Deterioration of Bituminous Roads
## Base, Surface and Material Types

### Surface Treatment
- Cape Seal
- Double Bituminous Surface Dressing
- Single Bituminous Surface Dressing
- Slurry Seal
- Penetration Macadam

### Asphalt Mix
- Asphalt Concrete
- Hot Rolled Modified Asphalt
- Rubberized Asphalt
- Polymer Asphalt Concrete
- Soft Bitumen Mix (Cold Mix)
- Porous Asphalt
- Stone Mastic

### Base
- Granular Base
- Asphalt Base
- Asphalt Pavement Base
- Stabilized Base
# Pavement Classification System

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Base Type</th>
<th>Pavement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asphalt Mix</strong></td>
<td>Granular Base</td>
<td>AMGB</td>
</tr>
<tr>
<td></td>
<td>Asphalt Base</td>
<td>AMAB</td>
</tr>
<tr>
<td></td>
<td>Stabilized Base</td>
<td>AMSB</td>
</tr>
<tr>
<td></td>
<td>Asphalt Pavement</td>
<td>AMAP</td>
</tr>
<tr>
<td><strong>Surface Treatment</strong></td>
<td>Granular Base</td>
<td>STGB</td>
</tr>
<tr>
<td></td>
<td>Asphalt Base</td>
<td>STAB</td>
</tr>
<tr>
<td></td>
<td>Stabilized Base</td>
<td>STSB</td>
</tr>
<tr>
<td></td>
<td>Asphalt Pavement</td>
<td>STAP</td>
</tr>
</tbody>
</table>
Base and Surface Types Over Time

- **Previous Surfacing 1988 (AMGB)**
  - 200mm Granular Roadbase
  - 150mm Granular Sub-base
  - Subgrade (CBR 8%)

- **1994 (AMAP)**
  - 50 mm AC Overlay
  - 100 mm

- **1998 (STAP) New Surfacing**
  - 25 mm Surface Dressing
Distress Modes

• Surfacing Distress
  - Cracking
  - Ravelling
  - Potholing
  - Edge-Break

• Deformation Distress
  - Rutting
  - Roughness

• Pavement Surface Texture Distress
  - Texture Depth
  - Skid Resistance

• Drainage Distress
  - Drainage
Distress Modes
Distress Modes
Surfacing Distress

- **Cracking Area**: Sum of rectangular areas circumscribing manifest distress (line cracks are assigned a width of 0.5 m), expressed as a percentage of carriageway area.
  - Structural Cracking
    - Narrow Cracking (1-3 mm crack width)
    - Wide Cracking (> 3 mm crack width)
  - Thermal Transverse Cracking

- **Ravelling Area**: Area of loss of material from wearing surface, expressed as a percentage of carriageway area.
Surfacing Distress

• **Number of Potholes**: Number of potholes per kilometer expressed in terms of the number of ‘standard’ sized potholes of area 0.1 m². A pothole being defined as an open cavity in road surface with at least 150 mm diameter and at least 25 mm depth.

• **Edge Break Area**: Loss of bituminous surface material (and possibly base materials) from the edge of the pavement, expressed in square meters per km.

HDM-4 assigns a depth of 100 mm to potholes and edge break area.
Deformation Distress

- **Rutting**: Permanent traffic-associated deformation within pavement layers which, if channelised into wheelpaths, accumulates over time and becomes manifested as a rut, expressed as the maximum depth under 2 m straightedge placed transversely across a wheelpath.

- **Roughness**: Deviations of surface from true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage, expressed in the International Roughness Index, IRI (m/km).
# Roughness Scales

<table>
<thead>
<tr>
<th>International Roughness Index</th>
<th>Bump Integrator Trailer TRRL</th>
<th>Quarter-car Index Index</th>
<th>Present Serviceability Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI m/km</td>
<td>BI mm/km</td>
<td>QI counts/km</td>
<td>PSI</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5.0</td>
</tr>
<tr>
<td>1</td>
<td>700</td>
<td>13</td>
<td>4.2</td>
</tr>
<tr>
<td>Good Paved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1400</td>
<td>26</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>2200</td>
<td>40</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>50</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>3800</td>
<td>65</td>
<td>2.0</td>
</tr>
<tr>
<td>6</td>
<td>4700</td>
<td>80</td>
<td>1.7</td>
</tr>
<tr>
<td>Good Unpaved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6500</td>
<td>100</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>8300</td>
<td>130</td>
<td>0.6</td>
</tr>
<tr>
<td>Poor Paved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>10000</td>
<td>156</td>
<td>0.0</td>
</tr>
<tr>
<td>16</td>
<td>14000</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>Poor Unpaved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>18000</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>22000</td>
<td>310</td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
BI &= 360 \text{ IRI}^{1.12} \\
QI &= 13 \text{ IRI} \\
SI &= 5 \text{ e}^{-0.18 \text{ IRI}} \\
\text{IRI} &= 0.0032 \text{ BI}^{0.89} \\
\text{IRI} &= \frac{\text{QI}}{13} \\
\text{IRI} &= 5.5 \ln \left(\frac{5.0}{\text{SI}}\right)
\end{align*}
\]
Pavement Surface Texture Distress

• **Texture Depth**: Average depth of the surface of a road expressed as the quotient of a given volume of standardized material (sand) and the area of that material spread in a circular patch on the surface being tested.

