI$)

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 ($k$)

# AASHTO DESIGN
# Traffic

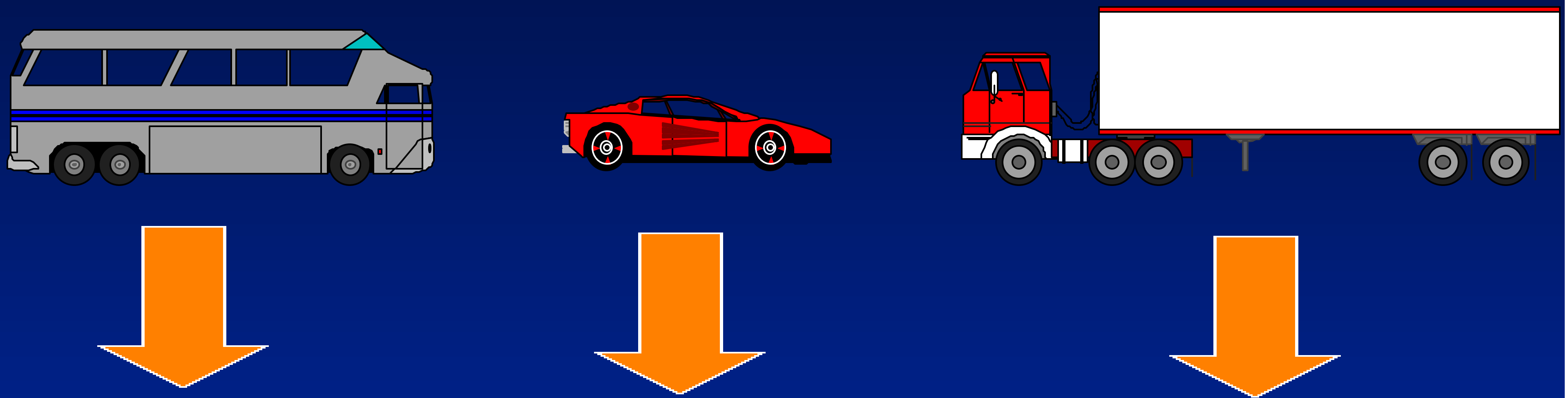
ESAL’s or E-18’s

The number and weight of all axle loads from the anticipated vehicles expected during the pavement design life - expressed in 18-kip (80 kN) **E**quivalent **S**ingle **A**xle **L**oads for each type of pavement.

—*Rigid ESAL’s or E-18’s*

—*Flexible ESAL’s or E-18’s*

# AASHTO DESIGN
# Traffic - ESALs



Equivalent Number of 18k Single Axle Loads

# ESALs GENERATED BY DIFFERENT VEHICLES/DAY

| VEHICLE | NUMBER | RIGID ESALs | FLEXIBLE ESALs |
|---|---|---|---|
| Single Units 2 Axle | 20 | 6.38 | 6.11 |
| Busses | 5 | 13.55 | 8.73 |
| Panel Trucks | 10 | 10.89 | 11.11 |
| Semi-tractor Trailer 3 Axles | 10 | 20.06 | 13.41 |
| Semi-tractor Trailer 4 Axles | 15 | 39.43 | 29.88 |
| Semi-tractor Trailer 5 Axles | 15 | 57.33 | 36.87 |
| Automobile, Pickup, Van | 425 | 1.88 | 2.25 |
| Total | 500 | 149.52 | 108.36 |

# AASHTO DESIGN
# Traffic

## Load Equivalence Factor (LEF)

The Ratio of the Effect (Damage) of a Specific Axle Load on Pavement Serviceability to the Effect Produced by an 18-kip Axle Load at the AASHO Road Test.

Change for each:

- Pavement Type
- Thickness
- Terminal Serviceability.

# AASHTO DESIGN
# Traffic

Load Equivalence Factor (LEF)

$$\frac{\text{No. of repetitions of 18-k SAL Load causing given } \Delta PSI}{\text{No. of repetitions of X-k Y-Axle Load for a same } \Delta PSI}$$

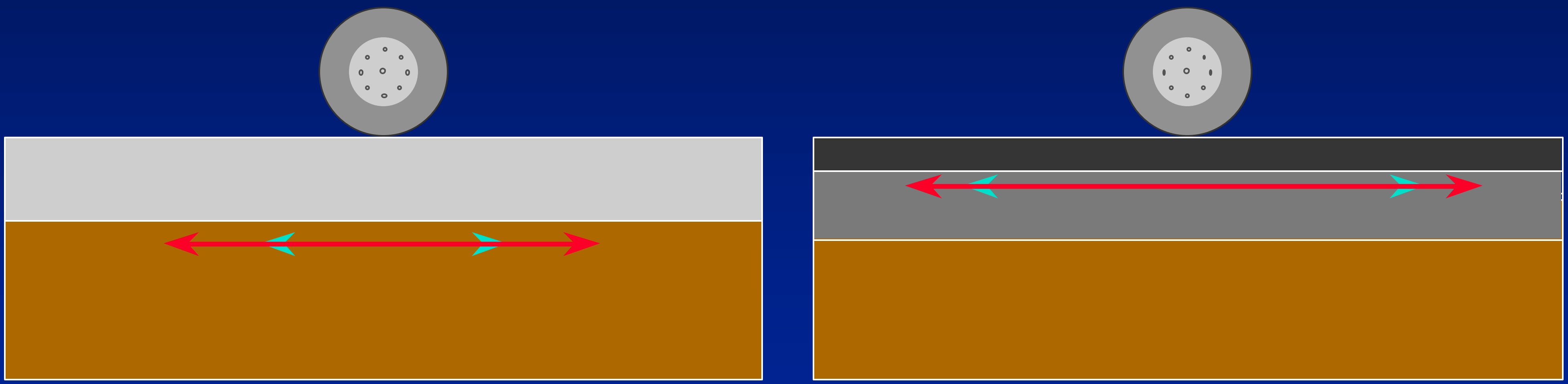
Change for each:

- Pavement Type
- Thickness
- Terminal Serviceability.

# LOAD EQUIVALENCY FACTORS

## FOR A GIVEN PAVEMENT STRUCTURE

For a Given Stress or Strain:



*Stress or Strain of X-kip Load on Axle Type Y*

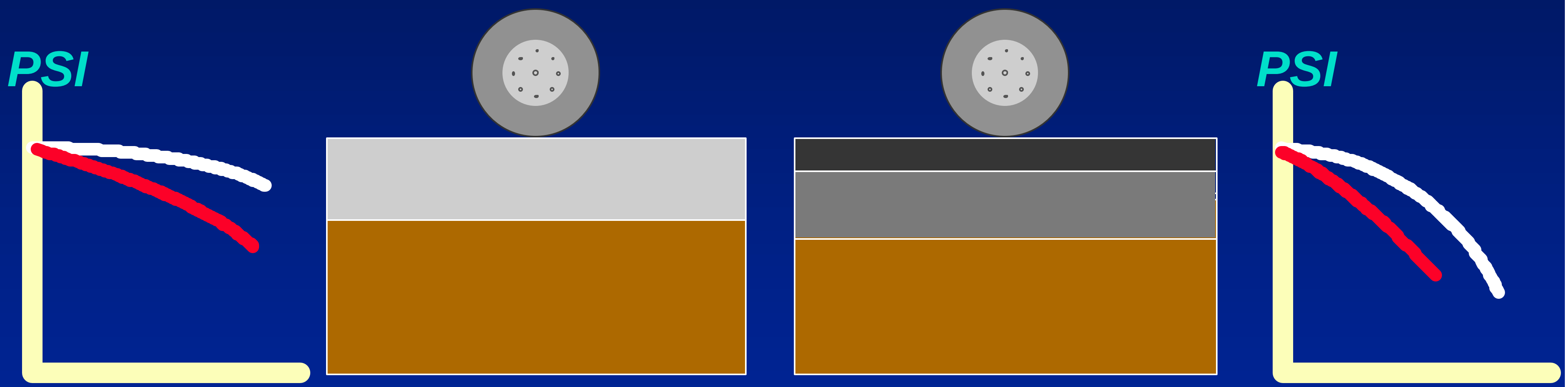
---

*Stress or Strain of 18-kip Load on a Single Axle*

# LOAD EQUIVALENCY FACTORS

## FOR A GIVEN PAVEMENT STRUCTURE

For a Given Serviceability Loss:




*# of Repetitions of 18-kip Load on a Single Axle*

---

*# of Repetitions of X-kip Load on Axle Type Y*

# AASHTO DESIGN
## Traffic

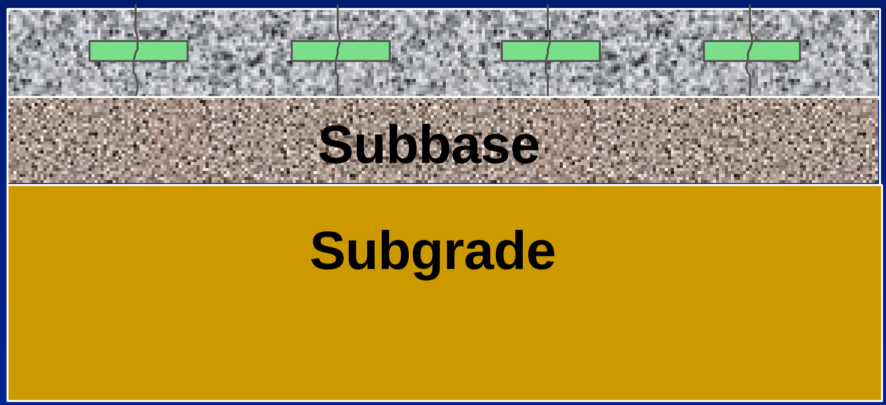
Concrete Response ≠ Asphalt Response

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

# Subgrade and Subbases

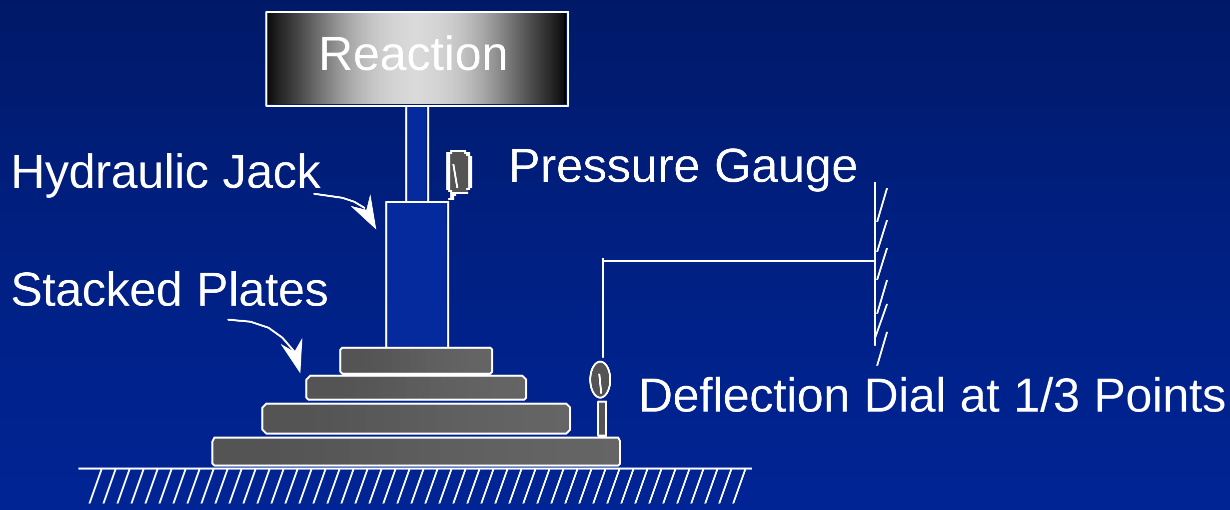
- Subbase
  - Layer of material directly below the concrete pavement.
- Subgrade
  - Natural ground, graded, and compacted on which the pavement is built.

