International Road Roughness Experiment (IRRE): Precursor to International Roughness Index (IRI)

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CEE 08563
Objectives

- Need for Roughness Measurement
- International Road Roughness Experiment (IREE)
- Findings
- International Roughness Index (IRI)
- Limitations
- Conclusions
- Questions
Need for Roughness Experiment

(A) Planar Surface  (D) Megatexture
(B) Microtexture  (E) Unevenness
(C) Macrotexture  (F) Vertical Profile
Need for Roughness Measurement

• Road performance measure
• Roughness weighted heaviest in PSI calculation
• Variation in surface elevation that induces vibrations in traversing vehicles.
• Dynamic wheel loads = deterioration
International Road Roughness Experiment

• Funded by the World Bank
• Performed in Brazil in 1982
• Brazil, England, France, United States, and Belgium
• Correlation and calibration of existing materials and indices
IRRE Site Determination

• 49 test sites in Brasilia
  – 13 Asphaltic Concrete
  – 12 Surface Treatment
  – 12 Gravel Roads
  – 12 Earth Roads
• Prerated with Opala-Maysmeter
• Six levels of roughness per road type
• Two sections having each level of roughness
IRRE Equipment
IRRE Equipment
IRRE Equipment
IRRE

- **Tangent roads**
  - 320 meters long

- **Test Speeds**
  - 20, 32, 50, and 80 km/hr

- **Repeatability**
  - RTRRMSs made five runs per speed
  - Trailers made three runs per speed per wheeltrack

- **Sequence**
  - Randomized within limitations
IRRE

- GEIPOT storage and repair garage central location
- Allowed shock absorber and tire temperature to stabilize
- Unpaved road sites still had unpaved roads for last 10 minutes so RTRRMSs never run “cold”
- Soiltest BPR Roughometer always towed to site
Findings

• Each RTRRMS produced five or six repeat roughness measurements for each of the 49 test sections for each of the three or four measurement speeds.

• Choice of road meter not of primary importance.

• Critical factor is methodology adopted to obtain and analyze roughness data.
Findings

• Spectral Analyses of Road Profile
• Correlation of Profile-Based Numerics
• Correlation of RTRRMS Numerics
• Correlation of Profile-Based Numerics with RTRRMS Numerics
• Calibration Requirements
IRI

• Criteria for the IRI
• Time Stable
  – IRI be mathematical function of longitudinal road profile and not standardized hardware
• Transportable
  – Manual methods
  – Present and future high-speed profilometers
• Relevance
  – Differences between two units more so by procedure than equipment
IRI

• Relevance
  – Two fundamental characteristics of RTRRMSs
    • Operating speed
    • Single versus two tracks

• Validity
  – Same roughness numeric for same road even with different types of RTRRMSs
  – Analysis must fit common measurement methods directly for profilometric methods
IRI

• Speed
  – Roughness varies with speed implies need for standard
  – IREE data supports 50 km/hr
  – User demand defined standard speed at 80 km/hr

• Single or two-track RTRRMS
  – Single-track chosen because of advantages
IRI

- Calibration reference selected as RARS_{80} Numeric
- Compatible with all profilometers
- Excellent correlation with subjective ratings (even though rejected as a standard)
- Can be viewed as time-stable measure indicative of public opinion
IRI

- Assigned over first 11m
  - \( Z'_1 = Z'_3 = (Y_a - Y_1)/11 \)
  - \( Z'_2 = Z'_4 = 0 \)
  - \( a = \frac{11}{dx} + 1 \)
IRI

• Calculation

- \( Z_1 = s_{11} \times Z'_1 + s_{12} \times Z'_2 + s_{13} \times Z'_3 + s_{14} \times Z'_4 + P_1 \times Y' \)
- \( Z_2 = s_{21} \times Z'_1 + s_{22} \times Z'_2 + s_{23} \times Z'_3 + s_{24} \times Z'_4 + P_2 \times Y' \)
- \( Z_3 = s_{31} \times Z'_1 + s_{32} \times Z'_2 + s_{33} \times Z'_3 + s_{34} \times Z'_4 + P_3 \times Y' \)
- \( Z_4 = s_{41} \times Z'_1 + s_{42} \times Z'_2 + s_{43} \times Z'_3 + s_{44} \times Z'_4 + P_4 \times Y' \)

• Where

- \( Y' = \frac{(Y_i - Y_{i-1})}{dx} = \text{slope} \)
- \( Z'_j = Z_j \) from previous position \( j=1\ldots4 \)
IRI

• Recitified Slope
  \[ RS_i = |Z_3 - Z_1| \]

• IRI statistic
  \[ IRI = \left[ \frac{1}{(n+1)} \right] \times \sum_{i=z}^{n} RS_i \]
IRI

IRI (m/km) (in/mi)

- erosion gulleys and deep depressions
- frequent shallow depressions, some deep
- frequent minor depressions
- surface imperfections
- new pavements
- airport runways and superhighways
- older pavements
- maintained unpaved roads
- rough unpaved roads

speed of normal use
- 30 km/h (19 mph)
- 50 km/h (31 mph)
- 60 km/h (37 mph)
- 80 km/h (50 mph)
- 100 km/h (62 mph)

0 = absolute perfection

Computer
Speed/Distance pick-up
Accelerometer
Height relative to reference
IRI

• Classifications of Measurement Methods
• **Class 1**: Precision profiles
• **Class 2**: Other profilometric methods
• **Class 3**: IRI estimates from correlation equations
• **Class 4**: Subjective ratings and uncalibrated measures
Equipment Limitations

- Raw data reporting
- Calibration process tedious
- Test speed range
- Mandated test speed
  - Requires calibration for this speed
- No real-time data display
IRI Limitations

- Speed restrictions
- Traffic congestion
- Short section lengths
- Pavement treatments
- Numerous traffic signals
- Intersection treatments
Conclusions

• Correlated existing hardware
• Created calibration criteria
  – Reference (RARS$_{80}$)
  – Speed
  – Sites
• IRI
  – Stable
  – Transportable
  – Simple
Questions

• Why was the IRRE performed?