• **Skid Resistance**: Resistance to skidding expressed by the sideways force coefficient (SDF) at 50 km/h measured using the Sideways Force Coefficient Routine Investigation Machine (SCRIM).
# Texture Depth and Skid Resistance

<table>
<thead>
<tr>
<th>SURFACE</th>
<th>SCALE OF TEXTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MACRO</td>
</tr>
<tr>
<td>A</td>
<td>COARSE</td>
</tr>
<tr>
<td></td>
<td>T_D ~ 2mm</td>
</tr>
<tr>
<td>B</td>
<td>COARSE</td>
</tr>
<tr>
<td></td>
<td>T_D ~ 2mm</td>
</tr>
<tr>
<td>C</td>
<td>FINE</td>
</tr>
<tr>
<td></td>
<td>T_D ~ 0.35mm</td>
</tr>
<tr>
<td>D</td>
<td>FINE</td>
</tr>
<tr>
<td></td>
<td>T_D ~ 0.35mm</td>
</tr>
</tbody>
</table>
Drainage Distress

- **Drainage**: Drainage condition (excellent, good, fair, poor or very poor), which defines the drainage factor.

The drainage factor, $DF$, is a continuous variable whose value can range between 1 (excellent) and 5 (very poor), depending on the type of drain (Paterson, 1998). The user will be required to input the type of drain (as listed in Table C2.10) and the condition of the drain as excellent, good, fair, poor or very poor.

**Table C2.10 Suggested range of drainage factor values**

<table>
<thead>
<tr>
<th>Drain type</th>
<th>Drain condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excellent $DF_{min}$</td>
<td>Very poor $DF_{max}$</td>
</tr>
<tr>
<td>Fully lined and linked</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Surface lined</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>V-shaped – hard</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>V-shaped – soft</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Shallow – hard</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Shallow – soft</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>No drain - but required</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>No drain - not required</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Construction Quality

• Poor construction quality: Results in greater variability in material properties and road performance. Defined by construction quality parameters.

  - Relative compaction of the base, sub-base and selected subgrade layers – COMP
  - Construction defects indicator for bituminous surfacings - CDS (based on binder content)
  - Construction defects indicator for the base - CDB based on gradation of material, aggregate shape (0 no defects, 1.5 several defects)
# Construction Defects Indicator for Bituminous Surfacings - CDS

## SURFACE CONDITION DEFECT CDS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
<th>CDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry (brittle)</td>
<td>Nominally 10% less than optimum binder content</td>
<td>0.5</td>
</tr>
<tr>
<td>Normal</td>
<td>Optimum binder content</td>
<td>1.0</td>
</tr>
<tr>
<td>Rich (soft)</td>
<td>Nominally 10% more than optimum binder content</td>
<td>1.5</td>
</tr>
</tbody>
</table>
### AASHTO Structural Number

- Measures the strength of a pavement
- Takes into account the thickness and strength coefficient of each pavement layer

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>A</th>
<th>B</th>
<th>A*B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>(mm)</td>
<td>(#)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Surface</td>
<td>25</td>
<td>0.20</td>
<td>5.0</td>
</tr>
<tr>
<td>Base</td>
<td>100</td>
<td>0.14</td>
<td>14.0</td>
</tr>
<tr>
<td>Subbase</td>
<td>150</td>
<td>0.10</td>
<td>15.0</td>
</tr>
<tr>
<td>Total (mm)</td>
<td></td>
<td></td>
<td>34.0</td>
</tr>
<tr>
<td>Total (inches)</td>
<td>=</td>
<td>Structural Number =</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### Structural Number Example 2

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>A</th>
<th>B</th>
<th>A*B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>(mm)</td>
<td>(#)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Surface</td>
<td>50</td>
<td>0.40</td>
<td>20.0</td>
</tr>
<tr>
<td>Base</td>
<td>150</td>
<td>0.14</td>
<td>21.0</td>
</tr>
<tr>
<td>Subbase</td>
<td>200</td>
<td>0.10</td>
<td>20.0</td>
</tr>
<tr>
<td>Total (mm)</td>
<td></td>
<td></td>
<td>61.0</td>
</tr>
<tr>
<td>Total (inches)</td>
<td>=</td>
<td>Structural Number =</td>
<td>2.4</td>
</tr>
</tbody>
</table>