Concrete Section



# Subgrade / Subbase Strength

## Modulus of Subgrade Reaction, k




k (psi/in) = unit load on plate / plate deflection

# Subgrade and Subbases

## Design

- Subgrade strength is **not** a critical element in the **thickness design**.
  - Has little impact on thickness.
- Need to know if pavement is on:
  - Subgrade (k ≈ 100 psi/in.),
  - Granular subbase (k ≈ 150 psi/in.),
  - Asphalt treated subbase (k ≈ 300 psi/in.)
  - Cement treated/lean concrete subbase (k ≈ 500 psi/in.).

# AASHTO DESIGN
## Subgrade Strength

Typical Soil Relationships

| *Soil Type* | *Strength* | *k-value (psi / in.)* | *Mr (psi)* | *CBR* |
|---|---|---|---|---|
| **Silts / Clays** | **Very Low** | **50-100** | **1000-1900** | **<3** |
| **Fine grained** | **Low** | **100-150** | **1900-2900** | **3-5.5** |
| **Sands** | **Medium** | **150-220** | **2900-4300** | **5.5-12** |
| **Gravely soils** | **High** | **220-250** | **4300-4850** | **>12** |
| **Bitumin.Treat.** | **High** | **350-450** | **100,000+** | **>12** |
| **Cement.Treat./LCB** | **High** | **400-600** | **500,000+** | **>12** |

# Subgrade and Subbases

## Performance

- Proper design and construction are **absolutely necessary** if the pavement is to perform.
  - Must be **uniform** throughout pavement's life.
- Poor subgrade/subbase preparation can not be overcome with thickness.
  - Any concrete pavement, built of any thickness, will have problems on a poorly designed and constructed subgrade or subbase.

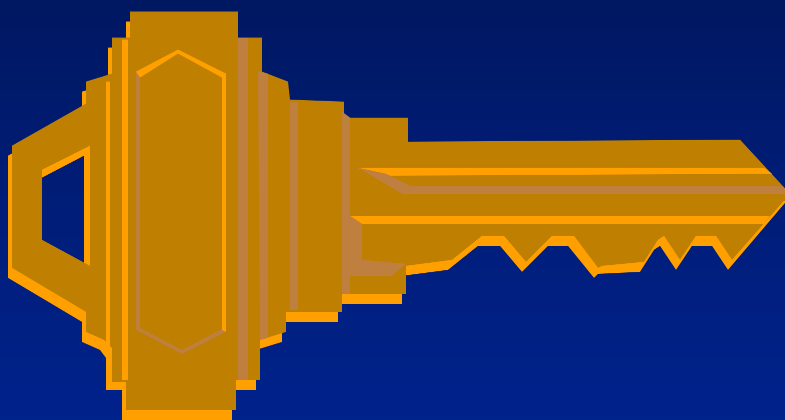
# UNIFORMITY:

The <u>Key</u> To

GOOD

PAVEMENT

PERFORMANCE



# Design for Uniform Support

## Sources of Non-Uniform Support

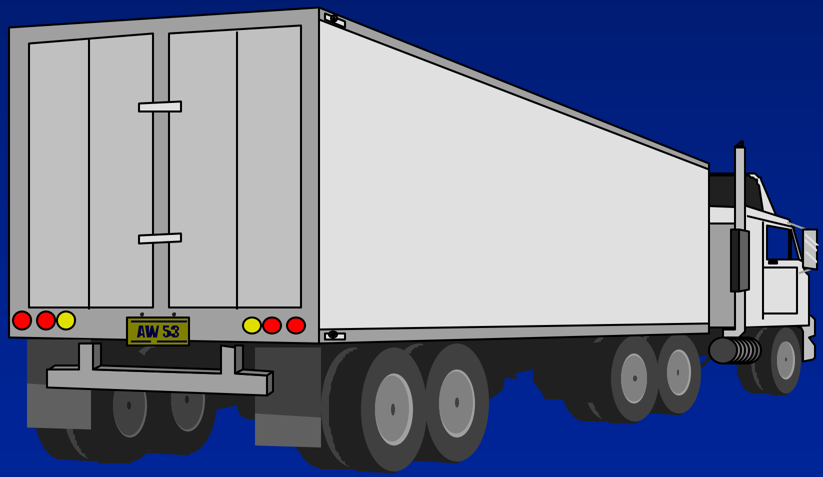
- Expansive soils
- Frost susceptible soils
- Pumping (loss of Support)
- Cut-fill transitions
- Poorly compacted excavations
  - Utility work
  - Culverts

# PAVEMENT DESIGN
## Subbase Effects

The current Design does not model the contribution of bases accurately.

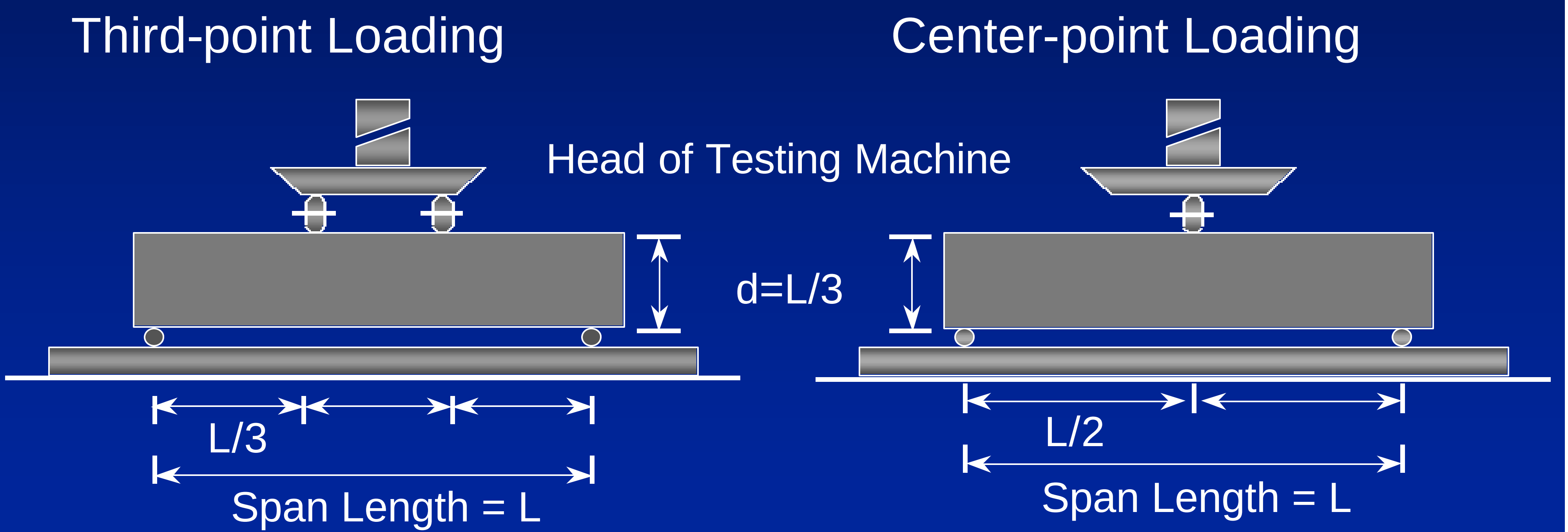
At the AASHO Road Test, it was found that the concrete pavements with granular bases could carry about 30% more traffic.

The current design procedures allows concrete pavements built with granular bases to carry about 5 - 8% more traffic.



# Concrete Properties

## Flexural Strength (S'c) Determination



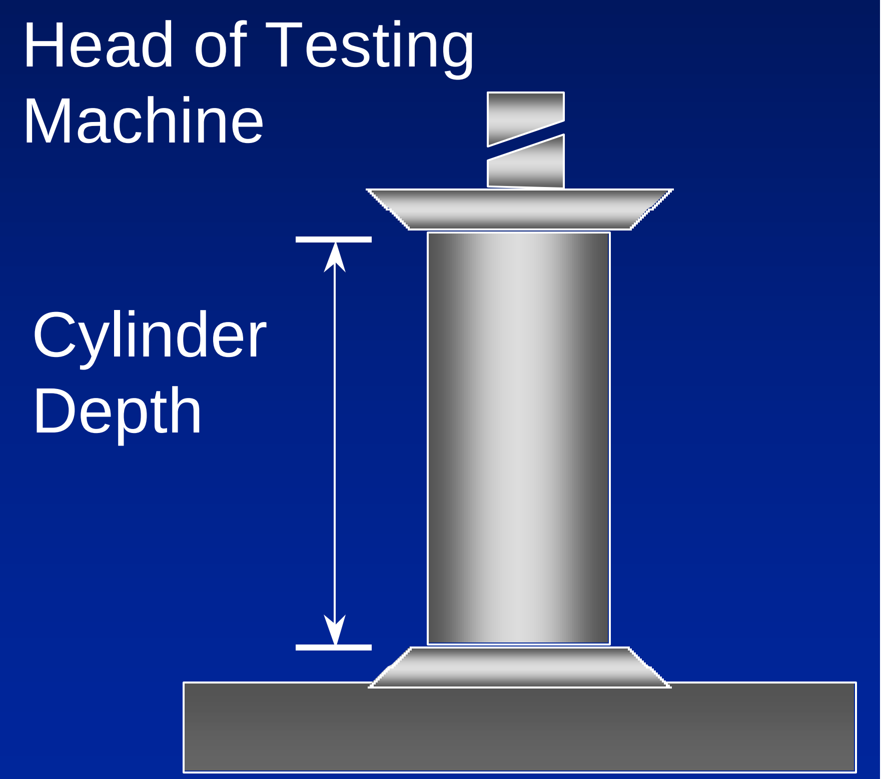
# Concrete Properties

Compressive Strength $f'_c$

$$S'_c = 8\text{-}10 \sqrt{f'_c}$$

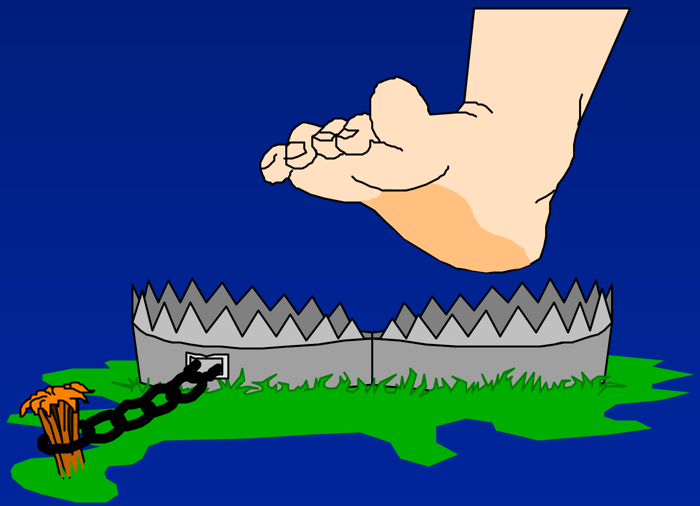
$f'_c$ = Compressive Strength (psi)

$S'_c$ = Flexural Strength (psi)