• Why is IRI a good method for measuring roughness?

• Why did the research team mobilize from a central location?
ASPHALT OVERLAYS
AND
PAVEMENT REHABILITATION

The Asphalt Institute
# Pavement Management Strategy

<table>
<thead>
<tr>
<th>Condition</th>
<th>Treatment</th>
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<tbody>
<tr>
<td>Deficient</td>
<td>Reconst./Rehab $1.5M/LM</td>
</tr>
<tr>
<td>4058 LM</td>
<td>Resurfacing $300K/LM</td>
</tr>
<tr>
<td></td>
<td>Preventive Maintenance $80K/LM</td>
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<tr>
<td>Fair</td>
<td>No Treatment</td>
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<tr>
<td>2985 LM</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>1244 LM</td>
<td></td>
</tr>
</tbody>
</table>
Procedure For Determining Present Serviceability Rating

1. Select a rating panel
2. Select rating sites
3. Compare tabulations

**Asphalt Overlay Design—Distress Index**

*y-axis*

Figure VII-1—Present Serviceability Rating (PSR) form

Asphalt Institute MS-17 1969
Figure 2. Illustration of the application of upper and lower benefit cutoff values on both decreasing and increasing condition indicators for the do-nothing case.
Figure 10.7 Different timing options for rehabilitation.

Figure 10.5 Types of treatments options considered in MYP.

Figure 1. Applying pavement treatments at the optimal time provides the most efficient use of funds to extend the life of the pavement.
Asphalt Institute Overlay Design Methods

• For flexible pavements there are two methods that AI developed for HMA and emulsified mixes

  – Effective Thickness \( (h_e) \)

  \[
  h_e = \sum_{i=1}^{n} h_i C_i E_i
  \]

  (Eq. 13.5)

  – Deflection \( (\delta_{rrd}) \)

    • Representative Rebound Method
Asphalt Institute Overlay Design Methods

• Effective Thickness ($h_e$)
  – Procedure 1 - for full depth asphalt only pavements
    » 3 steps
  – Procedure 2 – for full depth asphalt and layered pavement systems
    » 3 Steps

\[ h_e = \sum_{i=1}^{n} h_i C_i E_i \]  

(Eq. 13.5)
Asphalt Institute Overlay Design Procedure 1

• Effective Thickness \( (h_e) \)
  (Full Depth Asphalt Pavements)

  • Step 1
    – Input parameters
      • Initial Pavement Thickness \((h_i)\)
      • Conversion Factor \((C_i)\)
      • Equivalency Factor \((E_i)\)

  • Step 2
    – Knowing ESALs and Subgrade Resilient Modulus \((M_R)\), chart new pavement thickness \((h_n)\)

  • Step 3
    – For overlay thickness subtract effective thickness from new
      \[ h_{OL} = h_n - h_e \]  
      (Eq. 13.1)
Asphalt Institute Overlay Design Methods

• How were thickness conversion factors developed?

PSI of 3.3 Conversion Factor is 0.90

PSI of 2.5 Conversion Factor is 0.80

PSI of 1.5 Conversion Factor is 0.60

Figure 13.2 Conversion factors for full depth pavements. (After AI (1983).)
Example: A full-depth asphalt pavement consisting of a 2.5 inch HMA top layer and a 5 inch Type II emulsified asphalt base course is to be overlaid. The pavement PSI is 2.3. The Pavement PSI has been determined to be below its upper trigger point and above its lower acceptable trigger point in terms of PSI and age in years.

The existing pavement subgrade has a Resilient Modulus ($M_R$) of 10,000 psi and ESAL = $3 \times 10^6$. 

FHWA 1998
Asphalt Institute Overlay Design Procedure 1

• Determine effective thickness \((h_e)\) at time of analysis for each layer

\[
h_e = \sum_{i=1}^{n} h_i C_i E_i
\]  
(Eq. 13.5)

where: \(h_i\) = Initial layer thickness
\(C_i\) = Condition conversion factor
\(E_i\) = Equivalency factor
Asphalt Institute Overlay 
Design Procedure 1 – Step 1