### Structural Number Example 3

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>A</th>
<th>B</th>
<th>A*B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>(mm)</td>
<td>(#)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Surface</td>
<td>100</td>
<td>0.40</td>
<td>40.0</td>
</tr>
<tr>
<td>Base</td>
<td>200</td>
<td>0.14</td>
<td>28.0</td>
</tr>
<tr>
<td>Subbase</td>
<td>250</td>
<td>0.10</td>
<td>25.0</td>
</tr>
<tr>
<td>Total (mm)</td>
<td></td>
<td></td>
<td>93.0</td>
</tr>
<tr>
<td>Total (inches)</td>
<td>=</td>
<td>Structural Number =</td>
<td>3.7</td>
</tr>
</tbody>
</table>

### Structural Number Example 4

<table>
<thead>
<tr>
<th>Pavement Layer</th>
<th>A</th>
<th>B</th>
<th>A*B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>(mm)</td>
<td>(#)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Surface</td>
<td>150</td>
<td>0.40</td>
<td>60.0</td>
</tr>
<tr>
<td>Base</td>
<td>250</td>
<td>0.14</td>
<td>35.0</td>
</tr>
<tr>
<td>Subbase</td>
<td>300</td>
<td>0.10</td>
<td>30.0</td>
</tr>
<tr>
<td>Total (mm)</td>
<td></td>
<td></td>
<td>125.0</td>
</tr>
<tr>
<td>Total (inches)</td>
<td>=</td>
<td>Structural Number =</td>
<td>4.9</td>
</tr>
</tbody>
</table>
HDM-III Modified Structural Number

- The HDM-III Modified Structural Number includes the strength contribution of the sub-grade that is a function of the sub-grade CBR

\[
SNC = SN + SNSG
\]

\[
SN = \sum_{i=1}^{n} a_i h_i
\]

\[
SNSG = 3.51(\log_{10} CBR) - 0.85(\log_{10} CBR)^2 - 1.43
\]
The strength of bituminous pavements on HDM-4 is characterised by the adjusted structural number – SNP.

The SNP includes the strength contribution of the sub-grade that is a function of the sub-grade CBR.

The SNP applies a weighting factor to the sub-base and sub-grade contributions which reduces with increasing depth, so that the pavement strength for deep pavements is not over-predicted.

\[ SNP_d = SNBASU_d + SNSUBA_d + SNSUBG \]

SNBASU = contribution from surface and base layers
SNSUBA = contribution from sub-base layers
SNSUBG = contribution from subgrade
SNP and Drainage Effects

• The average annual SNP used in the models is derived from the dry season SNP$_d$, and the lengths of the dry season

$$SNP = f_s \times SNP_d$$

$f_s$ = function of SNP$_w$ / SNP$_d$ and length of dry season

• Drainage effect on pavement strength is modelled through the changes in the drainage factor DF [1 excellent - 5 very poor]

$$SNP_w / SNP_d = f = \text{function of DF, rainfall, surface distress}$$
Adjusted Structural Number and Benkelman or FWD Deflection

Benkelman or FWD Deflection

if base is not cemented
SNPk = 3.2 DEF^{-0.63}
if base is cemented
SNPk = 2.2 DEF^{-0.63}

if base is not cemented
DEF = 6.5 SNPk^{-1.6}
if base is cemented
DEF = 3.5 SNPk^{-1.6}
Road Deterioration Modelling

• Road investment decision support systems must have some form of pavement deterioration modelling capability
• Objective is to predict the future condition and the effects of maintenance
What We are Trying to Predict (1)

- Predict asset condition

**Decay in Condition (DETERIORATION)**

**Treatment Applied**

**Minimum Acceptable Standard (TRIGGER)**
What We are Trying to Predict (2)

- Predict long term pavement performance
- Predict effects of maintenance standards
- Calculate annual costs: Road Agency + Road User
Road Deterioration Depends On

- Original design
- Material types
- Construction quality
- Traffic volume and axle loading
- Road geometry and alignment
- Pavement age
- Environmental conditions
- Maintenance policy
Start Point Critical For Predictions
Types of Models

**Deterministic**
- Predict that there is a set outcome of an event
- Used for network or project analyses
- Give detailed work program for a section
- HDM-4