# Concrete Properties

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



**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**

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

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

$S'c_{design} = 614$ psi

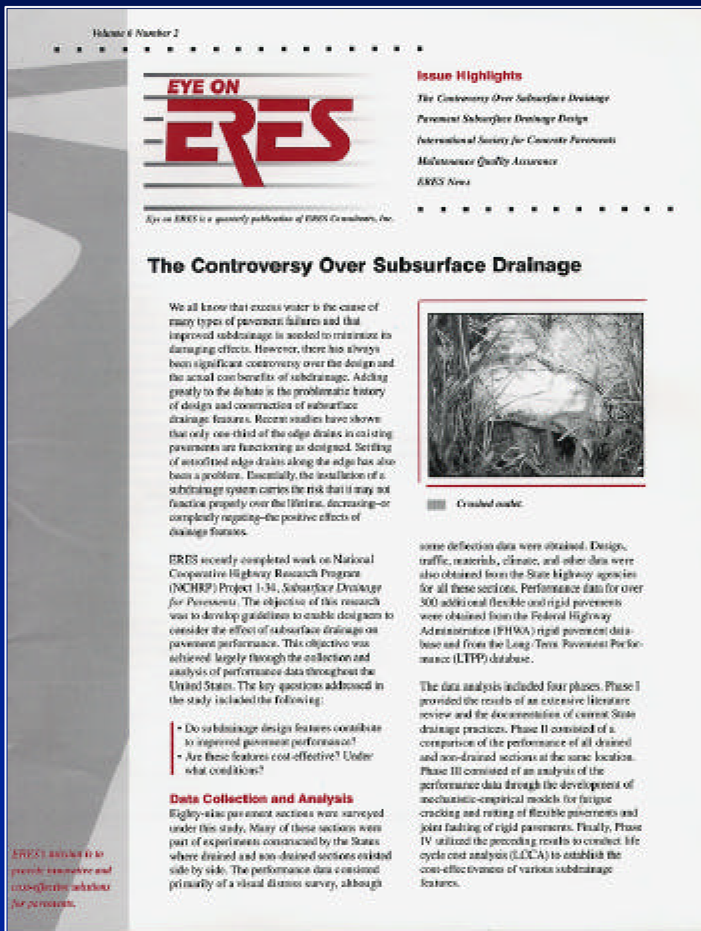
# Drainage

## Conditions for Pumping

- Subgrade Soil that will go into Suspension
- Free water between Slab and Subgrade
- Frequent Heavy wheels loads / Large Deflections

# Drainage

## NCHRP 1-34: Subsurface Drainage for Pavements



*Volume 6 Number 2*

EYE ON ERES

*Eye on ERES is a quarterly publication of ERES Consultants, Inc.*

**Issue Highlights**

*The Controversy Over Subsurface Drainage*
*Pavement Subsurface Drainage Design*
*International Society for Concrete Pavements*
*Maintenance Quality Assurance*
*ERES News*

*ERES' mission is to provide innovative and cost-effective solutions for pavements.*

### The Controversy Over Subsurface Drainage

We all know that excess water is the cause of many types of pavement failures and that improved subdrainage is needed to minimize its damaging effects. However, there has always been significant controversy over the design and the actual cost benefits of subdrainage. Adding greatly to the debate is the problematic history of design and construction of subsurface drainage features. Recent studies have shown that only one-third of the edge drains in existing pavements are functioning as designed. Setting of retrofitted edge drains along the edge has also been a problem. Essentially, the installation of a subdrainage system carries the risk that it may not function properly over the lifetime, decreasing—or completely negating—the positive effects of drainage features.

ERES recently completed work on National Cooperative Highway Research Program (NCHRP) Project 1-34, *Subsurface Drainage for Pavements*. The objective of this research was to develop guidelines to enable designers to consider the effect of subsurface drainage on pavement performance. This objective was achieved largely through the collection and analysis of performance data throughout the United States. The key questions addressed in the study included the following:

- Do subdrainage design features contribute to improved pavement performance?
- Are these features cost-effective? Under what conditions?

Crushed outlet.

**Data Collection and Analysis**

Eighty-nine pavement sections were surveyed under this study. Many of these sections were part of experiments constructed by the States where drained and non-drained sections existed side by side. The performance data consisted primarily of a visual distress survey, although some deflection data were obtained. Design, traffic, materials, climate, and other data were also obtained from the State highway agencies for all these sections. Performance data for over 300 additional flexible and rigid pavements were obtained from the Federal Highway Administration (FHWA) rigid pavement database and from the Long-Term Pavement Performance (LTPP) database.

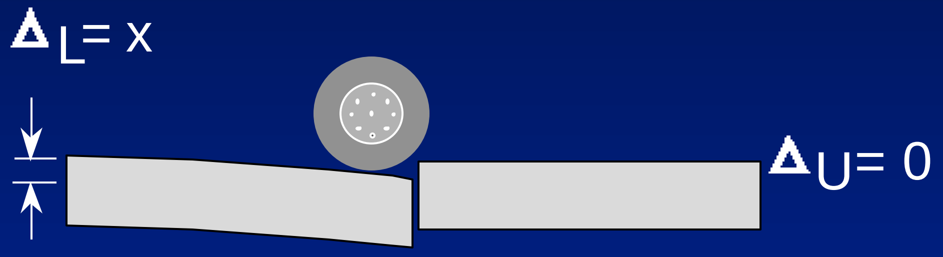
The data analysis included four phases. Phase I provided the results of an extensive literature review and the documentation of current State drainage practices. Phase II consisted of a comparison of the performance of all drained and non-drained sections at the same location. Phase III consisted of an analysis of the performance data through the development of mechanistic-empirical models for fatigue cracking and rutting of flexible pavements and joint faulting of rigid pavements. Finally, Phase IV utilized the preceding results to conduct life cycle cost analysis (LCCA) to establish the cost-effectiveness of various subdrainage features.

- Major Conclusions
  - For Doweled PCC Pavements, Drainage has little affect on Faulting
    - Does reduce D-cracking
  - Drainage significantly reduces fatigue cracking and rutting in AC Pavements
  - Day lighted drainage works best with permeable bases

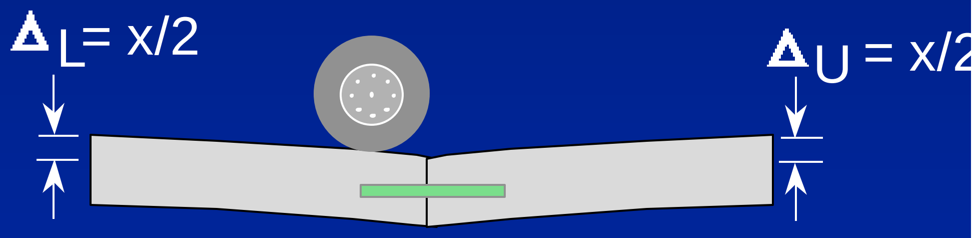
# Load Transfer

## Load Transfer

- A slabs ability to share its load with neighboring slabs
  - Dowels
  - Aggregate Interlock
  - Concrete Shoulders
    - Tied Concrete, curb & gutter, and extended lane have same effect.

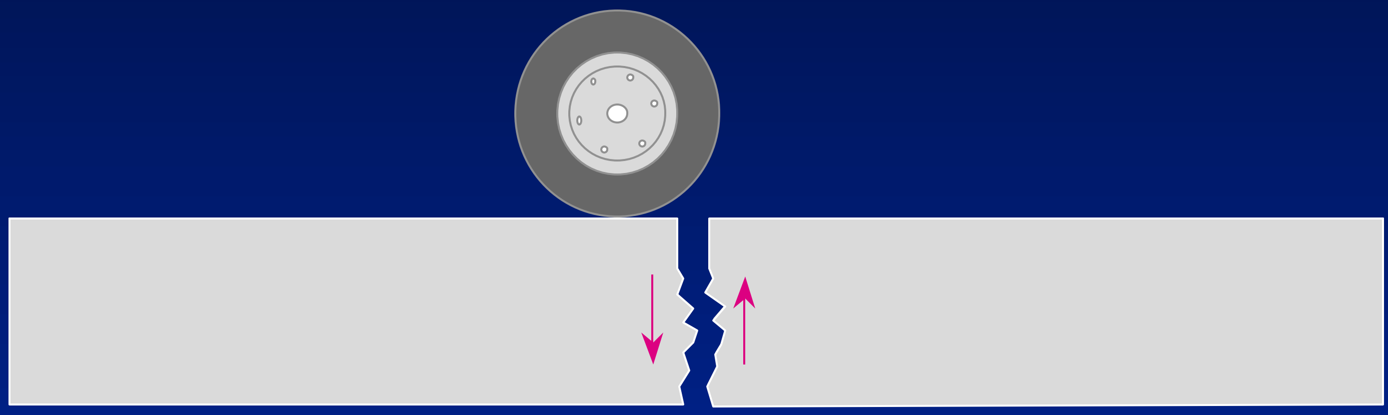


Poor Load Transfer



Good Load Transfer

# Aggregate Interlock



Shear between aggregate particles
below the initial saw cut

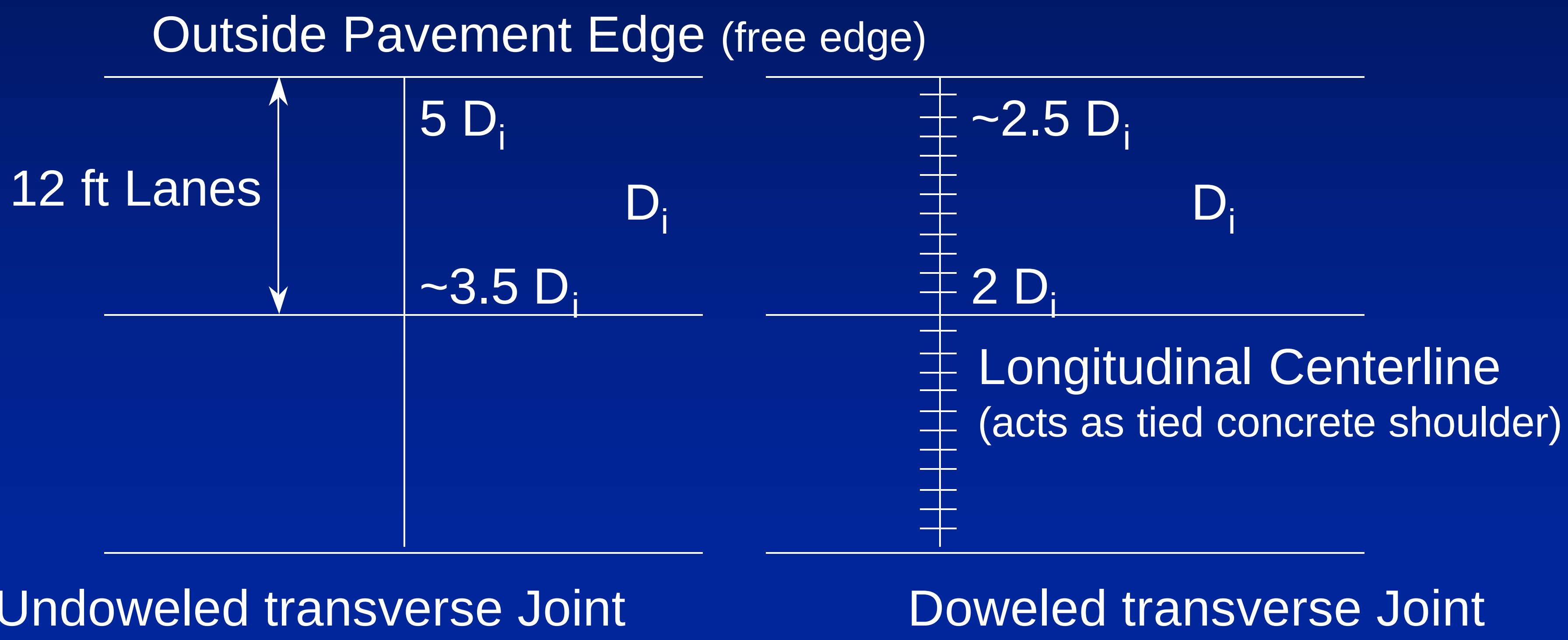
# Aggregate Interlock

# Dowel bars

- Lengths from 15-18 in.
- 6.0 in. min. embedment length
- Diameter
  - 1.25 - 1.50 in. for roads
  - 1.5 - 2.0 in. for airports
- Epoxy or other coating used in harsher climates for corrosion protection

