SARF COURSE

PRACTICAL ROAD PAVEMENT ENGINEERING

6. PRINCIPLES OF PAVEMENT DESIGN

PRINCIPLES OF PAVEMENT DESIGN

FUNCTIONS of a PAVEMENT

Primary Function: "To provide a surface condition that allows a safe, comfortable, economic ride for the vehicles using it."

Serviceability: A measure of the pavement's condition can be obtained in a number of ways:

Roughness : Profilometer – Car Instrument
Rut Depth : Straight Edge – Stringline
Cracking : Visuals (Degree and Extent)
Surface Texture : Skid Resistance (Scrim)

Some agencies have access to vehicles able to provide a visual record of the surface at a moderate travelling speed, profile measurements and other properties.

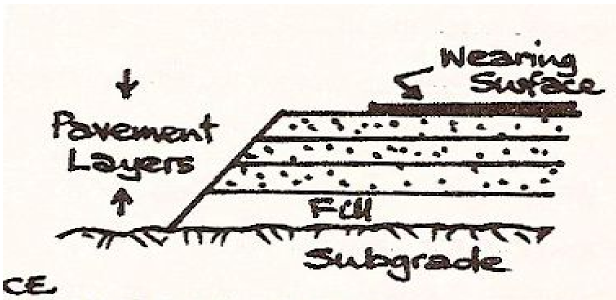
From AASHO Road Tests : subjective evaluation of ride by non-technical passengers rating from 0 = unusable to 5 = perfect.

Correlated with car roughness meters (RCA roadmeter, LDI) to provide Present Serviceability Index (PSI) or (IRI)

Performance: Serviceability for a time or cumulative traffic.

Functions to be designed:

- Subgrade protection
- Stable layer structure
- Durability
- Appropriate wearing surface



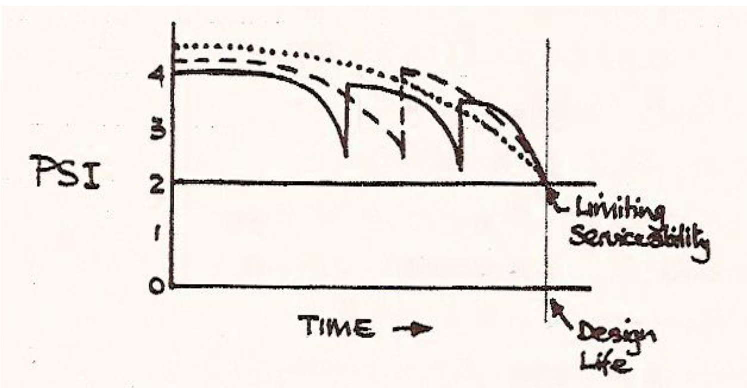
PAVEMENT TYPES

Rigid : Concrete → Slabs : CRC
Semi-rigid : Blocks → CTB or CTSB → BTB → ETB
Flexible : "Untreated" materials

DESIGN INPUT

- Traffic
- Environment – water and temperature
- Material – properties of available sources
- Construction – capabilities
- Maintenance

CONSIDERATIONS OFTEN MORE THAN ONE OPTION



≅ Initial Cost
≅ Cash Flow
≅ Level of Service
≅ Disruption

PRINCIPLES OF PAVEMENT DESIGN

ECONOMIC ANALYSIS

$$PWOC = C + M_1(1 + 1\text{-})^{-X1} + M_2(1 + 1\text{-})^{-X2} + \ldots\ldots\ M_n(1 + 1\text{-})^{-Xn} - s(1 + 1\text{-})^{-2}$$

PWOC = Present North of Cost   C = Initial Construction Cost   M = Maintenance Cost
x = time since construction   r = discount rate   s = salvage value   z = design life

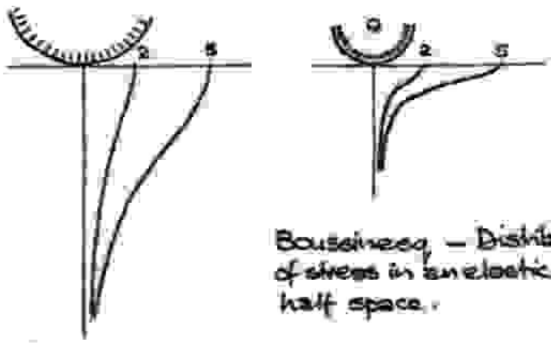
- ❖ Use your good solid past information and experience
- ❖ Don't get in a rut
- ❖ Don't make the same mistakes ……

SOME DESIGN METHODS

EMPIRICAL: CBR - AASHO - DCP

ANALYTICAL: Elastic Plate on Dense Liquid (Concr) ~ Multi-Layer
Elastic Solid (Mechanistic) ~ Visco-Elastic (Creep) ~ Elasto-Plastic (EP)

DAMAGE



Boussinesq – Distribution of stress in an elastic half space.