**Probabilistic**
- Predict that there is a probability of an outcome
- Used for network analyses
- Cannot give detailed work program for a section
• Usually based on Markov-Chain
• Good for getting overall network investment needs
• Cannot be used for planning investments on specific roads *i.e.* Link X needs treatment Y in year Z
Deterministic Models (1)

- **Empirical**
  based on statistical analysis of locally observed deterioration trends

- **Mechanistic**
  uses fundamental theories of pavement behaviour for their development

- **Structural mechanistic-empirical approach**
  based on identifying the functional form and primary variables and then applying various statistical techniques to quantify their impacts using empirical data (HDM-4 Models)
Deterministic Models (2)

• Mechanistic based models
  □ Greater flexibility than regression models
  □ More easily transferred to different pavements or conditions
  □ Data intensive

• Structured empirical approach
  □ Knowledge of how pavements perform used to set framework for statistical analysis
  □ Much less data intensive
  □ Used in HDM
Types of Deterministic Models (1)

• Absolute models
  predict the condition at a particular point in time as a function of independent variables and the road condition at construction time

• Incremental recursive models
  predict the change in condition from an initial state as a function of independent variables and the road condition at the beginning of the year
Types of Deterministic Models (2)

• Absolute
  □ Predicts the future condition
    ▪ $\text{CONDITION} = f(a_0, a_1, a_2)$
  □ Limited to conditions model developed for
  □ Problems with calibration
  □ Used on HDM-4 for concrete roads

• Incremental
  □ Predicts the change in condition from the current condition:
    ▪ $\Delta \text{CONDITION} = f(a_0, a_1, a_2)$
  □ Can use any start point so much more flexible
  □ Used in HDM-4 for Bituminous Roads
## Pavement Defects Modelled in HDM-4

<table>
<thead>
<tr>
<th>Bituminous</th>
<th>Concrete</th>
<th>Block*</th>
<th>Unsealed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>Cracking</td>
<td>Rutting</td>
<td>Gravel loss</td>
</tr>
<tr>
<td>Rutting</td>
<td>Joint spalling</td>
<td>Surface</td>
<td>*not in current</td>
</tr>
<tr>
<td>Ravelling</td>
<td>Faulting</td>
<td>texture</td>
<td>release</td>
</tr>
<tr>
<td>Potholing</td>
<td>Failures</td>
<td>Roughness</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>Serviceability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge break</td>
<td>rating</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roughness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface texture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skid resistance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Plus deterioration of drains
Deterioration Models - Bituminous

CRACKING
- Structural
- Thermal
- Reflection

RUTTING
- Initial Densification
- Structural Deformation
- Plastic Deformation
- Surface Wear

RAVELLING

POTHOLING
- Structural
- Cracking
- Rutting
- Potholing
- Patching
- Environment

ROUGHNESS
Interaction Mechanisms

Area of Cracking

Water ingress

Time

Rut depth

Time

Lower strength

Faster deformation

Uneven Surface

Spalling

Potholes

Patches

ROUGHNESS

Further cracking

Uneven surface

Shear

Patches

Interaction Mechanisms
Principles Of Deterioration Models

• Models are structured empirical
• Individual distresses modelled separately
• Relationships are incremental and recursive
  \[ dY = Ka_0 f(X_1, X_2, X_3, \text{ etc}) \]
• Modelled sequentially through to roughness
• Maintenance intervention at end of each year
Paved Roads Deterioration Sequence

Year Loop

Input pavement strength, condition, age for initial analysis year

Compute traffic loading

Compute surface distress increment

Compute roughness increment

Scheduled maintenance?
- N
- Y

Condition responsive?
- N
- Y

Patching?
- N
- Y

Compute post-maintenance condition, strength, age

Compute maintenance effects
Roughness

- Roughness = F(age, strength, traffic loading, potholes, cracking, ravelling, rutting, environment)
**Maintenance Effects**

Roughness at the Beginning of the Year

Roughness Increment during the analysis year

IRIa

Analysis Year

Maintenance Operation Effect

dIRI

IRIb

IRIb1 = IRIb0 + dIRI + dIRIoper

Roughness at the End of the Year

IRIb

dIRI

IRIa

Analysis Year

dIRIoper
Annual Change in Roughness

\[ \Delta R_I = K_{gp} [\Delta R_{Is} + \Delta R_{Ic} + \Delta R_{Ir} + \Delta R_{It}] + \Delta R_{Ie} \]

where

\( \Delta R_I \) = total incremental change in roughness during analysis year, in m/km IRI

\( K_{gp} \) = calibration factor for roughness progression

\( \Delta R_{Is} \) = incremental change in roughness due to structural deterioration during analysis year, in m/km IRI

\( \Delta R_{Ic} \) = incremental change in roughness due to cracking during analysis year, in m/km IRI