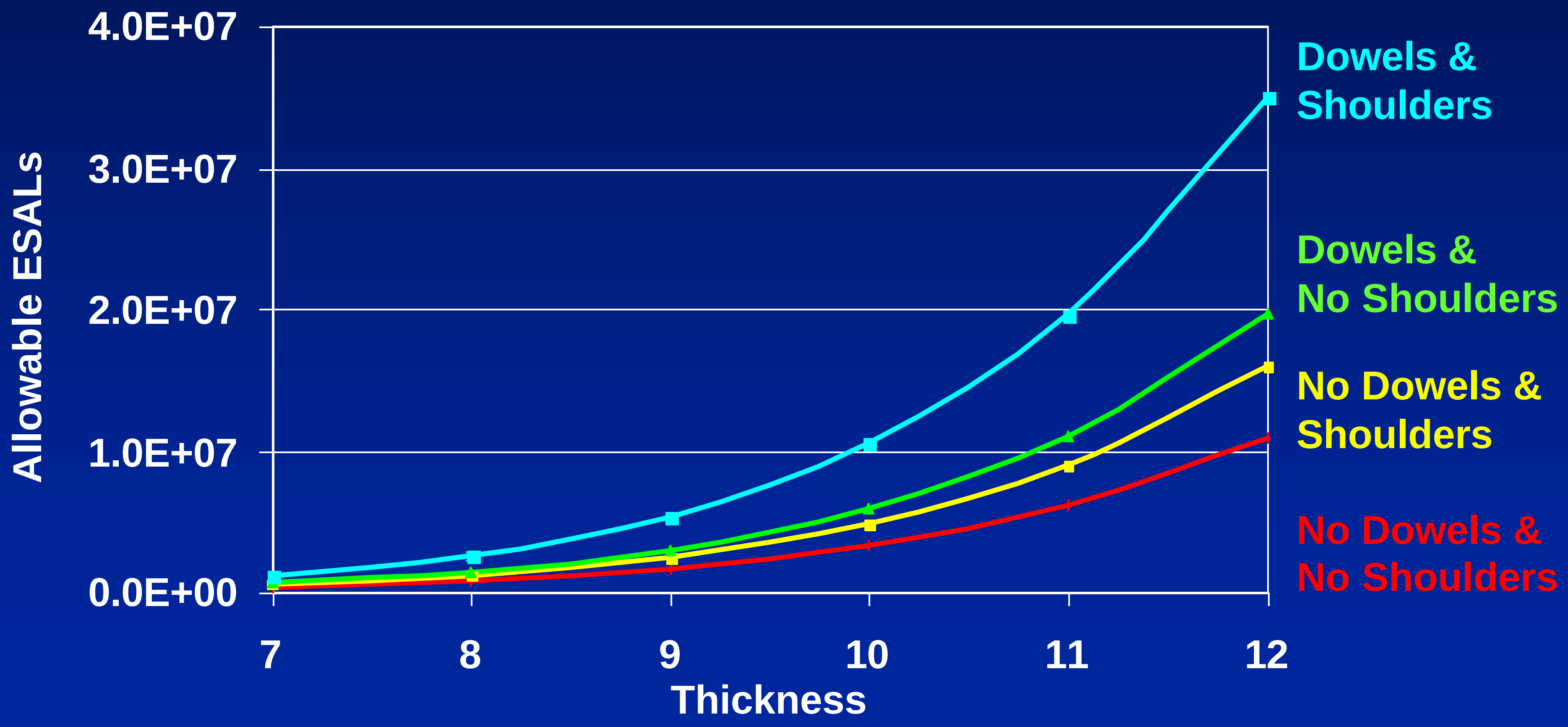
# Load Transfer

## Deflections in Concrete Pavement



# AASHTO DESIGN

## Effect of Dowels and Shoulders



# Concrete Pavement Design

## To Dowel or Not to Dowel?

Trucks Control Thickness

- Exclude dowels if:
  - Slab thickness < 7.0 in
- Include dowels if:
  - Slab thickness > 8.0 in.

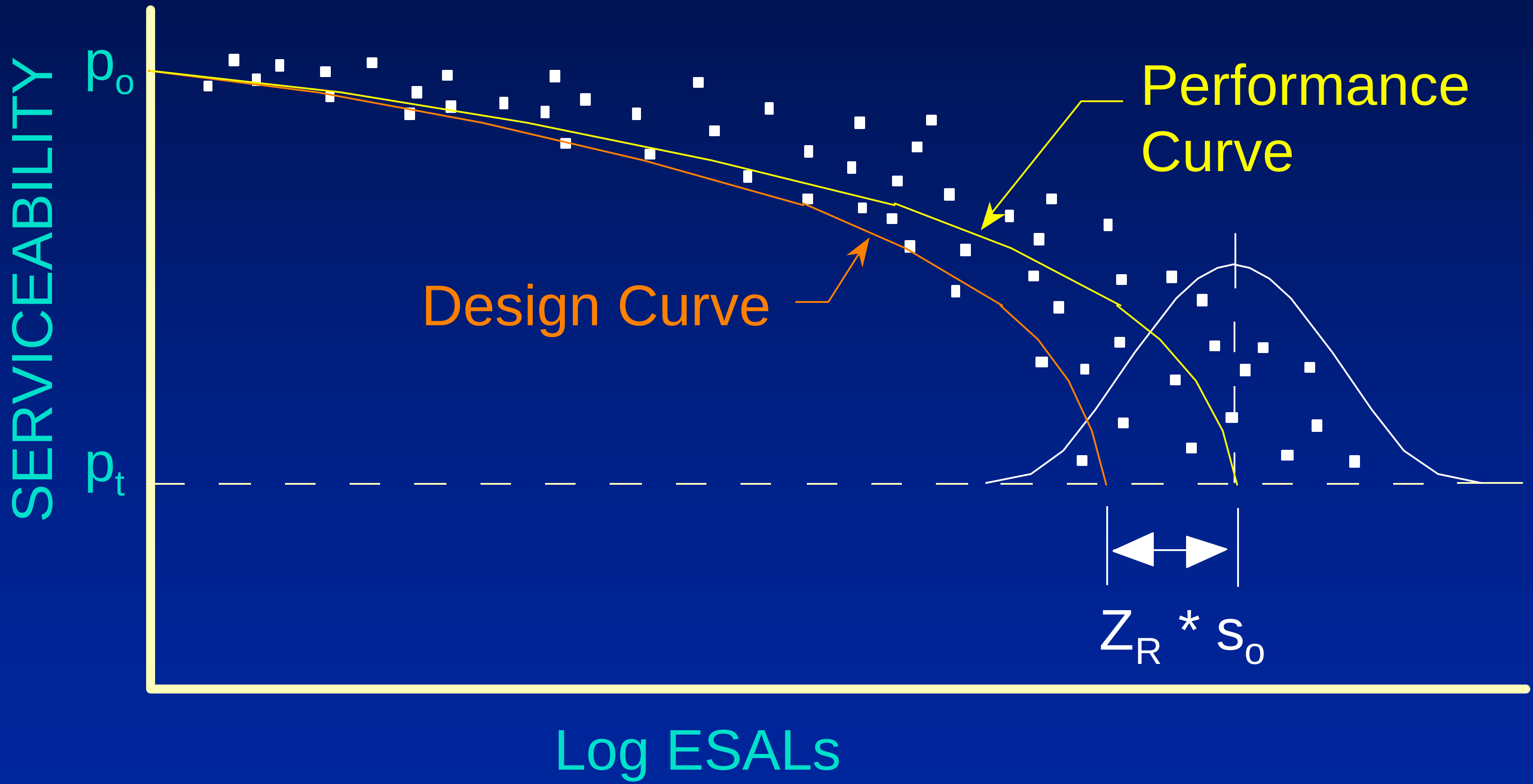
# AASHTO DESIGN
# Reliability

The statistical factors that influence pavement performance are:

- RELIABILITY, R
  - The statistical probability that a pavement will meet its design life.

- STANDARD DEVIATION, so
  - The amount of statistical error present in the design equations resulting from variability in materials, construction, traffic, etc.

# AASHTO DESIGN
## Reliability

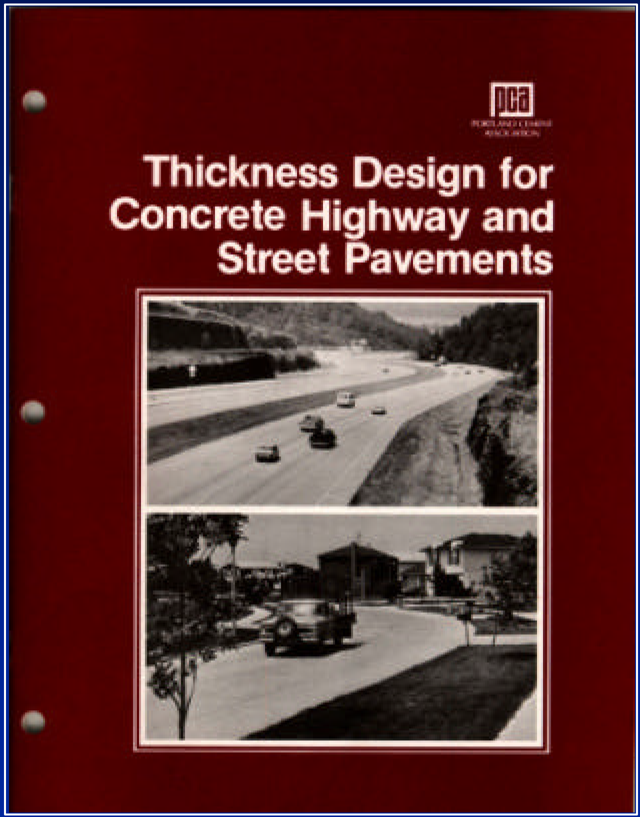



WinPAS

# PCAPAV Design Procedure

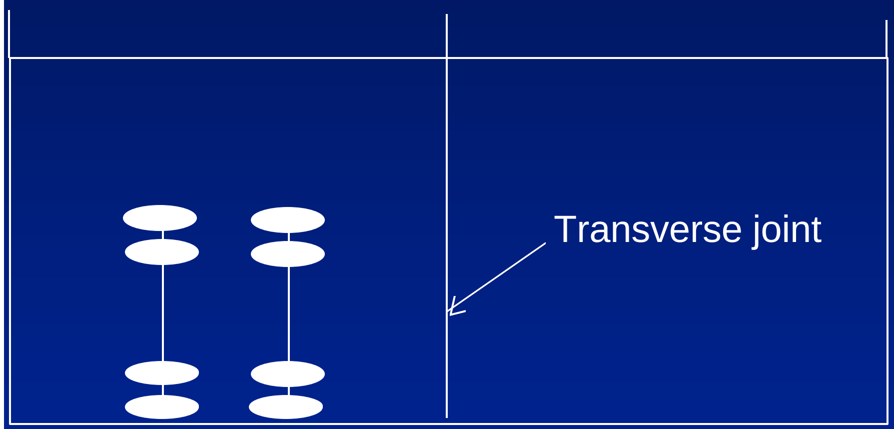
## Design Basics

- Mechanistic stress analysis
- Calibrated to field tests, test roads
- Control criteria can be either:
  - Fatigue (cracking)
  - Erosion (pumping)
- Available computer program (*PCAPAV)*



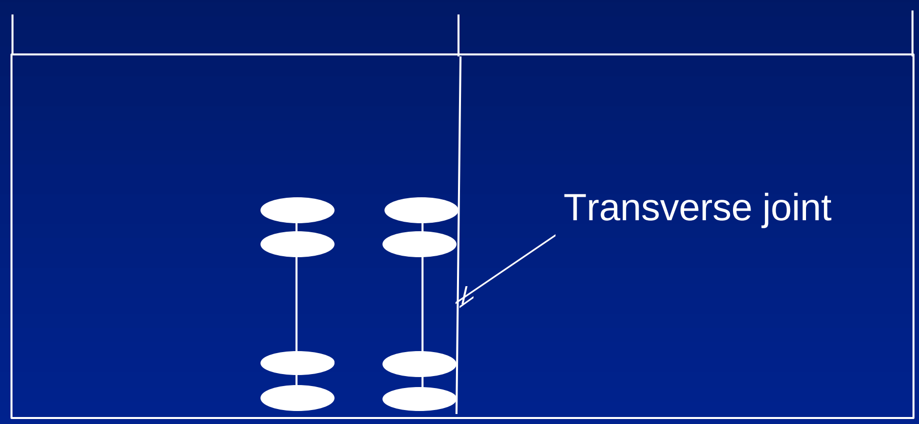
# Critical Loading Positions

## Fatigue




- Midslab loading away from transverse joint produces critical edge stresses

## Erosion




- Corner loading produces critical pavement deflections

# Differences Between Design Procedures

- Traffic Classification:
  - AASHTO - uses 18-kip ESALs
  - PCA - uses axle load distribution
- Reliability
  - AASHTO - Reliability
  - PCA - Load Safety Factors
- Drainage

# PCAPAV Design

Two design criteria:

- Fatigue
  - Keeps pavement stresses due to repeated loads within safe limits
- Erosion
  - Limits the effects of pavement deflections at edges, joints and corners.