≅ <u>Traffic</u>

(i) <u>Wheel Loads</u>

Tyre Pressure
Tyre Print
Tyre Load

Failure • Bearing Capacity
Static Loading due to lack of strength
• Fatigue ⟶ Rutting and cracking
Repeated (dynamic) Loading : due to consolidation and "brittleness"

(ii) <u>Tyre Forces</u> (Horizontal)

Breaking force : Turning movements : Abrasion

Failure • Breaking up of surface caused by horizontal shear Dynamic Loading : due to lack of horizontal shear strength.

≅ <u>Environmental</u>

(i) Water
Drainage and subsurface – see page

(ii) Temperature
Degradation of materials

(iii) Other
Tree Rods, moles, collapsing soils and heaving clays

≅ <u>Natural Disasters</u>

Floods, Earthquakes, Subsidence, Instability

TRAFFIC

- The simplest pavement design looks simply at a wheel load category.

- All other systems look at the full spectrum of wheel or axle loads. A degree of damage is apportioned by equating loads that cause the same stress, strain, deflection or distress hence producing an equivalent single wheel load. Most systems relate these loads to an equivalent number of standard or legal wheel or axle loads. The se standard axles are then accumulated to give a total standard axle load to be cleared during the design life of the pavement.

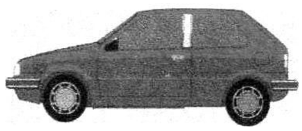
- In South Africa our legal axle load = 88kN (E80) [ESA] but axle loads for historical reasons are given by equivalent 80kN factor where

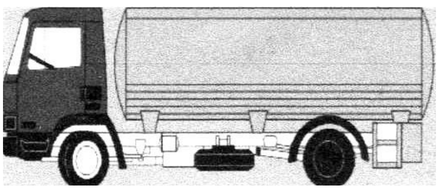
$$F = \left(\frac{P}{80}\right)^n$$

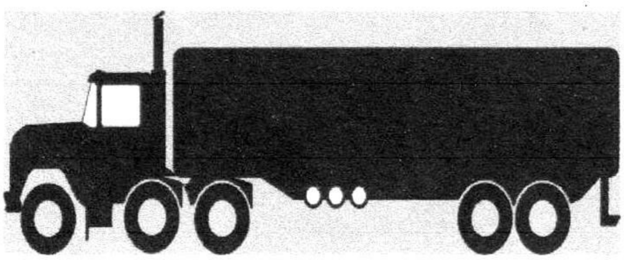
F = load equivalency factor P = axle load n = damage function
'n' typically in RSA taken as 4,2 but could be higher for thin stiff pavement and lower for deep structured pavements.

The equivalent traffic can be derived by summing the individual axles x F and is expressed as the "E80s".

From table 7 of TRH 4 it can readily be seen that, in terms of E80s …

(1)  An ordinary saloon car with < 15 kN axle load does no damage!

(2)  A "standard" Truck with 80 kN axle load would generate one E80.

(3)  A heavy vehicle with an E80 of 2,4 per axle would generate 9,6 E80s !

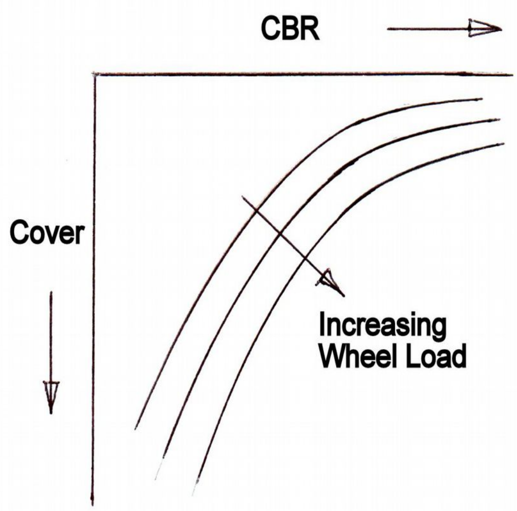
PRINCIPLES OF PAVEMENT DESIGN

DESIGN METHODOLOGIES

There are numerous design methodologies in use throughout the world. Three different approaches are presented very simply to illustrate the different approaches:

1. CBR DESIGN CURVEs

The method is based on the CBR test and was developed in the USA using an empirically derived set of CBR cover to subgrade curves.