To obtain C, input the PSI at the time of the proposed overlay. Here a PSI of 2.3 yields a C of 0.7

$$h_e = \sum_{i=1}^{n} h_i C_i E_i$$

To obtain E for each flexible layer, use the Table 13.2

<table>
<thead>
<tr>
<th>Material type</th>
<th>Equivalency factor (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot mix asphalt</td>
<td>1.00</td>
</tr>
<tr>
<td>Type I emulsified asphalt base</td>
<td>0.95</td>
</tr>
<tr>
<td>Type II emulsified asphalt base</td>
<td>0.83</td>
</tr>
<tr>
<td>Type III emulsified asphalt base</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Asphalt Institute Overlay
Design Procedure 1 – Step 1

\[
\begin{align*}
  h_e &= \sum_{i=1}^{n} h_i C_i E_i \\
  h_e &= \sum_{i=1}^{2} h_i C_i E_i \rightarrow (2.5 \times 0.7 \times 1.0) + (5.0 \times 0.7 \times 0.83) = 4.6''
\end{align*}
\]

Initial Height = 7.5”

Effective Height = 4.6”
Asphalt Institute Overlay Design Procedure 1 – Step 2

- Knowing ESALs and Subgrade Resilient Modulus ($M_R$) Chart New Pavement Thickness (Fig 11.11) to obtain new thickness ($h_n$).
  - The existing pavement subgrade has a Resilient Modulus ($M_R$) of 10,000 psi and ESAL = $3 \times 10^6$
Asphalt Institute Overlay
Design Procedure 1 – Step 2

Figure 11.11 Design chart for full-depth HMA (1 psi = 6.9 kPa, 1 in. = 25.4 mm). (After AI (1981a).)

\[ h_n = 10.6'' \]
Asphalt Institute Overlay Design Procedure 1 – Step 3

- Step 3  For overlay thickness subtract effective thickness from new

\[ h_{OL} = h_n - h_e \]  

(Eq. 13.1)

\[ h_{OL} = 10.6" - 4.6" \]

\[ h_{OL} = 6" \]
Asphalt Institute Overlay
Design Procedure 2

• Effective Thickness Method
  (Full depth asphalt & composite layered pavement systems)

• Step 1
  – Input parameters (For each layer in system)
    • Initial Pavement Thickness \((h_i)\)
    • Conversion Factor \((C_i)\)

• Step 2
  – Result Step 1 and calculate overlay thickness (Figure 11.11)

\[
h_{OL} = h_n - h_e
\]
<table>
<thead>
<tr>
<th>Classification of material</th>
<th>Description of material</th>
<th>Conversion factors&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
</table>
| I                          | (a) Native subgrade in all cases.  
(b) Improved subgrade, predominantly granular materials, may contain some silt and clay but have P.I. of 10 or less.  
(c) Lime-modified subgrade constructed from high-plasticity soils, P.I. greater than 10. | 0.0 |
| II                         | Granular subbase or base, reasonably well-graded, hard aggregates with some plastic fines and CBR not less that 20. Use upper part of range if P.I. is 6 or less; lower part of range if P.I. is more than 6. | 0.1–0.2 |
| III                        | Cement or lime-fly ash stabilized subbases and bases constructed from low plasticity soils, P.I. of 10 or less. | 0.2–0.3 |
| IV                         | (a) Emulsified or cutback asphalt surfaces and bases that show extensive cracking, considerable raveling or aggregate degradation, appreciable deformation in the wheelpaths, and lack of stability.  
(b) Portland cement concrete pavements (including those under asphalt surfaces) that have been broken into small pieces 2 ft (0.6 m) or less in maximum dimension prior to overlay construction. Use upper part of range when subbase is present, lower part of range when slab is on subgrade.  
(c) Cement or lime-fly ash stabilized bases that have developed pattern cracking, as shown by reflected surface cracks. Use upper part of range when cracks are narrow and tight, lower part of range with wide cracks, pumping, or evidence of instability. | 0.3–0.5 |
| V                          | (a) Asphalt concrete surface and base that exhibit appreciable cracking and crack patterns.  
(b) Emulsified or cutback asphalt surface and bases that exhibit some fine cracking, some raveling or aggregate degradation, and slight deformation in the wheelpaths but remain stable.  
(c) Appreciably cracked and faulted portland cement concrete pavement (including such under asphalt surfaces) that cannot be effectively undersealed. Slab fragments, ranging in size from ap- | 0.5–0.7 |
Moore _ Presentation Question #1

Full Depth Asphalt Pavement

Question:

A full-depth asphalt pavement consisting of a 2.0 inch HMA top layer and a 6 inch Type III emulsified asphalt base course is to be overlaid. The pavement PSI is 2.5. The Pavement PSI has been determined to be below its upper trigger point and above its lower acceptable trigger point in terms of PSI and age in years. The existing pavement subgrade has a Resilient Modulus (MR) of 10,000 psi and ESAL = 4 x 10^6

Moore _ Presentation Question #2

Question:

How were the thickness conversion factors (y-axis) developed?