# PCAPAV Design Procedure

## Design Factors

- Concrete Properties
  - Flexural strength (modulus of rupture)
- Subgrade Strength, or subgrade-subbase combination
  - modulus of subgrade reaction, k-value
- Weights, frequencies, and types of truck axle loads
- Load Transfer
- Load Safety Factor
- Design Period

# PCAPAV Design
## 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.
  - Axle loads of trucks

# PCAPAV Design

## Traffic

- Axle loads Distribution
  - The number of single and tandem axles over the design period
  - Expressed as Axles per 1000 trucks
  - Does not include panel and pickup trucks and other four-tire vehicles.

| Axle load Kips | Axles/1000 Trucks | Axles in design period |
|---|---|---|
| **Single Axles** | | |
| 28-30 | 0.58 | 6,310 |
| 26-28 | 1.35 | 14,690 |
| 24-26 | 2.77 | 30,140 |
| 22-24 | 5.92 | 64,410 |
| 20-22 | 9.83 | 106,900 |
| 18-20 | 21.67 | 235,800 |
| 16-18 | 28.24 | 307,200 |
| 14-16 | 38.83 | 422,500 |
| 12-14 | 53.94 | 586,900 |
| 10-12 | 168.85 | 1,837,000 |
| **Tandem Axles** | | |
| 48-52 | 1.96 | 21,320 |
| 44-48 | 3.94 | 42,870 |
| 40-44 | 11.48 | 124,900 |
| 36-40 | 34.27 | 372,900 |
| 32-36 | 81.42 | 885,800 |
| 28-32 | 85.54 | 930,700 |
| 24-28 | 152.23 | 1,656,000 |
| 20-24 | 90.52 | 984,900 |
| 16-20 | 112.81 | 1,227,000 |
| 12-16 | 124.69 | 1,356,000 |

# PCAPAV Design
## Traffic

### Traffic Categories

| | Two-way ADTT | Category | LSF |
|---|---|---|---|
| Light Residential | 3 | LR | 1.0 |
| Residential<br>Rural & secondary rds. | 10 - 30 | 1 | 1.0 |
| Collector streets<br>Rural & secondary rds.<br>(heavy trucks) | 50 - 500 | 2 | 1.1 |
| Minor Arterial Sts.<br>Primary roads | 300 - 600 | 2 | 1.2 |
| Major Arterial Sts. | 700 - 1500 | 3 | 1.2 |

# PCAPAV Design
## Load Safety Factors

Recommended values

- Interstate, interprovincial, multilane projects
  - LSF = 1.2.
- Highways and arterial streets
  - LSF = 1.1
- Roads, residential streets, and other streets that carry small volumes of truck traffic
  - LSF = 1.0

**PCAPAV**

# PCAPAV Design
## Simplified Procedure

- Designs presented in Tabular Form
  - Traffic
    - Type of road
    - Axle-load category (for the road type)
    - Avg. daily truck traffic
    - Probable maximum truck weights
  - Subgrade and Subbase
  - Dowels & slab edge support
  - Concrete strength

# PCAPAV Design
## Simplified Procedure

**No Dowels - No edge support**

| Foundation Support, k, MPa/m | | 40 | | | 80 | | |
|---|---|---|---|---|---|---|---|
| Flexural Strength, MPa | | 3.8 | 4.1 | 4.5 | 3.8 | 4.1 | 4.5 |
| Light Resident. | 2-way ADTT = 3 | 150 mm | 140 | 140 | 140 | 125 | 125 |
| Residential Rural & Sec. Rd. | ADTT = 10 | 165 | 150 | 140 | 150 | 140 | 140 |
| | 20 | 165 | 150 | 150 | 150 | 140 | 140 |
| | 50 | 175 | 165 | 150 | 150 | 150 | 140 |
| Collector Rural & sec. Rd. | ADTT = 50 | 190 | 190 | 175 | 175 | 165 | 165 |
| | 100 | 200 | 190 | 175 | 175 | 175 | 165 |
| | 500 | 215 | 215 | 190 | 190 | 175 | 175 |
| Minor Arterial | ADTT = 300 | 215 | 200 | 200 | 200 | 190 | 175 |
| | 600 | 225 | 215 | 200 | 200 | 190 | 190 |

# PCAPAV Design

## Simplified Procedure

**No Dowels - With Edge Support**

| Foundation Support, k, MPa/m | | 40 | | | 80 | | |
|---|---|---|---|---|---|---|---|
| Flexural Strength, MPa | | 3.8 | 4.1 | 4.5 | 3.8 | 4.1 | 4.5 |
| Light Resident. | 2-way ADTT = 3 | 125 mm | 125 | 125 | 125 | 125 | 125 |
| Residential<br>Rural & Sec. Rd. | ADTT = 10 | 140 | 125 | 125 | 125 | 125 | 125 |
| | 20 | 140 | 140 | 125 | 125 | 125 | 125 |
| | 50 | 150 | 140 | 125 | 140 | 125 | 125 |
| Collector<br>Rural & sec. Rd. | ADTT = 50 | 165 | 150 | 160 | 150 | 140 | 140 |
| | 100 | 175 | 165 | 160 | 150 | 150 | 140 |
| | 500 | 175 | 175 | 160 | 165 | 150 | 150 |
| Minor Arterial | ADTT = 300 | 190 | 175 | 165 | 175 | 165 | 150 |
| | 600 | 190 | 190 | 175 | 175 | 165 | 165 |

# Typical Concrete Pavement Thickness

- Depends on traffic load, subgrade, and climate.
  - City streets, secondary roads, and small airports
    - 100 to 175 mm (4 to 7 in.)
  - Primary roads and interstate highways
    - 175 to 280 mm (7 to 12 in.)
  - Large airports
    - 200 to 460 mm (8 to 18 in.)

# 1986-93 RIGID PAVEMENT DESIGN

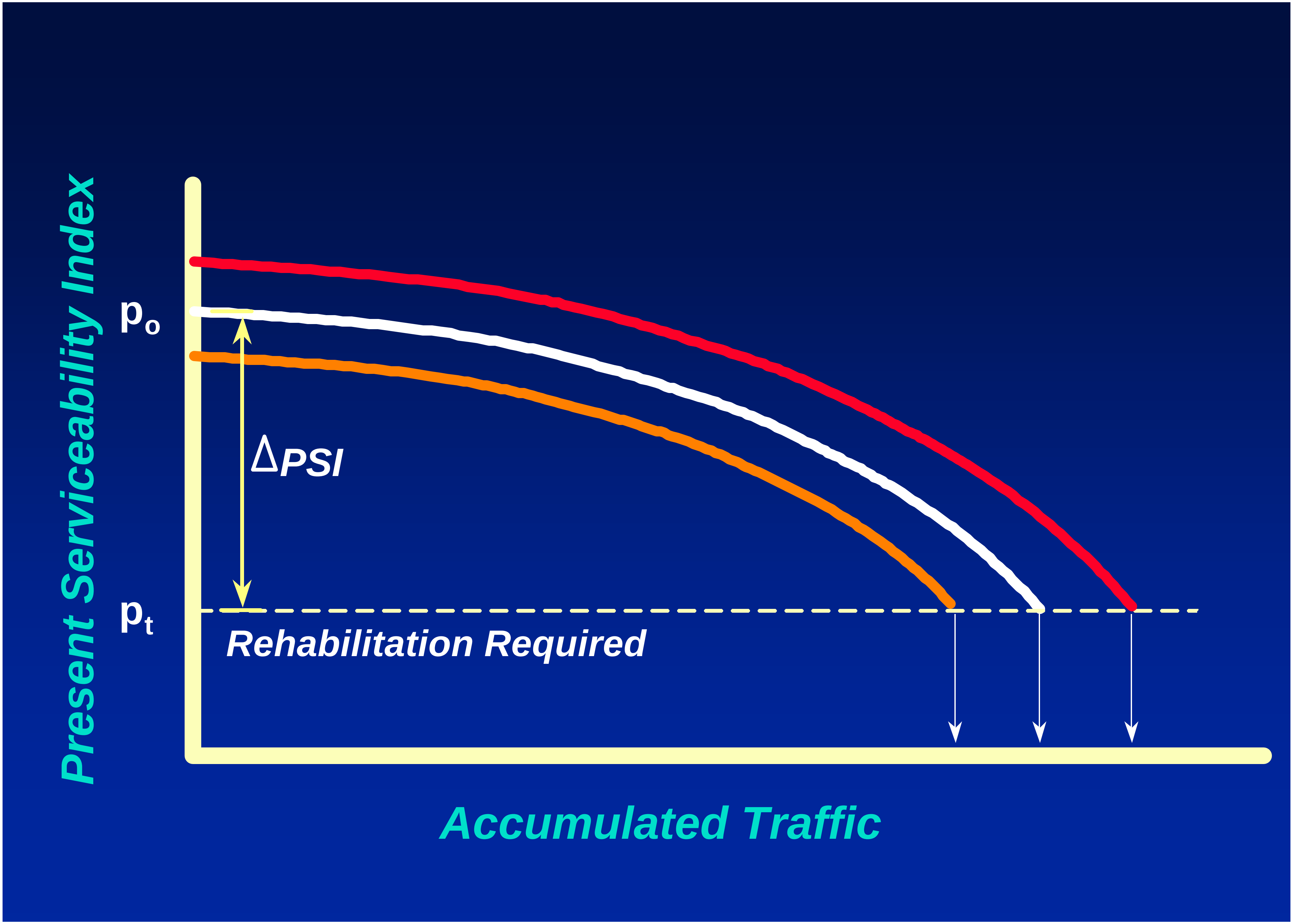
Factors Affecting Rigid Pavements

- 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, $S_o$)

# AASHTO DESIGN
# Serviceability

**Serviceability -**
the pavement's ability to serve the type of traffic (automobiles and trucks) that use the facility

Present Serviceability Index (PSI)



Present Serviceability Index
$p_o$
$\Delta_{PSI}$
$p_t$
Rehabilitation Required
Accumulated Traffic