ADVANTAGES: Easy to use
Based on practical experience

DISADVANTAGES: Does not provide for volume of traffic
Problem of CBR values for asphalt and cemented layers.
Makes no allowance for climatic conditions.

2. AASHO DESIGN PROCEDURE

Based on the results of the AASHO Road Test:

- Takes into account axle equivalency and calculates cumulative E_{80} axles over the design life = N (South African Modification).
- Adjusts cumulative traffic for environmental conditions using a regional factor R such that weighted traffic W = R x N.
- From a standard table based on the weighted traffic, a standard design structural number (DSN) is obtained.
- Using the formula RSN = 0,04 $(a_1D_1+a_2D_2+a_3D_3+a_4D_4)$, a standard road pavement is checked where a_n = coefficient of relative strength of a layer material and D_n = thickness of layer.

RSN > DSN for a successful design.

ADVANTAGES : Allows for traffic spectrum
Provides for climatic conditions
Allows for modified pavement material
Reasonably simple to use and some practical experience

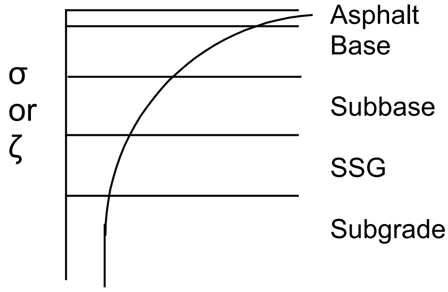
DISADVANTAGES : Developed in freeze/thaw zones of USA
Unbalanced pavement design

3. MECHANISTIC DESIGN

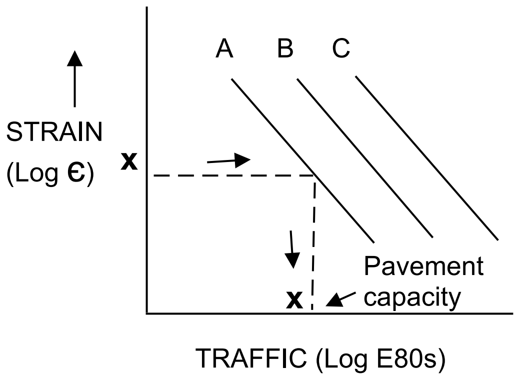
This method provides the background theoretical approach to the catalogue designs given in TRH4 and UTG3.

PRINCIPLES OF PAVEMENT DESIGN

- ≅ Takes into account the spectrum of traffic expressing traffic in terms of E80 accumulated axles.
- ≅ Calculates tensile and compressive stresses and strains in a multi layer pavement using elastic theory.
- ≅ Allows for cemented stiff layers.
- ≅ Assesses layer strengths on the basis of a catalogue of resilient moduli strengths obtained for typical materials.



- ❑ Based on the maximum vertical strain in the subgrade and tensile strain in asphalt and cemented layers, determined in the elastic layer analysis, relates through sets of semi-empirically based strain vs. traffic curves to provide traffic life of a pavement. Contains a number of adjustments, shift factors and checks.



ADVANTAGES :	Uses elastic properties (flexure under load) Has multiple checks for various layers Wide experience in RSA over the last 25 to 30 years.
DISADVANTAGES:	More cumbersome to use Adjustment factors Not good approach to cemented materials Does not allow input of fatigue data (way to go in the future).

In summary has stood RSA in good stead over last 35 years and provided backbone for our catalogue designs, which are very widely used. If further work is required and knowledge sought in the field of pavement design – NOW IS THE TIME TO MOVE ON!

The elastoplastic (EP) design method uses non-linear elastic theory (which includes an allowance for permanent (plastic) strain) to arrive at the numbers of load applications a flexible pavement will carry.