Figure 13.2 Conversion factors for full depth pavements. (After AI (1983).)
Asphalt Rubber Implementation in Pavements

Charles Cunliffe
Advanced Pavement Design and Analysis
Spring 2012
Outline

- Introduction
- Asphalt Rubber
  - Wet Process
  - Dry Process
- Common Uses
- Material Characteristics
- Summary
Introduction

- Automobile tires are becoming a growing waste material
  - Due to large volume and durability
- Approx. 290 million discarded annually in US

US Tire Waste 2003

- 77% Landfill/Stockpiled/illegally dumped
- 11% Recycled
- 5% Burned for fuel
- 3% Exported waste

(USEPA)
Civil Engineering Applications

- Reinforcement erosion control
- Reinforcing slopes
- Lightweight fill for retaining wall
- Rubberized Asphalt Concrete (RAC) Pavements
Crumb Rubber Modifier (CRM)

- Produced by grinding up whole scrap tires
  - Automobiles
  - Trucks
  - Buses
  - Tread buffings
- Ground to various gradations depending on intended use
- Used to “modify” asphalt concrete
Asphalt Rubber

- Rubberized Asphalt Concrete
- Rubber modification of asphalt concrete accomplished by:
  - Wet Process
    - Must meet ASTM D 6114
    - High Viscosity and Terminal Blend
      - Modify the asphalt binder with CRM
      - Then mix with aggregates
  - Dry Process
    - Portion of aggregate is replaced by CRM
Wet Process (ASTM)

- Composed of:
  - Asphalt Cement
  - Reclaimed tire rubber (CRM)
  - Additives

  - “the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles.”
Wet Process: High Viscosity

- Most widely used in:
  - California
  - Arizona
  - Florida
  - Texas
- Contains 18-22% CRM
- Particle sizes from #8 to #10 Max
- Mix temperature must be 400-425°F
- Interact Particles for designated period
  - Typically 45-60 minutes
Wet Process: No Agitation

- Most widely used in:
  - Arizona
  - Florida
  - Texas
  - California
- Contains from <5-15 % CRM
- Particle size ranges from 40 to 80 mesh top size
- Can also contain polymers
- Often called “No Agitation”
  - Does not require agitation to keep CRM evenly dispersed
Asphalt Cement and CRM interaction

- Material specific and depends on:
  - Asphalt Cement Source & Grade
  - Rubber Type/Source
  - Amount Of Rubber
  - Gradation Of Rubber
  - Interaction Time
  - Interaction Temperature
  - High Viscosity AR Binder
High Viscosity vs. Terminal Blend
Production of RAC using Wet Process

1. Waste tires ground to become
2. Bags of crumb rubber
3. Rubber is blended with asphalt
4. Aggregate bins
5. Aggregate is heated in drums
6. Asphalt/rubber blend is added to aggregate
7. Rubberized asphalt concrete is stored in silos
8. Trucks are filled and traveled to job site for paving

Credit: Arizona DOT, Better Roads graphic.
Dry Process

- Not used as commonly as Wet Process RAC
- Developed in Sweden in 1960’s
- Marketed as PlusRide (EnviroTire)
- Substitutes CRM 1 to 3% of aggregate in mix
  - Is mixed with aggregate first before mixing of binder
- CRM gradations range from $\frac{1}{4}”$ to #80
  - Replace part of the fine portion
Approved Materials

- Asphalt Cements
  - Depend on the climatic region
    - Hot climates: PG 64-16
    - Moderate climates PG 58-22
    - Cold climates PG 52-28

- Additives
  - Extender oils
  - High natural rubber (HNR)
  - Polymers
  - Anti-strip agents
Common Uses of Asphalt Rubber

• Spray Applications
  • Chip Seal
    • ARAM - Asphalt Rubber–Aggregate membrane
    • SAM - Stress Absorbing membrane

• Interlayer
  • SAMI - Stress Absorbing Membrane Interlayer
  • SAMI - R when rubber modified
  • ARMI - Asphalt rubber membrane interlayer
Common Uses of Asphalt Rubber

- Hot Mix Asphalt (HMA)
  - Gap graded mixes
  - Open graded mixes
  - Open graded high binder mixes
  - Dense graded mixes - Only with no agitation binders
- Mostly for overlays
  - Gap and open gradations most common
  - High viscosity (wet process)
Benefits of pavements using RAC

- Cost Effectiveness
  - More costly but thinner designs
  - Also reduces R & M
- Durability, Safety, and Noise Reduction
- Overlays for reducing reflective cracking
- Environmental Benefits
What makes Asphalt Rubber good?

- Thodesen (2009)
- Evaluated Current Modified Asphalt Binders Using the Multiple Stress Creep Recovery Test
  - Shortage of raw materials
  - Data has shown modified binders improve pavement performance
  - Analyzed both High Viscosity and Terminal Blend
  - Evaluate binder’s potential for permanent deformation
## Binders Tested

<table>
<thead>
<tr>
<th>Modified Asphalt</th>
<th>Additive Used</th>
<th>Concentration (% by weight of total blend)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS</td>
<td>Calprene 501C</td>
<td>3</td>
</tr>
<tr>
<td>Asphalt rubber</td>
<td>Ambient crumb rubber</td>
<td>20</td>
</tr>
<tr>
<td>SBS-CRM</td>
<td>Calprene 501C</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ambient crumb rubber</td>
<td>10</td>
</tr>
<tr>
<td>EVA</td>
<td>EVATENE 3325</td>
<td>6</td>
</tr>
<tr>
<td>Elvaloy</td>
<td>Elvaloy 4170</td>
<td>1</td>
</tr>
<tr>
<td>SBS-PPA</td>
<td>Calprene 501C</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Polylphosphoric acid</td>
<td>0.2</td>
</tr>
</tbody>
</table>
MSCR (ASTM D7405-08)

- Test developed as procedure for discriminating between modified binders
  - Performed using DSR on RTFO aged samples
Percent Recovery

- Purpose: determine presence of elastic response and stress dependence of modified and unmodified asphalt binders.