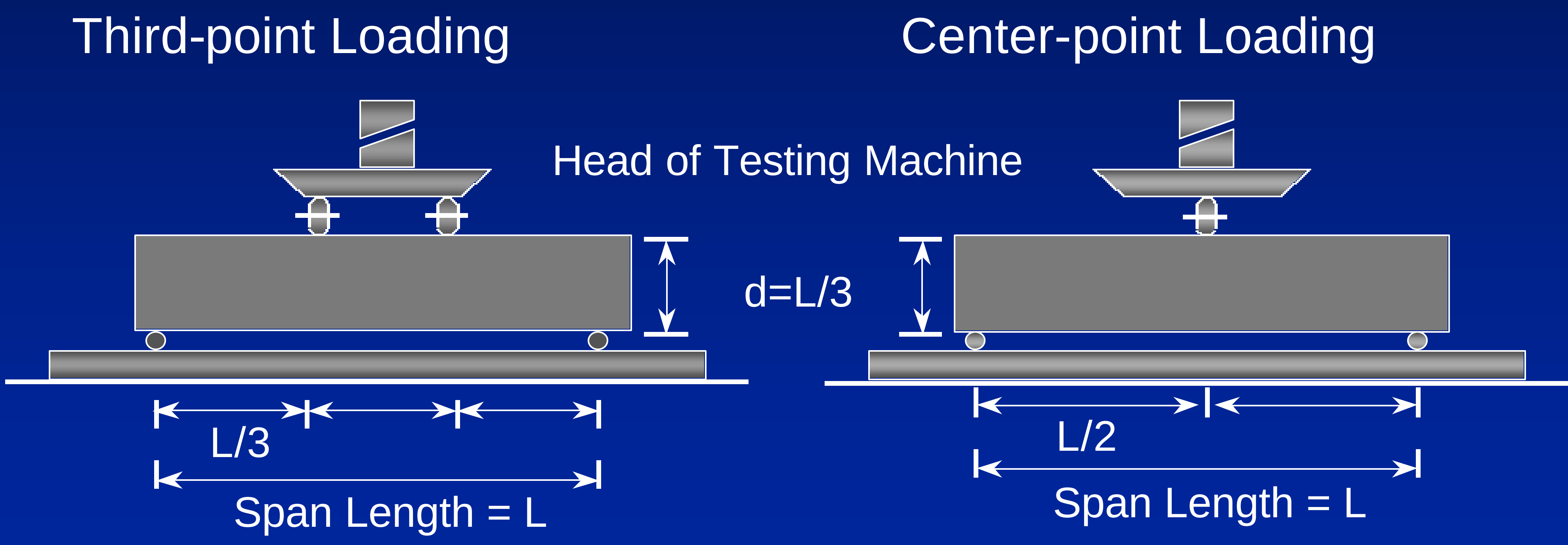
# AASHTO DESIGN
## Concrete Properties

There are two concrete properties that influence pavement performance

- Flexural Strength (Modulus of Rupture), $S'_c$
  - Average 28-day strength
  - 3rd-Point Loading
- Modulus of Elasticity, $E_c$

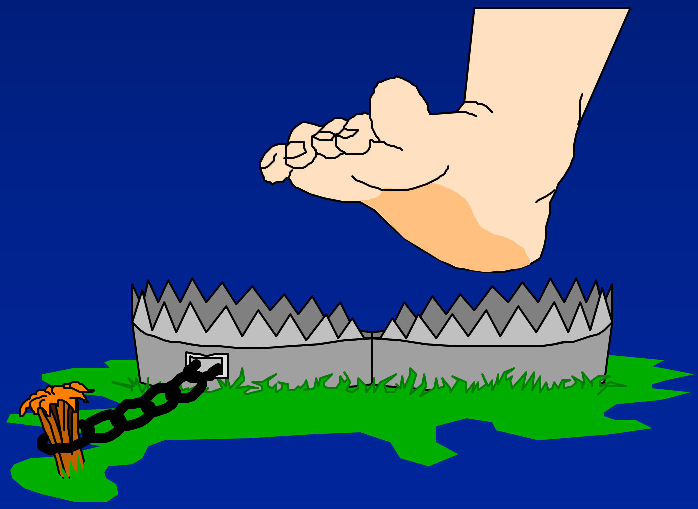
# AASHTO DESIGN
## Concrete Properties

Flexural Strength ($S'_c$) Determination



# AASHTO DESIGN
## Concrete Properties

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



**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**

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

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

**$S'c_{design} = 614$ psi**

# AASHTO DESIGN
## Concrete Properties

Modulus of Elasticity

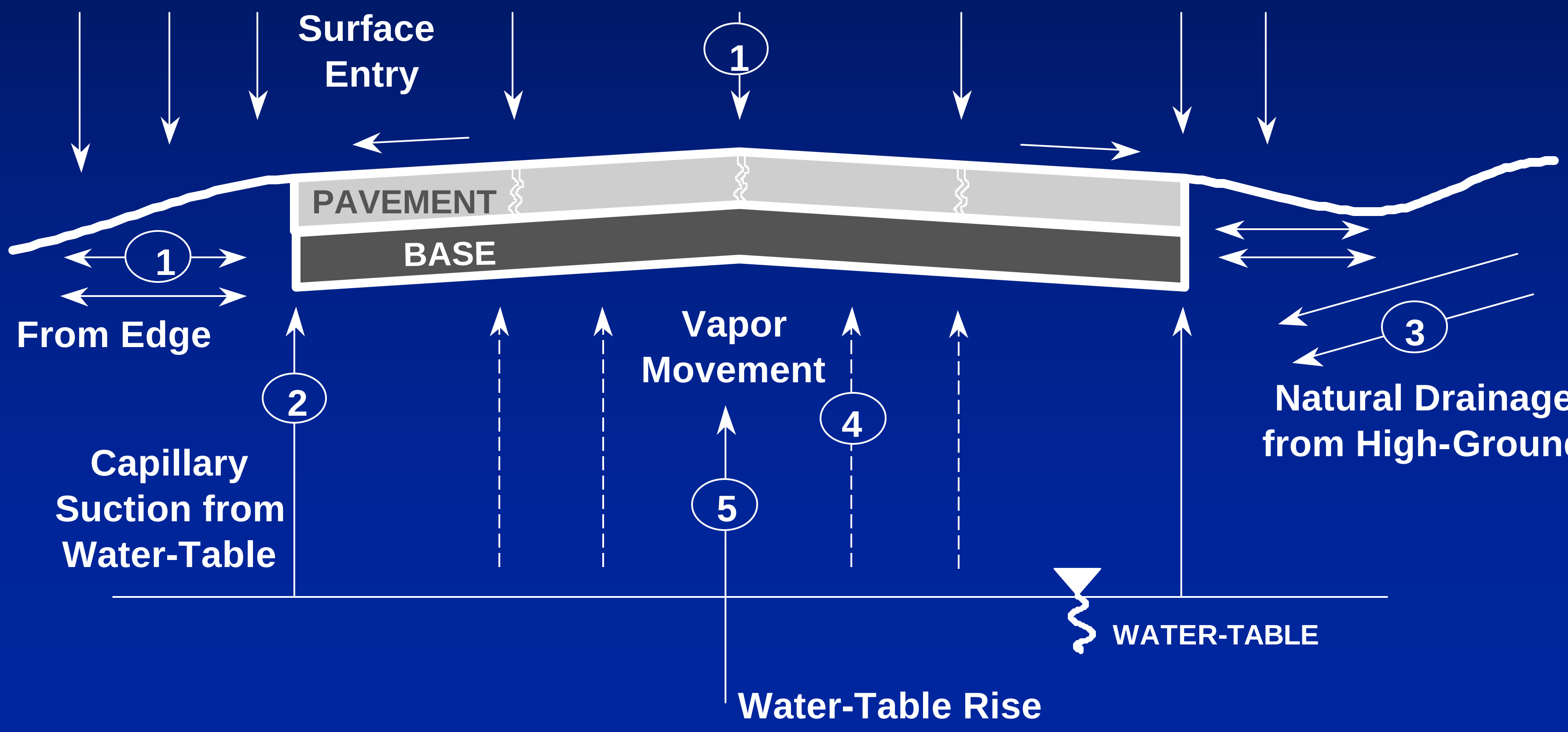
$E_c = 6750\ S'_c$

$E_c = 57{,}000\ (f'_c)^{0.5}$

| Flexural Strength | Modulus of Elasticity |
|---|---|
| 600 psi | 3,900,000 psi |
| 650 psi | 4,200,000 psi |
| 700 psi | 4,600,000 psi |

# AASHTO DESIGN
## Drainage , $C_d$

Avenues for water entry



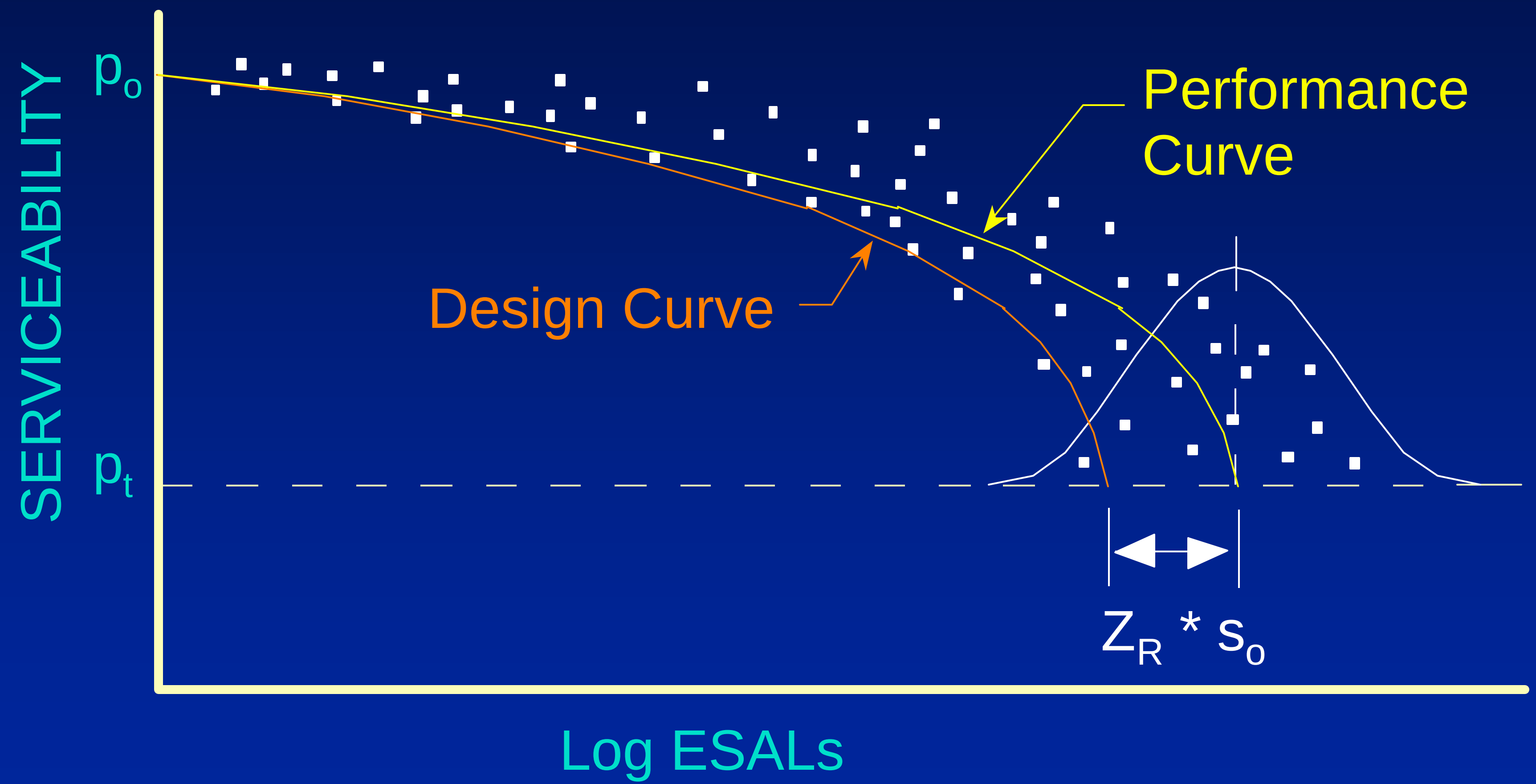
# AASHTO DESIGN
## Reliability

The statistical factors that influence pavement performance are:

- RELIABILITY, R - The statistical probability that a pavement will meet its design life.

- STANDARD DEVIATION, $s_o$ -The amount of statistical error present in the design equations resulting from variability in materials, construction, traffic, etc.