THE CATALOGUE DESIGN TRH 4 and UTG 3

SUMMARY OF MAIN POINTS (TRH 4)

- ≅ Road category - A to D
- ≅ Design strategy
- ≅ Design traffic – Traffic Class E0 $\longrightarrow$ E4
- ≅ Materials – TRH 14 – G1 to G10

PRINCIPLES OF PAVEMENT DESIGN

- ≅ Environment – Subgrade Design CBR
- ≅ Structural design and pavement type
- ≅ Practical considerations – Drainage, Compaction, subgrade
- ≅ Cost analysis – Present worth of cost (PWOC)
- ≅ Glossary of terms
- ≅ Appendix A – Worked example
- ≅ Catalogues

<u>Other current catalogues</u> : UTG 3 - Urban conditions
UTG 2 - Segmental blocks

CATALOGUE DESIGN EXAMPLE

ROAD : Part of a national route (N) in the Border area of the Eastern Cape – 2 lanes.

TRAFFIC : 600 vehicles per day with about 20% heavy vehicles, moderately Laden, steady growth.

SUBGRADE : Predominantly shales and mudrocks.

MATERIAL AVAILABLE : Hard rock dolerite
Weathered (sugar) dolerite
Shale

CONSTRUCTION COMPLETION DATE : in 3 years time

SELECT A SUITABLE PAVEMENT DESIGN USING TRH 4

1. • Select the road category (Table 1)

2. • Structural design period : 20 Y

3. • Design Traffic

AADT* : 600 Heavy v.p.d. : 120
Heavies per lane : 60 Loading factor (Table 5) : 1,6
E80 / lane / day : 96 Growth Rate (Table 10) : 6%
E80's end of construction : (Table 11 : 96 x 3Y @ 6% (1,19) = 114
Cumulative E80s over design period : 114 x 14 232 = 1,6 x 10^6
Traffic class (Table 4) : ES3
* 2 way

4. • List materials available

Surfacing : Asphalt, Concrete & Seals
Base : Hard rock Dolerite
Subbase : Dec Dol. (Weathered Dolerite)
SSG : Shale and Dec Dol.

5. • Environment
   Climatic Region (Figure 4) : WET
   Material Depth : 1000 mm (Upper bound because of wet conditions)
   Design CBR of subgrade : EST. Estimate lowest CBR

6. • Select pavement type
   Table 19 : Granular cemented or asphalt cemented
   Selected layers
   Table 22 : Design CBR 3-7

7. • Catalogue selection summary

   Type : Granular base climatic region : Wet
   Road Cat. : B Traffic class : ES3

Surfacing	:	30 Asphalt A	Compaction (Table 17)
Base	:	150 G1	86% App D or 85% Bulk per Dens.
Subbase	:	150 C4	95% MDD*
SSG	:	150 x 2 № G7 on G9	95% upper, 93% lower, MDD
Material Depth	:	1000 mm	*Some Authorities require 97%

8 • Cost Analysis **Note:** All costs based on typical 1992 rates near East London

Compare with hot mix ASPH base design: 30A, 80 BTB, 200 C4 (Catalogue page 99).

Calculate Initial construction cost (R/m^2):

Payment type	**Granular**	**BTB**
Surfacing	R9,00/m^2	R9,00/m^2
Base	R120/m^3 x 0,125 m = R15,00/m^2	R250/m^3 x 0,09 = R22,50/m^2
Subbase	R23/m^3 x 0,150 m = R3,45/m^2	R23/m^3 x 0,150 m = R3,45/m^2
All other work	Incl. P & Gs etc R40 m/^{2}	Incl. P & Gs etc R40/m^2
TOTAL	**R67,45/m^2**	**R74,95/m^2**

NB *Values used in the above table are old! However, the principle of comparatives remains valid and useful. Do the exercise using today values!*

Maintenance Measures

From Table 23 : Surfacing Life

Granular : 10-15 - based on experience : 12

Bituminous : 8-15 - based on experience : 12

Climatic Region : WET ∴ STS better equipped to resist water ∴ longer life

Select possible maintenance strategies

Granular : Year 10 : Bit-Rubber 13mm seal Year 16 : 30A overlay
Bituminous : Year 12 : Ordinary 13mm seal Year 17 : Bit-Rubber 13mm seal