\[ \epsilon_r(\tau, N) = \frac{(\epsilon_1 - \epsilon_{10}) \cdot 100}{\epsilon_1} \]

Where,

- \( \epsilon_r(\tau, N) \): Percent recovery for \( N=1 \) to 10
- \( \tau \): Stress applied during creep
- \( \epsilon_1 \): Adjusted creep strain (after 1.0 s) of each cycle
- \( \epsilon_{10} \): Adjusted recovery strain (after 10.0 s) of each cycle
Non-Recoverable Creep Compliance ($J_{nr}$)

- Non-recoverable creep compliance provides indication of stress dependence of the binder
- FHWA: Indicator of rutting
- $J_{nr}$ and Rutting are proportional

\[ J_{nr}(\tau, N) = \frac{\varepsilon_{10}}{\tau} \]

Where,

- $J_{nr}(\tau, N)$: Non-recoverable creep compliance for $N=1$ to $10$
- $\tau$: Stress applied during creep
Complete loading cycle at 70°C
First cycle at 70°C and 100 Pa

The graph shows the strain over time for different materials: AR, Elvaloy, EVA, SBS-CRM, SBS-PPA, and SBS. The x-axis represents time in seconds, ranging from 0 to 11 seconds, and the y-axis represents strain in percentage, ranging from 0% to 25%. The materials are differentiated by different markers and colors.

The graph indicates how each material responds to the given conditions, with some materials showing a steeper increase in strain than others.
Percent recovery at 100 and 3200 Pa at 70°C

![Graph showing percent recovery at different shear stresses for various materials.](image_url)
$J_{nr}$ Values for 3200 Pa

- **Temperature ($^\circ$C)**: 64, 70, 76
- **Materials**:
  - AR
  - Elvaloy
  - EVA
  - SBS-CRM
  - SBS-PPA
  - SBS

The chart shows the $J_{nr}$ values for different temperatures and materials, with error bars indicating variability.
Summary

• Used tires is a huge source of waste material, majority of which ends up in stockpiles or landfills.
• CRM can been used in both wet and dry processes for production of RAC
• AR binder has a higher percent recovery which leads to less pavement deformation, distresses and longer design life
Questions?
References

1. IWMB “A Basic Introduction to RAC Usage”
2. IWMB “Application and Usage-Rubberized Asphalt Concrete (RAC)”
   www.calrecycle.ca.gov/Tires/RAC/Training/RAC102.pdf
3. FHWA Tech Brief “THE MULTIPLE STRESS CREEP RECOVERY (MSCR) PROCEDURE”
   www.gummiasfalt.se/getfile.ashx?cid=172365&cc=3&refid=29
6. Kuennen “Asphalt Rubber Makes a Quiet Comeback”
   www.blacklidgeemulsions.com/images/br05-04rdsci.pdf
Quiz

1. What are the two main processes for making RAC and what is the main difference between the two?

2. Which two types of gradations are most commonly used for overlays using High Viscosity Asphalt Rubber Binders and why?

3. Describe the MSCR test process and how Asphalt Rubber Modified binders compare to other modified binders test results.
What is runway grooving?

Bristol Airfield, UK
www.bristolairfield.co.uk

NASA-KSC, Florida
www.petermcrow.wordpress.com
What is runway grooving?

- Groove configuration
  - Pitch
  - Width
  - Depth

Standard Groove pattern

FAA Workshop (2011)

1/4 x 1/4 in.
Grooves Spaced
at 1 1/2, 2, and 3 in.
Why runway grooving is required?

- **Hydroplaning**
  - Wet pavement surfaces
  - Poor drainage
  - Pavement texture

- **Loss of friction**
  - Wear and tear of aircraft tires
  - Contaminants – rubber deposits, oil spillage, jet fuel, dust, snow, water, etc.

- **Effects**
  - Poor braking performance
  - Loss of directional control
Why runway grooving is required?

- Runway traction studies in Great Britain (1950s)
  - World wide accident rate – 2.2 per million flights
  - Passenger injuries / fatalities – 7.6% of accidents

- Accidents due to loss of adhesion with runway – 35% of accidents
  - Ice / Snow – 9.7%
  - Low wet friction – 10.8%
  - Aquaplaning (no friction) – 14.6%
Why runway grooving is required?

- Not used for drainage
  - But provides forced water escape from the runway surface

- Does not eliminate hydroplaning
  - But reduces hydroplaning to a manageable level

- Does not increase friction capability
  - But provides sufficient braking and directional control to aircraft
Research Programs

- Research in the U.S began in early 1960s
- NASA: landing-loads track (1962, 1964)
- NASA: Langley research center conference (1966)
- FAA: 18 test groove patterns at airfields throughout the U.S
- Landing research runway at NASA Wallops station (1967)
Pavement Grooving Evaluation at the Landing-Loads Track

- Can grooving be used to ensure minimum design friction on a wet / contaminated runway?

- Can grooving reduce the risk of hydroplaning?