\( \Delta R_{Ir} \) = incremental change in roughness due to rutting during analysis year, in m/km IRI

\( \Delta R_{It} \) = incremental change in roughness due to potholing during analysis year, in m/km IRI

\( \Delta R_{Ie} \) = incremental change in roughness due to environment during analysis year, in m/km IRI
dRI = 134 * Exp (m * Kgm * AGE3) * [1 + SNPKb]^-5 * YE4

m = environmental coefficient (#)
Kgm = calibration factor (#)
AGE3 = pavement age (years)
SNPKb = adjusted structural number function of surface distress (#)
YE4 = annual number of equivalent standard axles (million ESA/lane/year)
Roughness Increment Due to Surface Distress

\[ dRlc = a_0 \times dACRA \]
\[ dACRA = f(\text{annual increase in cracking}) \]

\[ dRlr = a_0 \times dRDS \]
\[ dRDS = f(\text{annual increase in rutting}) \]

\[ dRlt = a_0 \times dPOT \]
\[ dPOT = f(\text{annual increase in potholes}) \]
Roughness Increment Due to Environment

dRle = Kgm * m * Rla

Kgm = calibration factor (#)
m = environmental coefficient (#)
Rla = Roughness at start of the year (IRI, m/km)

<table>
<thead>
<tr>
<th>Moisture Classification</th>
<th>Tropical</th>
<th>Sub-tropical hot</th>
<th>Sub-tropical cool</th>
<th>Temperate cool</th>
<th>Temperate freeze</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>0.005</td>
<td>0.010</td>
<td>0.015</td>
<td>0.025</td>
<td>0.040</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>0.010</td>
<td>0.015</td>
<td>0.025</td>
<td>0.035</td>
<td>0.060</td>
</tr>
<tr>
<td>Sub-humid</td>
<td>0.020</td>
<td>0.025</td>
<td>0.040</td>
<td>0.060</td>
<td>0.100</td>
</tr>
<tr>
<td>Humid</td>
<td>0.025</td>
<td>0.030</td>
<td>0.060</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td>Per-humid</td>
<td>0.030</td>
<td>0.040</td>
<td>0.070</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Moisture Classification

<table>
<thead>
<tr>
<th>Moisture Classification</th>
<th>Description</th>
<th>Thornthwaite Moisture Index</th>
<th>Annual Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>Very low rainfall, High evaporation</td>
<td>-100 to -61</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>Low rainfall</td>
<td>-60 to -21</td>
<td>300 to 800</td>
</tr>
<tr>
<td>Sub-humid</td>
<td>Moderate rainfall, or strongly seasonal rainfall</td>
<td>-20 to +19</td>
<td>800 to 1600</td>
</tr>
<tr>
<td>Humid</td>
<td>Moderate warm seasonal rainfall</td>
<td>+20 to +100</td>
<td>1500 to 3000</td>
</tr>
<tr>
<td>Per-humid</td>
<td>High rainfall, or very many wet-surface days</td>
<td>&gt; 100</td>
<td>&gt; 2400</td>
</tr>
</tbody>
</table>
# Temperature Classification

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Description</th>
<th>Temperature range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>Warm temperatures in small range</td>
<td>20 to 35</td>
</tr>
<tr>
<td>Sub-tropical - hot</td>
<td>High day cool night temperatures, hot-cold seasons</td>
<td>-5 to 45</td>
</tr>
<tr>
<td>Sub-tropical - cool</td>
<td>Moderate day temperatures, cool winters</td>
<td>-10 to 30</td>
</tr>
<tr>
<td>Temperate - cool</td>
<td>Warm summer, shallow winter freeze</td>
<td>-20 to 25</td>
</tr>
<tr>
<td>Temperate - freeze</td>
<td>Cool summer, deep winter freeze</td>
<td>-40 to 20</td>
</tr>
</tbody>
</table>
• **Structural Cracking**: This is effectively load and age/environment associated cracking.

• **Transverse Thermal Cracking**: This is generally caused by large diurnal temperature changes or in freeze/thaw conditions, and therefore usually occurs in certain climates.