PRINCIPLES OF PAVEMENT DESIGN

Assign Costs : Bit-Rubber 13mm Seal : R7,00/m^2
Ordinary 13mm seal : R4,50/m^2
30 A Overlay : R10/m^2 (additional estab. Costs)

NB *As above do exercise using today costs.*

Estimate Salvage Value (S) (9.6 on pg 71)

Granular 30% of initial construction = R20,00/m^2
Bituminous 30% of initial construction = R22,50/m^2

Sensitivity study take S = O

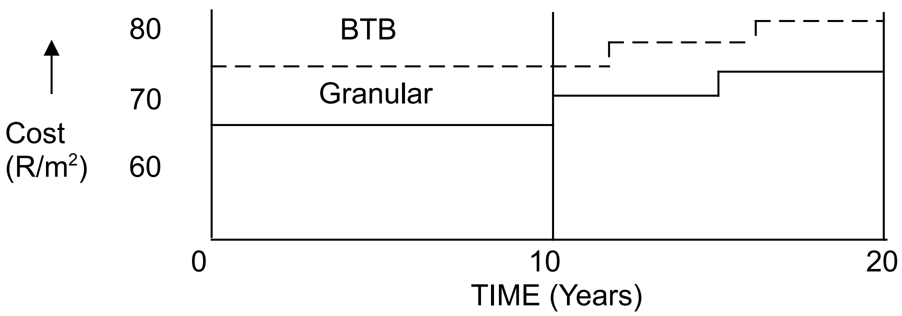
$$PWOC = C + M_1(1+r)^{-X1} + M_2(1+r)^{-X2} + \ldots\ldots\ldots - S(1+r)^{-Z}$$

use r = 8% (Can run sensitivity check with r = 6% to 12%)

Granular PWOC = R67,45 + Brs_{y12} + AG_{y16} – Salvage
= R67,45 + R7,00 $(1 + 0{,}08)^{-10}$ + R10,00 $(1 + 0{,}08)^{-16}$
- R20,00 $(1 + 0{,}08)^{-20}$
= R67,45 + R3,24 + R2,92 – R4,29
= R69,32/m^2

Bituminous PWOC = R74,95 + Sy12 + Brs_{y12} – Salvage
= R74,95 + 14,5 $(1{,}08)^{-12}$ + R7,00 $(1{,}08)^{-17}$ - R22,50 $(1{,}08)_{-20}$
= R74,95 + R1,79 + R1,89 – R4,82
= R73,81/m^2

Construct Cash-flow Diagram



Disruption to travelling public

Two each – maintenance operations v. similar.

Practical considerations

Because of BTB, contractor might establish drum mixer on site and cost could be lower.

Alternative design : Test by competitive tender. Would be worth considering both options ∵ allow for both with alternatives in the Tender Document.

Post Script : It is very largely heavy vehicles that do the damage. Consider traffic data carefully e.g. Construction traffic, new developments and expanded facilities.

SARF COURSE

PRACTICAL ROAD PAVEMENT ENGINEERING

7. FLEXIBLE PAVEMENT REHABILITATION: INVESTIGATION & DESIGN

REHABILITATION - INVESTIGATION & DESIGN

1 NETWORK LEVEL PMS

Identify at network level projects for possible rehab essential for network management.

2 DESK STUDY

Collect and study any as-built and ride quality data
Previous maintenance & rehab measures
Traffic data ⟶ Cumulative to date/growth rate.

3 FIELD INVESTIGATION

PHASE 1 – VISUAL INSPECTION

The entire length of the pavement is walked (including setting out the distance at 20m intervals using a wheel and identified paint marks). All forms of distress are shown on the Detailed Visual Inspection Sheet (e.g. Fig 29). The distress is sketched on the sheet to approximate scale and size (can also record approx. size i.e. 3m x 5m or 15m long) and identified as per Table 1 and Degree rated as per Table 2.

This inspection can in at least 80% of cases provide the information required to carry out the rehab design.

It is most important to correctly and accurately record the pavement condition – don't rush it or skip the process.

Remote sensing vehicles are available but analysis of the data requires careful evaluation and processing. The design engineer must always correlate such data with a personal field inspection!

The individual types of distress are defined in TRH6 together with guidelines for categorising degree of distress i.e. a crocodile crack (C) would be degree 3 and noted on the sheet as "C3". TMH9 is used to assist assessors to identify types and degrees of distress.