- What is the most favorable groove configuration?
Pavement Grooving Evaluation at the Landing-Loads Track

- Test carriage with speed up to 100 knots
- 5 types of aircraft tires
- Transversely grooved precast concrete strips

Pavement grooving and traction studies (1969)
Pavement Grooving Evaluation at the Landing-Loads Track

- 19 different groove configurations
- Groove depth of 1/8 in. and ¼ in. is used for each configuration

<table>
<thead>
<tr>
<th>Groove width, in.</th>
<th>Groove pitch, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1 1/2</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1/4</td>
<td>1</td>
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<td></td>
<td>1 1/2</td>
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<td></td>
<td>2</td>
</tr>
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<td>3/8</td>
<td>1</td>
</tr>
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Pavement grooving and traction studies (1969)
Tests to evaluate grooved pavement performance

- Aircraft tire rolling resistance
  - Used flooded and damp conditions
  - Tire pressure of 400 psi
  - Critical hydroplaning speed = 180 knots
  - $4^\circ$ yaw

www.grc.nasa.gov
Tests to evaluate grooved pavement performance

- Aircraft tire rolling resistance

Figure 2: Effect of runway wetness condition and surface configuration on rolling resistance of unbraked smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 4°; inflation pressure, 400 lb/in².
Tests to evaluate grooved pavement performance

- Aircraft tire cornering capability
Aircraft tire cornering capability (contd.)

(b) Sawed grooves; flooded (0.2 to 0.3 in.).

Figure 3.- Effect of runway wetness condition and surface configuration on the cornering force of smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 40°; inflation pressure, 400 lb/in².
Aircraft tire cornering capability (contd.)

(c) Sawed grooves; damp.
Tests to evaluate grooved pavement performance

- Aircraft tire breaking effectiveness
  - Slip ratio
  - Free rolling condition and locked-wheel / full-skid condition

Figure 4.- Effect of runway surface configuration on locked-wheel friction coefficient of smooth, type VIII, 27.5 × 7.5 tire. Yaw angle, 40°; inflation pressure, 400 lb/in².
Tests to evaluate grooved pavement performance

- Pavement Grooving results in:
  - No significant increase in aircraft rolling resistance
  - Improvement in aircraft tire cornering force or steering capability
  - Improvement in aircraft tire breaking capability
  - The 1 in. x ¼ in. x ¼ in. groove configuration provided best results
FAA specifications for runway grooving

- Standard groove configuration is $\frac{1}{4}$ in. in depth and $\frac{1}{4}$ in. in width
- Center to center distance is 1 $\frac{1}{2}$ in.
- Depth of 60% or more of the grooves shall not be less than $\frac{1}{4}$ in.
- Grooves shall be continuous and transverse to the direction of aircraft landing / take off
Grooves shall not vary more than 3 in. in alignment for 75 ft. along runway length
Grooves shall not be closer than 3 in. or more than 8 in. from transverse joints
Grooves shall be sawed no less than 6 in. and no more than 18 in. from in-pavement light fixtures
Grooves shall be terminated within 10 ft. of the runway pavement edge
References

- FAA Advisory Circular: 150/5320-12c
- *Runway Traction Studies* (Hall, 1968)
What is hydroplaning? What are its causes?

What is the standard runway groove configuration used by the FAA?

What are the benefits of runway grooving?

THANK YOU!!!
Present Serviceability Rating
Present Serviceability Index

K. Mclver
Advanced Pavement, Prof. Mehta
SP12
Questions for you

• What is the general process (high level overview) of the creating the PSI?

• How does the PSR take into account human variability?

• How are the measurements selected likely to impact a driver's opinion of the road?
• The now notorious AASHO road test (1950s)
• Road test required a solid definition of “performance”
  – “Performance” was completely objective
    • EG. Rut depth, crack length, spalling area, etc.

• Is the road “good”? Is it “good enough”? 
A way to define performance

• Carey and Irick (1960) developed Present Serviceability Rating/Index

• Get some end users to say how good or not good a road is at present

• Then, develop an equation to model this
  – Purely subjective -> Objective of subjective
Experimental design

• Set up a testing panel
• Establish roads to test
  – Wide variety and severity of distresses
  – Must be able to collect objective data too
• Time (2 years)
• Make some critical assumptions
Rating process

• Get some uninvolved people to drive the roads
  – Individual cars
• Use standard definitions and form to rate
• Check ratings
  – Professional (truck) drivers
  – Canadians
  – Rerate in 2 weeks

Fig 9.23 / pg. 389 new book (incomplete)
Pavements

• Total of 123 different test sections
  – 74 flexible
    • 24 from the AASHO Road Test itself
  – 49 rigid

• 1200 ft or more in length

• 10 flexible and 7 rigid also check rated
  – Not consistently

<table>
<thead>
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<th>Truck Drivers</th>
<th>Canadian Raters</th>
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<td>4.5</td>
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<td>1.5</td>
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<tr>
<td>1.0</td>
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</tbody>
</table>
Built in assumptions

• Panel is effectively superhuman
  – Completely honest
  – Perfect understanding
  – Very long attention span, even for the 1960s
  – “Good sportsmanship”
  – Long memories
    • But not too long

• Equipment is used correctly

• Calculations are correct (some weren’t)
Objective measurements

• Ask panel what was important in giving ratings
  – Longitudinal and transverse profiles mostly

• Three measurements used
  – Mean slope variance
  – Mean rut depth
  – Cracking/Patching
Mean slope variance

- Measured with a profilometer
- Takes continuous 1\textsuperscript{st} derivative (slope) of points 9 in. apart down the road
- Sample this data every foot and produce a SV

\[ SV = \frac{\sum (S - \bar{S})^2}{n - 1} \]