For each type of cracking, separate relationships are given for predicting the time to initiation and the rate of progression.
Structural Cracking

Modelled as ‘All’ and ‘Wide’ cracking

Cracking Initiation - years
Time to initiation of ‘All’ cracking - ICA
Time to initiation of ‘Wide’ cracking - ICW

Cracking Progression - % of total carriageway area
Progression of ‘All’ cracking - ACA
Progression of ‘Wide’ cracking - ACW
Cracking Initiation and Progression

![Graph showing the percentage area affected by cracking over time. The graph indicates a significant increase in affected area over 20 years, with two distinct phases: initiation and progression.](image-url)
Cracking Initiation Model (1)

ICA = $K_{cia}\{CDS^2 a_0 \exp[a_1 SNP + a_2 (YE4/SN^2)] + CRT\}$

ICA time to cracking initiation, in years

- CDS construction quality
- SNP structural number of pavement
- YE4 traffic loading
- $K_{cia}$ calibration factor
- CRT effect of maintenance
Cracking Initiation Model (2)
Cracking Progression Model (1)

\[ dACA = K_{cpa} \left( \frac{CRP}{CDS} \right) z_A \left[ (z_A \cdot a_0 \cdot a_1 \cdot \delta t_A \cdot YE4 \cdot SNP^{a_2} + SCA^{a_1} )^{1/a_1} - SCA \right] \]

- CRP = retardation of cracking progression due to preventive treatment
- Progression of All cracking commences when \( \delta t_A > 0 \) or ACAa > 0
Cracking Progression Model (2)

Time Since Crack Initiation (years)

Area of Structural Cracking (%)

- SNPd = 6
- YE4 = 1.0

- SNPd = 3
- YE4 = 0.1

Area of Structural Cracking

- All Cracking
- Wide Cracking
Transverse Thermal Cracking

Modelled as No. of transverse cracks

Time to Initiation of Thermal Cracking - ICT

Progression of Thermal Cracking - NCT
NCT converted to ACT (area of thermal cracking)

Total Area of Cracking - ACRA
ACRA = ACA + ACT
Transverse Thermal Cracking

- Temperate freeze
- Humid
- Sub-tropical hot
- Arid

Surface Age (Years)

Transverse Thermal Cracking (No/km)
HDM-4 Rut Depth model based on four components

- Initial Densification - RDO
- Structural Deformation - RDST
- Plastic Deformation - RDPD
- Wear from Studded Tyres - RDW
Rut Depth Progression (2)

- Initial Densification (First Year)
- Densification - No Cracking
- Structural Deterioration - With Cracking
Rut Depth Progression (3)

- Rutting = $F(\text{age, traffic, strength, compaction})$
Ravelling

Time to Initiation of Ravelling
(years)
IRV

Progression of Ravelling
(area of carriageway)
ARV
Ravelling Initiation

![Graph showing ravelling initiation period vs. AADT for different CDS values (1.25, 1.0, 0.75)].
Ravelling Progression

![Graph showing Ravelling Progression with CDS values 0.75, 1.0, and 1.25.](Image)

- **Area of Ravelling (%)** vs **Time Since Ravelling Initiation (years)**
- **CDS = 0.75**
- **CDS = 1.0**
- **CDS = 1.25**
Potholing

Time to Initiation of Potholes
(years)

IPT

Progression of Potholing
(number of potholes)

NPT
Potholing Initiation

Granular base
MMP = 100 mm/month

Traffic (million axles/lane/year)

Time to Pothole Initiation (years)

HS = 150 mm
HS = 100 mm
HS = 50 mm
HS = 20 mm
Potholing Progression (1)

Pothole progression is affected by the time lapse between the occurrence and patching of potholes - TLF

<table>
<thead>
<tr>
<th>Maintenance Frequency</th>
<th>TLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2 weeks</td>
<td>0.02</td>
</tr>
<tr>
<td>1 month</td>
<td>0.06</td>
</tr>
<tr>
<td>2 months</td>
<td>0.12</td>
</tr>
<tr>
<td>3 months</td>
<td>0.20</td>
</tr>
<tr>
<td>4 months</td>
<td>0.28</td>
</tr>
<tr>
<td>6 months</td>
<td>0.43</td>
</tr>
<tr>
<td>12 months</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Potholing Progression (2)

Potholes caused by:

- Cracking
- Ravelling
- Enlargement
Potholing Progression (3)

Traffic (million axles/lane/year)

Traffic (million axles/lane/year)

Potholing (no./km/year)

Granular base
ACW = 40%
MMP = 100 mm/month
TLF = 1

HS = 25 mm
HS = 50 mm
HS = 100 mm
Edge Break (1)

Loss of surface, and possibly base materials from the edge of the pavement

Commonly arises on narrow roads with unsealed shoulders

HDM-4 predicts the volume of material loss
Edge Break (2)

Edge Step = 50 mm
Average Speed = 50 km/h
Rainfall = 200 mm/month

AADT

Edge Break (m3/km/year)

Width = 3.5 m
Width = 4.5 m
Width = 5.5 m
Bituminous Road Work Effects
Road Work Effects