TMH9: DRAFT (1990) "Pavement Management Systems : Standard Visual Assessment Manual".

PHASE 2 - FIELD TESTING

The visual assessment data is transferred to initial Assessment Summary Sheets together with the desk study data and a preliminary evaluation made of the overall pavement condition. Based on the overall pavement condition areas where structural problems exist, can be identified. These areas may be identified by carrying out field tests of which there are a number. As this part of the investigation can be costly, the type and extent of field tests must be carefully balanced against the degree of uncertainty that exists re the reason for the distress and the subsequent rehabilitation design.

(i) Trial Pits : Establish the pavement layer types and thickness, sampling for laboratory tests to establish quality of layers and response (where necessary) to stabilization agents

(ii) DCP Tests : To give indication of in situ strength of pavement layers and also the subgrade.

(iii) Deflectograph (Benkelman Beam) : Pavement deflections under load.

(iv) IDM Tests : Structural evaluation of pavement response (elastic) to load.

REHABILITATION - INVESTIGATION & DESIGN

SUMMARY

NETWORK PMS (Identify problem areas).

→ PROJECT LEVEL INVESTIGATION

→ WALKOVER (cornerstone of investigation)

→ PRELIM ID of STRUCTURAL PROBLEMS

→ FIELD TESTS

4 ANALYSIS

4.1 DATA SUMMARY

All the data collected should be summarised on the Assessment Summary Sheets. The visually recorded distress is categorised into 3 classes based on the extent of degree 3 to 5 distress as follows:

- ≅ Sound Condition = Extent of Distress (3 to 5) < X
- ≅ Warning Condition = X ≤ Extent of Distress (3 to 5) < Y
- ≅ Severe Condition = Y ≤ Extent of Distress (3 to 5).

The extent of X and Y are given for various types of distress in the following tables : (usually over an interval of 100m).

TABLE 15: PERFORMANCE CRITERIA FOR VISUALLY RECORDED DISTRESS

Distress Parameter	Category of Road					
	A		B		C & D	
	X	Y	X	Y	X	Y
Cracking:						
≅ Crocodile	5%	15%	10%	20%	15%	25%
≅ Longitudinal	30%	60%	45%	75%	60%	90%
≅ Other*	10%	30%	20%	40%	30%	50%
Deformation:	5%	15%	10%	20%	15%	25%
Disintegration:						
≅ Patching	10%	30%	20%	40%	30%	50%
≅ Ravelling	20%	40%	30%	50%	40%	60%
Smoothing:	20%	40%	30%	50%	40%	60%

* Combinations of cracking or cracking other than crocodile or longitudinal

Mechanical measurements such as DCP, PSI/IRI, deflection and radius of curvature are categorised as follows:

Sound < X ≤ Warning < Y ≤ Severe

TABLE 17 PERFORMANCE CRITERIA for the ASSESSMENT of SERVICEABILITY

Road category	Riding quality (PSI)		Riding quality (IRI)		Riding quality (HRI)		Rut depth (mm)		Skid Resistance (SFC80)	
	X	Y	X	Y	X	Y	X	Y	X	Y
A B C	3,0 2,5 2,0	2,5 2,0 1,5	2,9 3,5 4,2	3,5 4,2 5,1	2,0 2,7 3,5	2,7 3,5 4,5	10 10 10	20 20 20	Refer road authority	

TABLE 18 : PERFORMANCE CRITERIA for the ASSESSMENT of STRUCTURAL CAPACITY

Parameter	Base material	Moisture regime	Category of road					
			A		B		C	
			X	Y	X	Y	X	Y
Deflection (Benkelman Beam) (mm)	NGB (UBS) NGB (TSB) LCB BTB CTB	- - - - -	0,4 0,3 0,3 0,2 0,2	0,7 0,6 0,6 0,5 0,4	0,5 0,4 0,4 0,3 0,3	1,0 0,9 0,8 0,7 0,6	0,7 0,6 0,6 0,5 0,4	1,4 1,3 1,2 1,0 0,8
Radius of Curvature (m) (Dehlen Curvature Metre)	NGB (UBS) NGB (TSB) LCB BTB CTB	- - - - -	100 150 200 300 300	80 80 100 130 150	80 110 150 200 200	45 60 75 90 100	60 80 100 130 150	30 30 30 30 30
DCP Values (DSN_{800}) *	- - - -	M1 M2 M3 M4	350 430 540 670	155 190 240 300	230 290 360 440	110 130 160 200	155 190 240 300	70 90 110 140

* DSN = DCP structure number

OVERALL STRUCTURAL CONDITION

Based on the individual types of distress, the overall pavement conditions should be assessed. This exercise requires experience and an understanding of the interdependence of various types of distress.