- Average both wheelpaths to get mean slope variance.
Profilometer

- Runs at 20 MPH
  - Must remain in wheelpath
SV statistics

• Unitless — slope here has no dimension
• On order of $10^{-6}$

• Strong impact on PSR:
  – $R_f^2 = 0.80...$
  – $R_r^2 = 0.88...$

• A high slope variance shows pitch and toss
  – People don’t like that
Mean rut depth

• Measured with a depth gage (manual)
  – Depth of the rut v. two feet in either direction
• Take readings every 20 feet, both wheelpaths

• Arithmetic mean average

$$ \overline{RD} = \frac{\sum RD}{n} $$
RD statistics

- Units of length (inches or mm)
- At most 0.5 in., usually very low

- Not important to PSR:
  - $R^2 = 0.02...$

- Not really needed
  - Included because of raters requests
  - Also, prevailing wisdom of the time
Cracking and patching

- Major and minor cracking
- Areas patched

- Added together after data collection

- Have to measure areas manually
  - Highly prone to error and boredom
How cracked is this?

“Crack in Pavement” — Chris Campbell
CC-BY-NC
http://www.flickr.com/photos/cgc/4431720/
C&P statistics

- Area per area (unitless) or length per area
- Anywhere from 0 to 1

- Differing impact:
  - $R_f^2 = 0.38\ldots$
  - $R_r^2 = 0.81\ldots$

- Cracks in rigid pavement feel worse
How to derive a PSI formula

• Need to have \(\text{PSI} = f(SV, RD, C + P) = \text{PSR}\)

• If we have a road with XYZ SV, RD, C + P, we should be able to get a PSI from the function that replicates a full blown PSR
General form of equation

• Want an accurate, but simple equation
  – No involved calculus, etc. This is the 1960s

• Linear form
  – Transform data into linear relationship

\[ PSR = PSI + E = C + A_1 f(SV) + A_2 f(RD) + ... \]
NO EXTRAPOLATIONS

• Every selection/range of data is the only one the equation will be valid for

• If you don’t test roads with potholes on them, you cannot use the equation to model roads with potholes

• If you only get PSRs from 3 to 5...
Obtaining the subfunctions

- Plot measurements v. PSR and look for trends

- So, PSR is a function of C + P for rigid surfaces
- PSR isn’t closely related to rut depth
• For rigid and flexible
  – $f(SV) = \log_{10} [1 + SV]$
  – $f(C+P) = [C + P]^{\frac{1}{2}}$
• Also for flexible
  – $f(RD) = RD^2$
• Therefore:
  • $PSI_f = A_0 + A_1 \log_{10} [1 + SV] + A_2 RD^2 + B_1 [C + P]^{\frac{1}{2}}$
  • $PSI_r = A_0 + A_1 \log_{10} [1 + SV] + B_1 [C + P]^{\frac{1}{2}}$
Other options

• Could expand to additional terms
  – Infinite series

• Could have linearized differently

• Could have included other factors
  – This was incomplete when published
  – “…more study [...] still underway at the Road Test.”
Coefficients obtained

- \( \text{PSI}_f = 5.03 - 1.91 \log_{10} [1 + SV] - 1.38 RD^2 - 0.01(C + P)^{\frac{1}{2}} \)

- \( \text{PSI}_r = 5.41 - 1.91 \log_{10} [1 + SV] - 0.09(C + P)^{\frac{1}{2}} \)

- A_0 > 5?
  - Mathematical, not rational
TABLE 1
DATA FOR 74 SELECTED FLEXIBLE PAVEMENTS

| Pvt. Loc. Code | Present Serviceability Ratings | Acceptability Opinions | Longitudinal and Transverse Roughness | Major Cracking | Patching | Transformations | PSI 121 | Resid |
|----------------|--------------------------------|------------------------|--------------------------------------|----------------|----------|----------------|---------|
|                | AASHO Panel                    |                        | AASHO Panel                          |                |          |                |         |
|                | 1st PSR                        | Replic. diff. in PSR   | Std. dev. of PSR among raters       |                |          |                |         |
|                | Truck Dr'Vs                    | PSR                    | PSR                                  |                |          |                |         |
|                | Canad. Raters                  | PSR                    | PSR                                  |                |          |                |         |
|                | Fraction                       | Yes                    | No                                   |                |          |                |         |
|                | SV Mean Slope Variance in Wh/kin (x10⁴) |               |                                      |                |          |                |         |
|                | AR Mean AASHO Rim'n' in Kin/ml @ 10 mph |               |                                      |                |          |                |         |
|                | RD Mean Rut Depth, (in.)       |                        |                                      |                |          |                |         |
|                | RDV Mean Rut Depth Variance in²/100000 ft² |               |                                      |                |          |                |         |
|                | Class 2 + Class 3, ft²/100000 ft² |                        |                                      |                |          |                |         |
|                | Long. & Trans.                |                        |                                      |                |          |                |         |
|                | P F¹² per 1000 ft²            |                        |                                      |                |          |                |         |
|                | Log (1+SV)                     |                        |                                      |                |          |                |         |
|                | RD²                            |                        |                                      |                |          |                |         |
|                | Sq. rt. C + P                 |                        |                                      |                |          |                |         |
| F 3            | 4.3                            | 4.5                    | 1.0                                  | 2.8            | 0.7      | -0.01          | 3.9     |
| F 4            | 2.6                            | 2.0                    | 0.0                                  | 0.0            | 0.0      | -0.0           | 3.0     |
| F 5            | 3.3                            | 3.5                    | 0.6                                  | 0.6            | 0.6      | -0.0           | 3.1     |
| F 6            | 4.4                            | 4.2                    | 1.0                                  | 0.4            | 0.4      | -0.0           | 3.2     |
| F 7            | 3.8                            | 3.6                    | 0.6                                  | 0.6            | 0.6      | -0.0           | 3.1     |
Lies... and statistics