Condition

Traffic / Time

Reconstruct

Overlay
Road Works
Road Works Modelling

- Timing of works over the analysis period
- Calculation of the physical quantities or amounts of works to be undertaken
- Estimating the costs of works
- Resetting / changing one or more of the characteristics that define the road
Road Work Effects

- Can group pavement deterioration into:
  - Surface
  - Structural
- Surface deterioration can be halted at almost any point by maintenance
- Structural deterioration rates can be reduced by maintenance, but never halted
Road Work Classification

Preservation

- **Routine**
  - Patching, Edge repair
  - Drainage, Crack sealing

- **Periodic**
  - Preventive treatments
  - Rehabilitation
  - Pavement reconstruction

- **Special**
  - Emergencies
  - Winter maintenance

Development

- **Improvements**
  - Widening
  - Realignment
  - Off-carriageway works

- **Construction**
  - Upgrading
  - New sections
## Road Works Activities (1)

<table>
<thead>
<tr>
<th>Works Class</th>
<th>Works Type</th>
<th>Works Activity / Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine Maintenance</td>
<td>Routine Pavement</td>
<td>patching, edge-repair, crack sealing, spot-regravelling, shoulders repair, etc.</td>
</tr>
<tr>
<td></td>
<td>Drainage</td>
<td>culvert repairs, clearing side drains</td>
</tr>
<tr>
<td></td>
<td>Routine Miscellaneous</td>
<td>vegetation control, markings, signs</td>
</tr>
<tr>
<td>Periodic Maintenance</td>
<td>Preventive Treatment</td>
<td>fog seal, rejuvenation</td>
</tr>
<tr>
<td></td>
<td>Resurfacing</td>
<td>surface dressing, slurry seal, cape seal, regravelling</td>
</tr>
<tr>
<td></td>
<td>Rehabilitation</td>
<td>overlay, mill and replace, inlay</td>
</tr>
<tr>
<td></td>
<td>Reconstruction</td>
<td>partial reconstruction, full pavement reconstruction</td>
</tr>
<tr>
<td>Special</td>
<td>Emergency</td>
<td>clearing debris, repairing washout/subsidence, traffic accident removal, etc.</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>snow removal, salting, gritting, etc.</td>
</tr>
</tbody>
</table>
## Road Works Activities (2)

<table>
<thead>
<tr>
<th>Works Class</th>
<th>Works Type</th>
<th>Works Activity /Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement</td>
<td>Widening</td>
<td>partial widening, lane addition,</td>
</tr>
<tr>
<td></td>
<td>Realignement</td>
<td>horizontal and vertical geometric improvements, junction improvement</td>
</tr>
<tr>
<td></td>
<td>Off-carriageway</td>
<td>shoulders addition, shoulders upgrading, NMT lane addition, side drain improvement, etc.</td>
</tr>
<tr>
<td>Construction</td>
<td>Upgrading</td>
<td>upgrading by changing the surface class</td>
</tr>
<tr>
<td></td>
<td>New section</td>
<td>dualisation of an existing section, new section (link)</td>
</tr>
</tbody>
</table>
Maintenance Interventions

• Scheduled
  □ Fixed intervals of time between interventions
  □ Interventions at fixed points of time

• Responsive
  □ Pavement condition
  □ Pavement strength
  □ Surface age
  □ Traffic volumes/loadings
  □ Accident rates
Maintenance Effects

- Depending on distress maintenance has different effects

- Pothole Repair
- Crack Sealing
- Surface Treatment

Distress Quantity

Rutting

Cracking

IRI

Time or Traffic
Maintenance May Affect

- Pavement strength
- Pavement condition
- Pavement history
- Maintenance cost

REMEMBER … the type of treatment dictates what it will influence
Works Duration – One Year

Path: Scheduled intervention

- Cbo = Ca1
- Cb1
- Cb2 = Ca3
- Cb4

Path: Responsive intervention

- Ca2
- Ca0

Note:
- Cay = Variable at the beginning of year y
- Cby = Variable at the end of year y

Road variable

Works Duration – One Year

- Scheduled intervention

- Responsive intervention

- Percent total costs

- Years

- Years
Works Duration – Up to Five years

Note:
Cay = Variable at the beginning of year y
Cby = Variable at the end of year y