4.2 UNIFORM SECTIONS

From the Assessment Summary Sheets, the route being investigated should be divided into sections of uniform condition e.g.

km 0 to km 15,5 : Isolated failures, general condition fair
km 15,5 to km 18,7 : Severe condition, possibly base failure

Typically, pavements should be grouped in the following way:

- ≅ No significant problems
- ≅ Surface problems only (no sign of structural distress)
- ≅ Sections showing localized distress
- ≅ Structural defects evident

Certain test data such as DCP, Deflections & Radius of curvature, and IDM values, can be interpreted such that an indication can be obtained as to the layer or zone of layers where there is a structural inadequacy. This information together with the visual observations and test pit data, should be used to establish the most likely cause of distress.

*** IMPORTANT :**

Wrong distress diagnosis could lead to wrong treatment for rehabilitation.

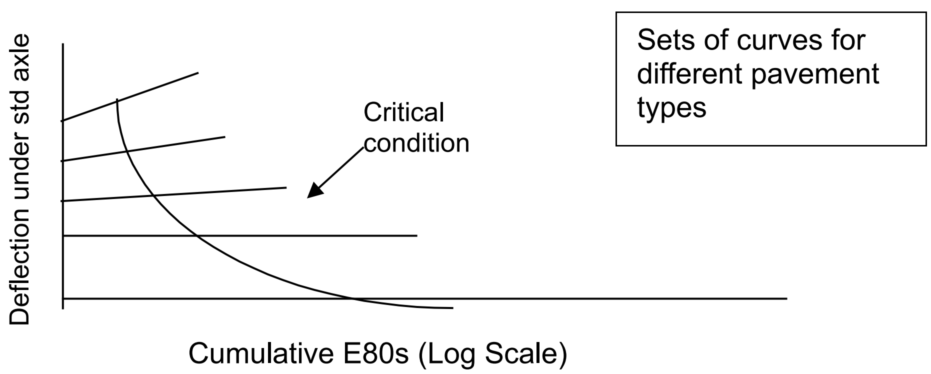
Summarise all the data (both visual, mechanical and historical) using Pavement Situation ID Sheet (see Figure 16 TRH12)

4.3 STRUCTURAL ANALYSIS

<u>RESIDUAL LIFE</u> Where a pavement has not yet failed, it is of value to determine residual or remaining life. The following methods can be used:

TRRL deflection measurement curves
DCP curves
IDM tables
Mechanistic Design
Experienced Judgement

TRRL
Deflection
Curves



REHABILITATION - INVESTIGATION & DESIGN

REHABILITATION OPTIONS

Before attempting a structural design, we need to examine the pavement condition and identify possible options,

e.g.	Base failure	- rework existing base
	Thin pavement	- overlay
	Surface distress	- renew surface

These options would be identified for each uniform section. It is quite likely that more than one option might be suitable.

DESIGN METHODS Empirical & Theoretical

Empirical
(a) Experience based on Condition Assessment
(b) Deflection based (Limitations for semi-rigid)
(c) DCP

Theoretical
(d) Mechanistic

5. ECONOMIC ANALYSIS

$$PWOC = R + M_1 (1 + r)^{-X1} + M_2 (1 + r)^{-X2} \ldots\ldots -S (1 + r)^{-Z}$$

R = initial rehab cost M = measures required during the design period

S = salvage value X = time since initial rehab Z = design period

Particularly when dealing with rehab projects, a stage construction approach is often adopted i.e. over a period of 20 years on option could be :