# AASHTO DESIGN
## Reliability

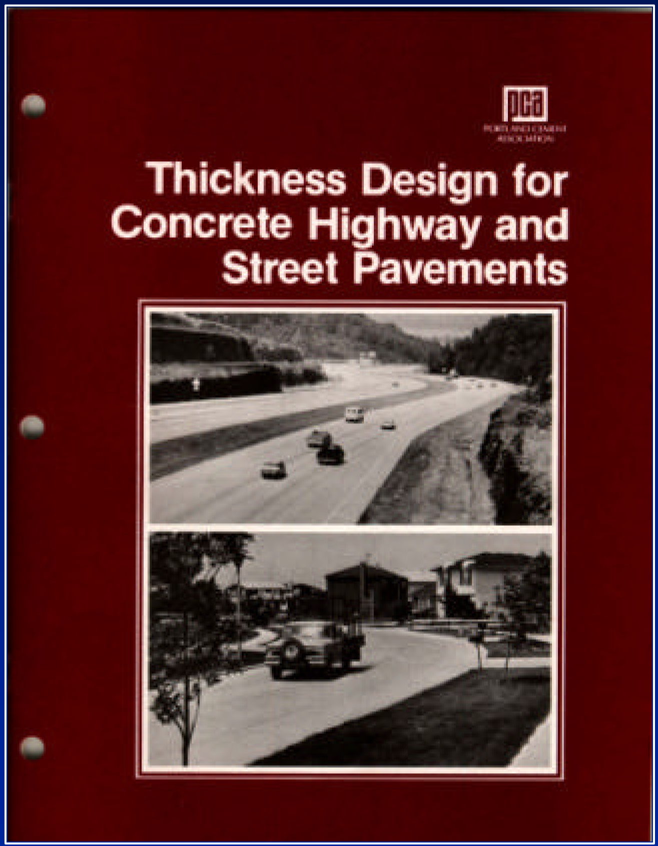



WinPAS

# PCAPAV Design Procedure

## Design Basics

- Mechanistic stress analysis
- Calibrated to field tests, test roads
- Control criteria can be either:
  - Fatigue (cracking)
  - Erosion (pumping)
- Available computer program (*PCAPAV)*



# Differences Between Design Procedures

- Traffic Classification:
  - AASHTO - uses 18-kip ESALs
  - PCA - uses axle load distribution
- Reliability
  - AASHTO - Reliability
  - PCA - Load Safety Factors
- Drainage
  - PCA does not include

# PCAPAV Design

Two design criteria:

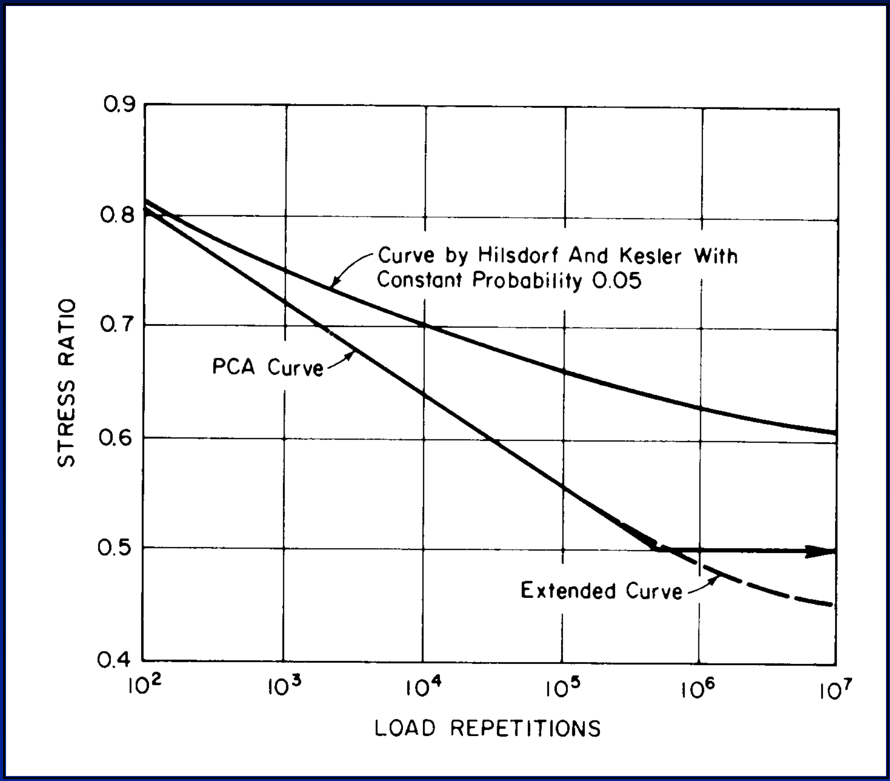
- Fatigue
  - Keeps pavement stresses due to repeated loads within safe limits
- Erosion
  - Limits the effects of pavement deflections at edges, joints and corners.

# Fatigue Analysis

- Performed for edge stresses (critical stresses)
- Based on stress ratio

$$SR = \frac{\text{Equivalent Flexural Stress}}{\text{28-Day Modulus of Rupture}}$$

- Fatigue not consumed by repetitions of one load is available for repetitions of other loads.



# Fatigue Analysis

- Allowable number of load repetitions for each axle group is determined from nomographs
- % Fatigue is calculated for each axle group

$$\% \text{ Fatigue} = \frac{\text{Expected repetitions}}{\text{Allowable repetitions}}$$

- Total fatigue consumed should not exceed 100%.

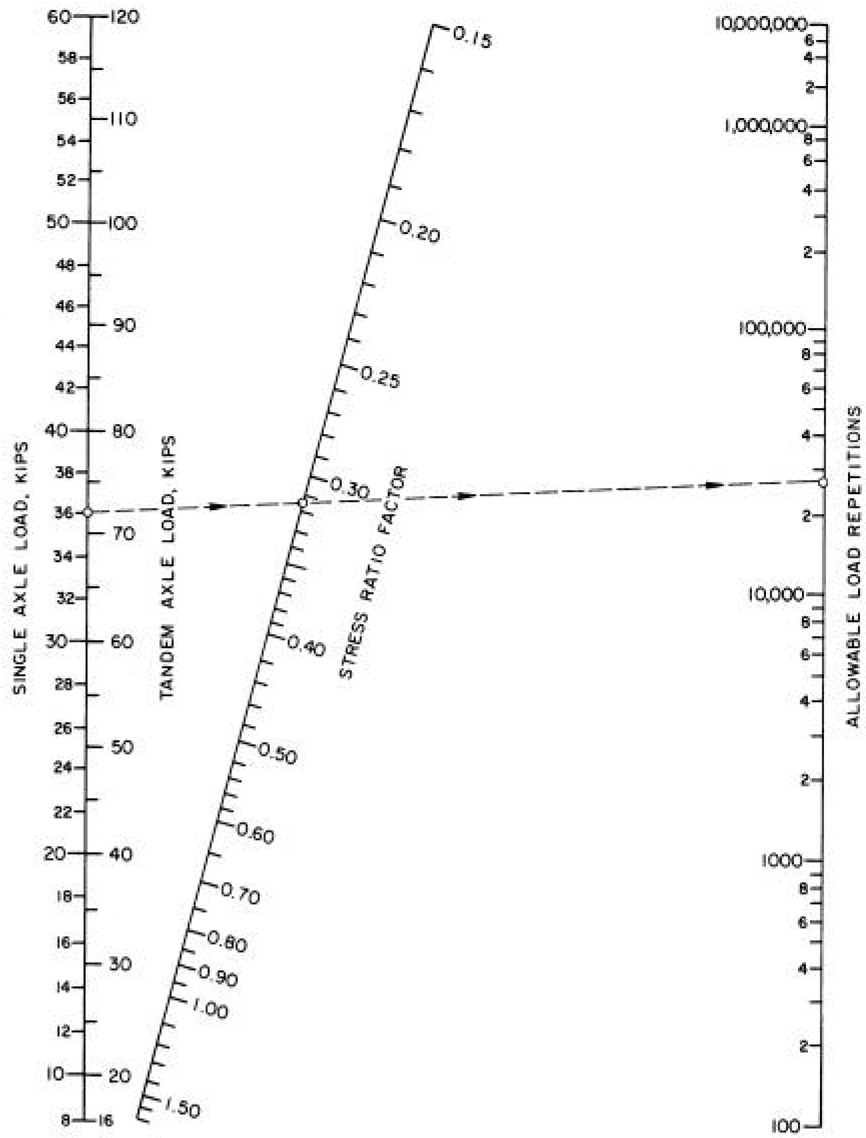



Fig. 5. Fatigue analysis—allowable load repetitions based on stress ratio factor (with and without concrete shoulder).

# Erosion Analysis

- Repetitions of heavy axle loads cause:
  - pumping; erosion of subgrade, subbase and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints.
- Erosion is a function of Power, or rate of work.

$$\text{Power} = \frac{\text{corner deflection } (w) * \text{pressure } (p) * \text{area}}{\text{duration of deflection.}}$$

- A thin pavement with its shorter deflection basin receives a faster load punch than a thicker slab.

# Erosion Analysis

- Performed for corner deflections (critical deflections)
- Erosion factor is determined from tables
- Allowable number of load repetitions for each axle group is determined from nomographs
- Erosion Damage is calculated for each axle group

$$\% \text{ Erosion Damage} = \frac{\text{Expected repetitions}}{\text{Allowable repetitions}}$$

- Total erosion damage from all axle groups should be less than 100%

# PCAPAV Design

## Design controlled by:

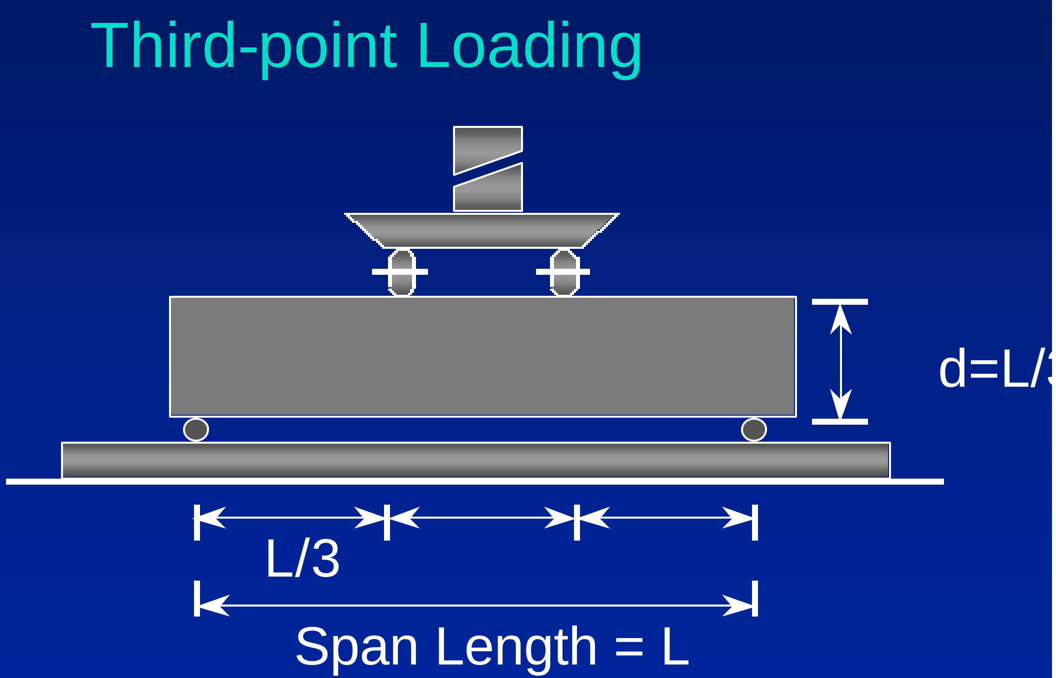
- Fatigue usually controls design of light-traffic pavements
  - Single-axles usually cause more fatigue damage
- Erosion usually controls design of undoweled medium- and heavy-traffic pavements
  - Tandem-axles usually cause more erosion damage