Road variable
Responsive intervention

Cao

0  1  2  3  4
Years

Percent total costs

40
30

0 1 2 3 4
Years

Scheduled intervention
# Hierarchy of Roads Works

<table>
<thead>
<tr>
<th>Works Type</th>
<th>Works Activity / Operation</th>
<th>Hierarchy</th>
<th>Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>New section</td>
<td>Dualisation of an existing section</td>
<td>1</td>
<td>per km</td>
</tr>
<tr>
<td>Upgrading</td>
<td>Upgrading to a new surface class</td>
<td>2</td>
<td>per km</td>
</tr>
<tr>
<td>Realignment</td>
<td>Geometric realignment</td>
<td>3</td>
<td>per km</td>
</tr>
<tr>
<td>Widening</td>
<td>Lane addition</td>
<td>4</td>
<td>per m2 or per km</td>
</tr>
<tr>
<td></td>
<td>Partial widening</td>
<td>5</td>
<td>per m2 or per km</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>Pavement reconstruction</td>
<td>6</td>
<td>per m2 or per km</td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>Mill and replace</td>
<td>7</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Overlay rubberised asphalt</td>
<td>8</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Overlay dense-graded asphalt</td>
<td>9</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Overlay open-graded asphalt</td>
<td>10</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Inlay</td>
<td>11</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Thin overlay</td>
<td>12</td>
<td>per m2</td>
</tr>
<tr>
<td>Resurfacing</td>
<td>Cape seal with shape correction</td>
<td>13</td>
<td>per m2</td>
</tr>
<tr>
<td>(Resealing)</td>
<td>Cape seal</td>
<td>14</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Double surface dressing with shape correction</td>
<td>15</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Double surface dressing</td>
<td>16</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Single surface dressing with shape correction</td>
<td>17</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Single surface dressing</td>
<td>18</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Slurry seal</td>
<td>19</td>
<td>per m2</td>
</tr>
<tr>
<td>Preventive</td>
<td>Fog sealing</td>
<td>20</td>
<td>per m2</td>
</tr>
<tr>
<td>Treatment</td>
<td>Rejuvenation</td>
<td>21</td>
<td>per m2</td>
</tr>
<tr>
<td>Routine</td>
<td>Edge repair*</td>
<td>22</td>
<td>per m2</td>
</tr>
<tr>
<td>Pavement</td>
<td>Patching*</td>
<td>22</td>
<td>per m2</td>
</tr>
<tr>
<td></td>
<td>Crack sealing*</td>
<td>22</td>
<td>per m2</td>
</tr>
</tbody>
</table>
# Pavement Type After Maintenance

<table>
<thead>
<tr>
<th><strong>Existing Pavement Type</strong></th>
<th>AMGB</th>
<th>AMSB</th>
<th>AMAB</th>
<th>AMAP</th>
<th>STGB</th>
<th>STSB</th>
<th>STAB</th>
<th>STAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine works</td>
<td>AMGB</td>
<td>AMSB</td>
<td>AMAB</td>
<td>AMAP</td>
<td>STGB</td>
<td>STSB</td>
<td>STAB</td>
<td>STAP</td>
</tr>
<tr>
<td>Preventive Treatment</td>
<td>AMGB</td>
<td>AMSB</td>
<td>AMAB</td>
<td>AMAP</td>
<td>STGB</td>
<td>STSB</td>
<td>STAB</td>
<td>STAP</td>
</tr>
<tr>
<td>Reseal</td>
<td>STAP</td>
<td>STAP / STSB</td>
<td>STAP</td>
<td>STAP</td>
<td>STGB</td>
<td>STSB</td>
<td>STAB</td>
<td>STAP</td>
</tr>
<tr>
<td>Overlay</td>
<td>AMAP</td>
<td>AMAP / AMSB</td>
<td>AMAP</td>
<td>AMAP</td>
<td>AMGB</td>
<td>AMSB</td>
<td>AMAB</td>
<td>AMAP</td>
</tr>
<tr>
<td>Inlay</td>
<td>AMGB</td>
<td>AMSB</td>
<td>AMAB</td>
<td>AMAP</td>
<td>STGB</td>
<td>STSB</td>
<td>STAB</td>
<td>STAP</td>
</tr>
<tr>
<td>Mill &amp; replace to</td>
<td><strong>AP</strong></td>
<td><strong>AP</strong></td>
<td><strong>AP</strong></td>
<td><strong>AP</strong></td>
<td>N/A</td>
<td><strong>SB</strong></td>
<td><strong>AB</strong></td>
<td><strong>AP</strong></td>
</tr>
<tr>
<td>intermediate surface</td>
<td><strong>GB</strong></td>
<td><strong>SB</strong></td>
<td><strong>AB</strong></td>
<td><strong>AP</strong></td>
<td><strong>GB</strong></td>
<td><strong>SB</strong></td>
<td><strong>AB</strong></td>
<td><strong>AP</strong></td>
</tr>
<tr>
<td>Mill &amp; replace to base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* will depend on the 'critical' thickness (Hmin) of the existing bituminous surfacing

** indicates that this is dependent on the specific works activity (i.e., operation) and the surface material
HDM Series – Volume 4