Year 0 = Light Rehab – rework & establish existing base

Year 8 = Asphalt overlay

Year 16 = Seal

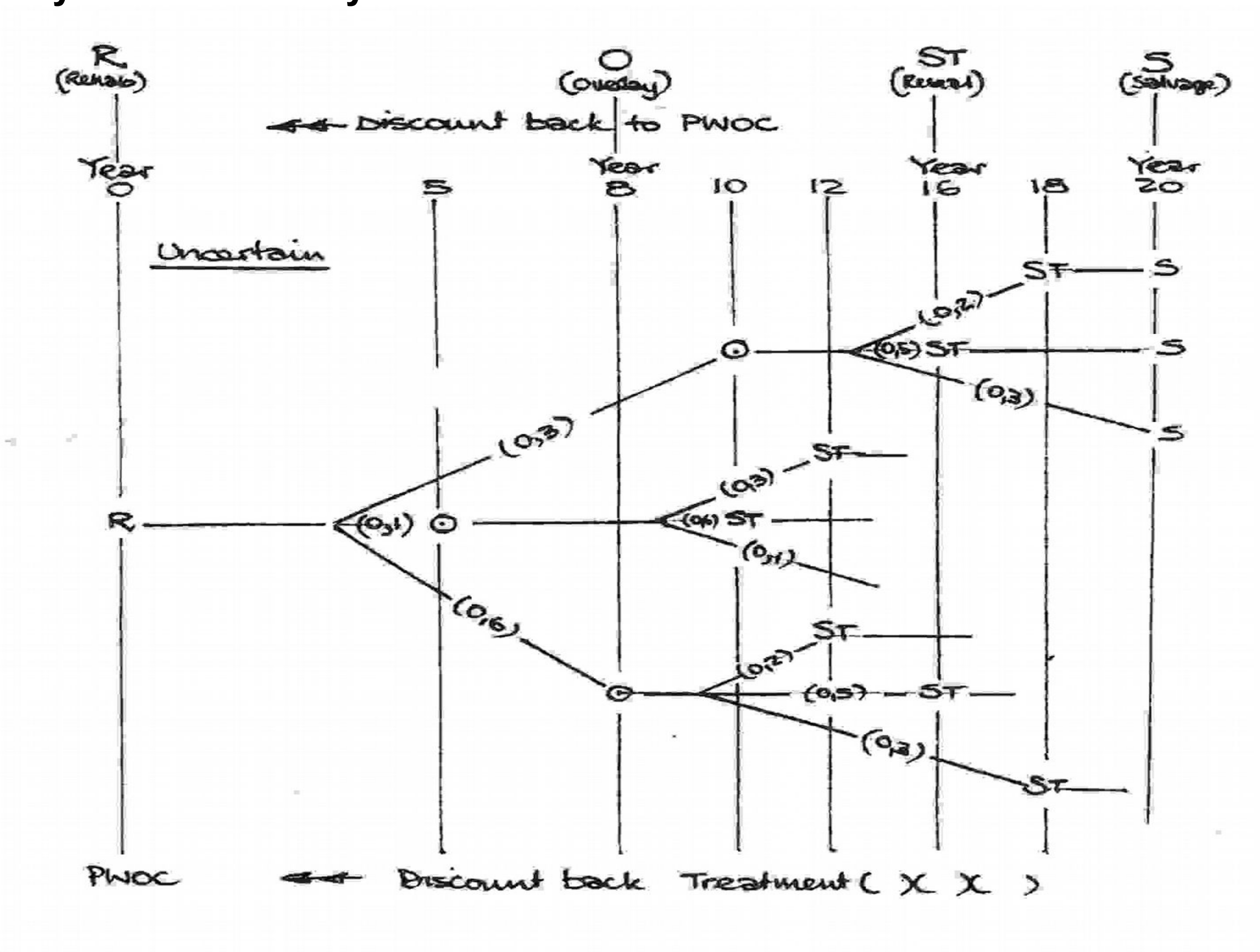
UNCERTAINTY

There may be considerable uncertainty as to exactly how long a particular measure may last e.g. can one be sure that at exactly 8 years an overlay will be required? Or put another way, will the whole section be at the same condition at year 8 or will some parts be worse or better?

We handle this uncertainty by using principles of Bayesian analysis and decision trees as follows:

REHABILITATION - INVESTIGATION & DESIGN

Bayesian Tree Analysis



6. SELECTION OF MOST EFFECTIVE STRATEGY

≅ REVIEW OPTIONS EXAMINING:-

Initial capital cost Cash Flow Total PWOC	Finance
Geometrics Pavement Width PSI / IRI	Safety and Service
Number of treatments verses time	Disruption to travelling public

≅ TEST CLIENT / USER REQUIREMENTS

With regard to Financial Constraints
Safety
Disruption

Select strategy that best covers the requirements.