# PCAPAV Design Procedure

- Selection of an adequate thickness is dependent upon the choice of other design features:
  - Jointing system
  - Shoulder type
  - Subbase type

# PCAPAV Design Procedure
## Concrete Properties

- Flexural Strength (Modulus of Rupture),
  - Avg. 28-day strength in 3rd-point loading
- Other Factors
  - Fatigue Properties
  - Concrete Strength Gain with Age



# PCAPAV Design

## Concrete Properties

Comparison of $f'_c$, MR, and Required Thickness

| Compressive Strength | Third Point Flexural Strength | Effect on Slab Thickness |
|---|---|---|
| 3000 psi | 450 - 550 psi | 7.0 in |
| 4000 psi | 510 - 630 psi | 6.5 in. |
| 5000 psi | 570 - 710 psi | 6.0 in. |

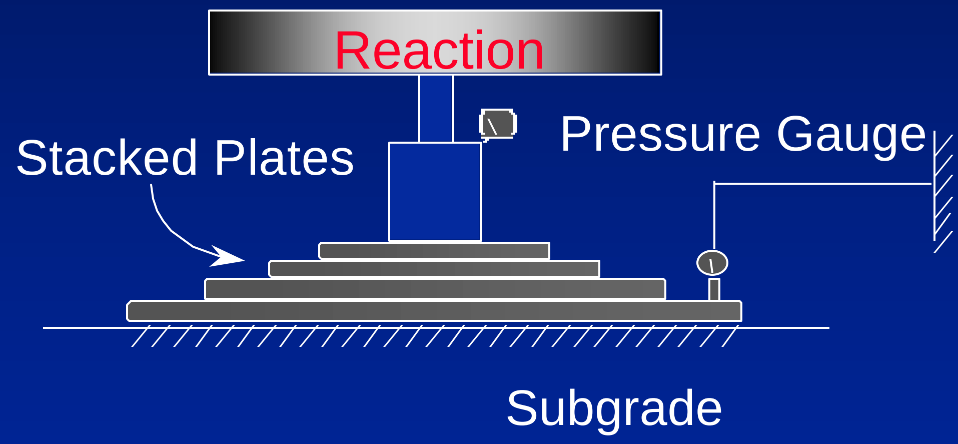
# PCAPAV Design
## Subgrade Properties

Modulus of Subgrade Reaction, k-value

$$k = \frac{\text{Plate load on subgrade}}{\text{Plate deflection on subgrade}}$$

$$k = \frac{5.0 \text{ psi}}{0.5 \text{ in}} = 100 \text{ psi / in.}$$

Plate-Load Test



# PCAPAV Design
## 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.
- Lean concrete subbases increases k-value.

# PCAPAV Design
## Subgrade Properties

Comparison of Soil Types and k-value

| k-value | Type of Soil | Remarks |
|---|---|---|
| 100 psi/in. | Silts and clays | Satisfactory |
| 200 psi/in. | Sandy soils | Good |
| 300 psi/in. | Sand-gravels | Excellent |

## Effect of Untreated Subbase on k-value

| Subgrade k-value (psi/in) | Subbase k-value | | | |
|---|---|---|---|---|
| | 4 in. | 6 in. | 9 in. | 12 in. |
| 75 | 85 | 96 | 117 | 140 |
| 150 | 165 | 180 | 210 | 243 |
| 225 | 235 | 242 | 280 | 330 |
| 300 | 320 | 330 | 367 | 430 |

## Effect of Cement-treated Subbase on k-value

| Subgrade k-value (psi/in) | Subbase k-value | | | |
|---|---|---|---|---|
| | 4 in. | 6 in. | 9 in. | 12 in. |
| 75 | 220 | 294 | 386 | 496 |
| 150 | 367 | 477 | 680 | 845 |
| 225 | 514 | 698 | 900 | -- |

# PCAPAV Design
## Subgrade Properties

### Effect of Untreated Subbase on k-value

| Subgrade k-value (psi/in) | Subbase k-value | | | |
|---|---|---|---|---|
| | 4 in. | 6 in. | 9 in. | 12 in. |
| 75 | 85 | 96 | 117 | 140 |
| 150 | 165 | 180 | 210 | 243 |
| 225 | 235 | 242 | 280 | 330 |
| 300 | 320 | 330 | 367 | 430 |

# PCAPAV Design
## Subgrade Properties

Effect of Cement-treated Subbase on k-value

| Subgrade k-value (psi/in) | Subbase k-value 4 in. | 6 in. | 9 in. | 12 in. |
|---|---|---|---|---|
| 75 | 220 | 294 | 386 | 496 |
| 150 | 367 | 477 | 680 | 845 |
| 225 | 514 | 698 | 900 | -- |

# PCAPAV Design
## Design Period

- 20 to 35 years is commonly used
- Shorter or longer design period may be economically justified in some cases
  - A special haul road to be used for only a few years.

# PCAPAV Design
## 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.
  - Axle loads of trucks

# PCAPAV Design

## Traffic

- Axle loads Distribution
  - The number of single and tandem axles over the design period
  - Expressed as Axles per 1000 trucks
  - Does not include panel and pickup trucks and other four-tire vehicles.

| Axle load kN | Axles/1000 Trucks | Axles in design period |
|---|---|---|
| **Single Axles** | | |
| 125-133 | 0.58 | 6,310 |
| 115-125 | 1.35 | 14,690 |
| 107-115 | 2.77 | 30,140 |
| 97.8-107 | 5.92 | 64,410 |
| 88.8-97.8 | 9.83 | 106,900 |
| 80.0-88.8 | 21.67 | 235,800 |
| 71.1-80.0 | 28.24 | 307,200 |
| 62.2-71.1 | 38.83 | 422,500 |
| 53.3-72.2 | 53.94 | 586,900 |
| 44.4-53.3 | 168.85 | 1,837,000 |
| **Tandem Axles** | | |
| 213-231 | 1.96 | 21,320 |
| 195-213 | 3.94 | 42,870 |
| 178-195 | 11.48 | 124,900 |
| 160-178 | 34.27 | 372,900 |
| 142-160 | 81.42 | 885,800 |
| 125-142 | 85.54 | 930,700 |
| 107-125 | 152.23 | 1,656,000 |
| 88.8-107 | 90.52 | 984,900 |
| 71.1-88.8 | 112.81 | 1,227,000 |
| 53.3-71.1 | 124.69 | 1,356,000 |

# PCAPAV Design
## Traffic

### Traffic Categories

| | Two-way ADTT | Category | LSF |
|---|---|---|---|
| Light Residential | 3 | LR | 1.0 |
| Residential<br>Rural & secondary rds. | 10 - 30 | 1 | 1.0 |
| Collector streets<br>Rural & secondary rds.<br>(heavy trucks) | 50 - 500 | 2 | 1.1 |
| Minor Arterial Sts.<br>Primary roads | 300 - 600 | 2 | 1.2 |
| Major Arterial Sts. | 700 - 1500 | 3 | 1.2 |

# PCAPAV Design
## Load Safety Factors

### Recommended values

- Interstate, interprovincial, multilane projects
  - LSF = 1.2.
- Highways and arterial streets
  - LSF = 1.1
- Roads, residential streets, and other streets that carry small volumes of truck traffic
  - LSF = 1.0

# PCAPAV Design

## Other Loads

### Warping and Curling of Concrete

- Warping - moisture variations.
  - Creates compressive restraint stresses in the slab bottom.
- Curling - temperature variations.
  - During the day, the top surface is warmer than the bottom and stresses develop at the slab bottom.
  - During the night, the top is colder and stresses develop at the slab surface.
- Assumed to cancel each other out.

# PCAPAV Design

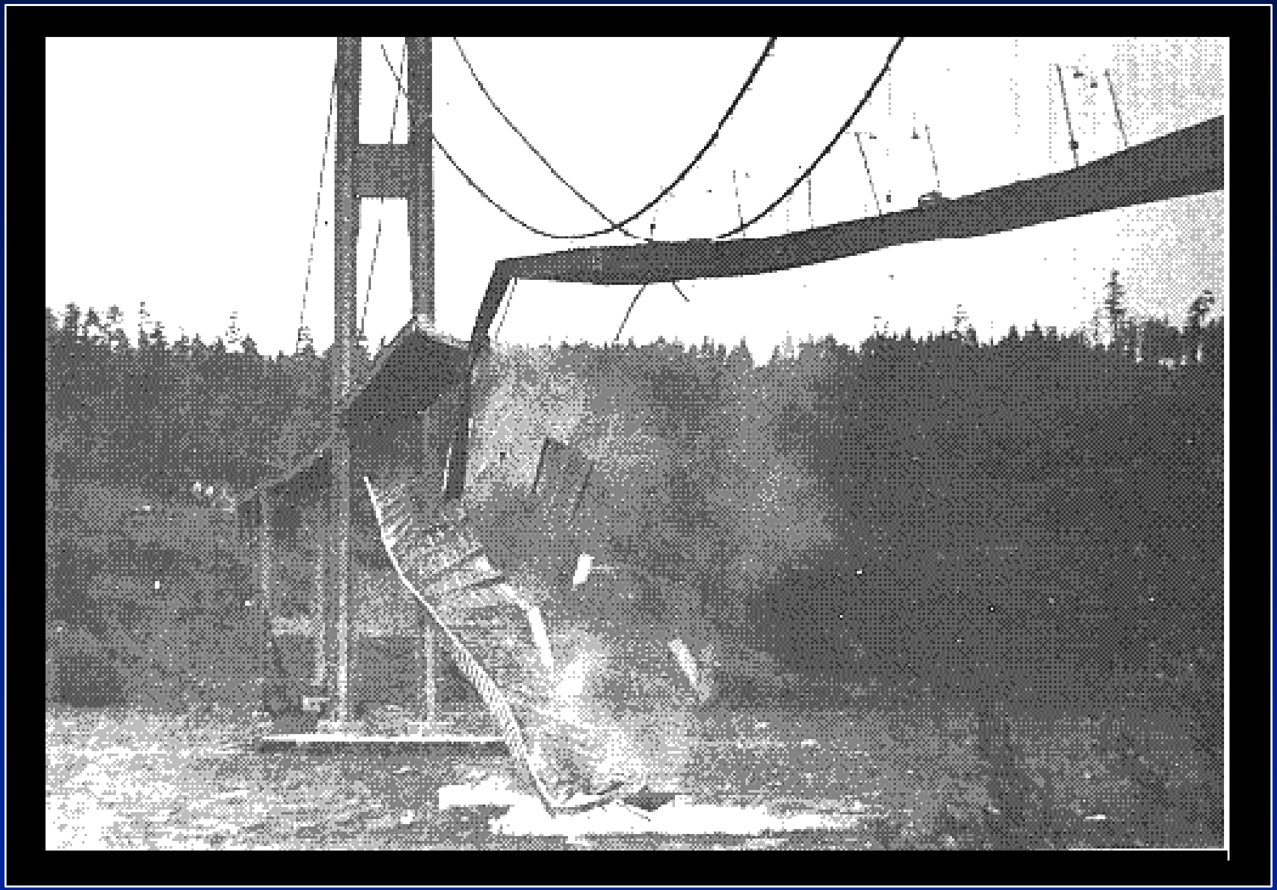
## Design Procedures

- Rigorous
  - Detailed axle-load-distribution data is available
- Simplified
  - Axle-Load Data Not Available
  - Designer does not directly use the axle-load data
  - Tabular form

# PCAPAV Design
## Rigorous Procedure

- Requires the following design factors:
  - Type of joint and shoulder
  - Concrete flexural strength (MR) at 28 days
  - k-value of subgrade or subgrade-subbase combination
  - Load safety factor (LSF)
  - Axle-load distribution
  - Expected number of axle-load repetitions
- Use PCAPAV Computer Program

# Design Tip



Don't Drink and Design