• For flexible, variation accounted for = 0.844
• For rigid, variation accounted for = 0.916

• Good, *if the assumptions are good*

• Fortunately it’s not a black box; we can make our own
Newer; better, faster

• This was the original PSI

• It is not the ONLY PSI possible
  – C&I openly suggested others make their own
  – Other quasi-PSI/PSRs out there

• Probably worth updating anyway, after 60 years
  – Improved measuring methods
Last slide

Big Q
Design analysis of latex-modified concrete overlays

Ilan Levy
4/26/2012
Advanced Pavement Analysis and Evaluation
CEE 08563
Overlay Introduction

- Used to restore pavement surface course
- Improve ride quality
- Increase safety
- Reduce life cycle costs
- Extend life
Latex Modified Concrete Overlay

- Thin layer typically 1 - 2 in. thick

- Addition of styrene-butadiene as modifier

- Replaces a portion of mixing water

- Styrene-butadiene polymers reduces permeability and water absorption.
Need for LMC Overlay

• Deicing operations – leads to deterioration
• Salts penetrate concrete cover – initiates corrosion
• Delamination
• Spalling
Applications and Advantages

Bridge Deck Rehabilitation

Parking Garage Structures
Latex Modified
Advantages

Fig. 5—Bond strength of latex-modified mortars.

Fig. 8—Chloride ion resistance of latex-modified concrete.
Overlay Design

- A mechanistic-empirical approach
- Requires pavement performance
- Distress equations
- Deflection and Modulus testing
- Design goal of overlay thickness/material properties
Mechanistic-Empirical Process

• Obtain data on traffic loading/Deflection

• Input variable for existing models

• Adjustment of model with relevant factors specific to case study

• Predict overlay performance and properties
Reflective Cracking Model

- Using previous models as a basis for predictive performance.
- Paris’ Law
- Crack propagation model:
  \[ \Delta C = k_1 A (K_{bending})^n \Delta N_i + k_2 A (K_{shearing})^n \Delta N_i + k_3 A (K_{thermal})^n \]

- Crack damage model
  \[ D = \sum \Delta C / h \]
Reflective Cracking Model

- Paris and Erdogan crack propagation law
- Effectively predict reflective cracking in overlays
- Determines fracture properties of overlay material

\[
\frac{dc}{dN} = A \times (\Delta K)^n
\]

- $c$ = crack length
- $N$ = # of loading cycles
- $\Delta K$ = stress intensity factor

- $A$ and $n$ are fracture properties of the overlay

- Develop SIF regression equations
Data Collection

- First step to obtain data – Field Measured

Obtain crack identification and crack depth estimation

- Ground penetrating radar
- Dynamic ultrasonic sensor
- Radar sensor
Overlay Testing

- Obtain samples of overlay section
- Overlay tester (OT) performed in laboratory testing.

![Figure B4. A and n Output from the Macro.](image)

\[ A = 6.4531 \times 10^{-8} \]
\[ n = 4.1819 \]
Data Collection

\[
K_{\text{bending/shearing}} = K_a \left[ K_b \left( \frac{c}{H_1} \right)^3 + K_c \left( \frac{c}{H_1} \right)^2 + K_d \left( \frac{c}{H_1} \right) + K_e \right]
\]
Stress Intensity Factors can be developed into regression equation relating crack length

\[ SIF = 0.2911 \times E \times MOD \times c^{-0.4590} \]
Paris’ Law with LMCO

Crumb rubber:
A=1.707E-7, n=4.098
Latex:
A=7.650E-8, n=4.176

\[ \Delta C = k_1 A (K_{bending})^n \Delta N_i + k_2 A (K_{shearing})^n \Delta N_i + k_3 A (K_{thermal})^n \]
• To summarize the M-E approach – implement a previously established model for analysis (Paris’ law on crack propagation)
• Appropriate context of failure mode in reflective cracking as it applies to LMCO
• The SIF computations allow for analysis of reflective crack propagation caused by traffic.
• Fracture properties (A and n) determined in lab (OT)

\[ \Delta C = k_1 A (K_{\text{bending}})^n \Delta N_i + k_2 A (K_{\text{shearing}})^n \Delta N_i + k_3 A (K_{\text{thermal}})^n \]

\[ \frac{dc}{dN} = A \times (\Delta K)^n \]
Determining fracture properties

For this case:

\[ A = 2.6220 \times 10^{-7} \]
\[ n = 4.0790 \]
Important Questions

• What is the primary intent and application of latex modified concrete overlay?

• What are some of the mechanistic inputs in developing the reflective cracking model?

• Why is a cracking failure model appropriate for this context?