COST EFFECTIVE DESIGNS FOR LOW VOLUME SEALED ROADS IN TROPICAL AND SUB TROPICAL COUNTRIES

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1. INTRODUCTION

Since 1994, TRL in collaboration with a number of road authorities and consultant partners have been engaged in extensive studies of the performance of low volume sealed roads within Southern Africa (Greening and Gourley, 1999). The roads included in service primary and secondary roads with ages varying from thirty years old to relatively new roads and specially constructed experimental sections. The roads examined were located in Botswana, Malawi, Zambia and Zimbabwe. The primary objectives of the studies were:

i)   To derive cost effective pavement materials and design standards which promote greater use of local resources;

ii)   To produce calibrated road deterioration relationships for these categories of road taking full account of important design and construction parameters;

iii)   To justify improvements to current practice from a technical and economic viewpoint.

The guiding philosophy of the studies has been that the emphasis in road works in the region has moved from construction to the maintenance and rehabilitation of primary roads, and the upgrading of rural secondary and feeder roads. Transport economics dictate that the latter can only be an affordable option if costs are kept to a minimum, and therefore the determination of life cycle costs of alternative pavements under prevailing design, construction and maintenance practice and local traffic and environmental conditions is necessary. Experience has also shown that design criteria for low volume roads, particularly in the drier parts of the region, could be considerably relaxed giving rise to significant cost savings with little disbenefit to road users or increased risks to asset owners.

This paper contains a summary of the new materials specifications and design requirements for low volume sealed roads derived from studies in the region and describes the experimental design and performance of studies of secondary and feeder roads in Zimbabwe which have been crucial to the derivation of recommendations. The observed rates of deterioration on these roads are compared with those predicted by the Highway Development and Management tool HDM-4 (Kerali et al, 1996) in order to derive appropriate calibration factors for cracking, rutting and roughness progression models. These have then been applied in an economic evaluation to derive life-time costs of sealed roads built to different standards.

The details quoted herein form the basis of new design guidelines for low volume roads adopted by Zimbabwe's MoTE (MoTE, 1998). They draw on the results of regional research programmes carried out by the TRL and collaborating authorities and earlier stages of the Zimbabwe Secondary and Feeder Road Development Project (SFRDP, 1995). The guidelines are a major step forward from the traditionally

accepted design criteria applied to the design of trunk roads, in that they recognise the controlling influence of the road environment on the deterioration of lighter pavement structures, and their incorporation into international standards is an important next step. Research is also continuing to provide improved solutions in the wetter climatic areas.

2. PAVEMENT DESIGN AND SPECIFICATIONS

2.1 Current Standards

The Zimbabwe MoTE pavement design procedure is perhaps one of the most comprehensive and well founded sets of standards in the region and, together with TRL's Road Note 31 (TRL, 1993) and the South African TRH 4 (NITRR 1980), has been used as a basis for considering possible improvements to technical standards. It uses a design catalogue based on pavement standard (i.e. the pavement life defined by the number of equivalent 80 kN axle repetitions) and the subgrade soil strength (i.e. the design soaked CBR). There are five pavement standards for sealed roads in Zimbabwe; 3M, 1M, 0.3M, 0.1M and 0.05M. A 1M standard corresponds to a design traffic level of between 0.3 and 1.0 million equivalent standard axles (esa) applied over a 20 year period.

Subgrade materials are tested for grading, plasticity index and soaked CBR. Four design subgrade CBR classes are used. These are:

- SG9 - any soil with a design CBR of 9 or more

- SG5 - any soil with a design CBR of 5 or more but less than 9

- SG3 - any non expansive soil with a design CBR of 3 or more but less than 5

- SGE - any expansive soil.

The MoTE design makes an allowance for the different climatic areas in the country. This is achieved by increasing or decreasing the effect of traffic in these areas. In the eastern areas of the country where the climate is wetter, the traffic (esa) is multiplied by a factor of 1.2, whilst in the drier southern areas a factor of 0.8 is applied.

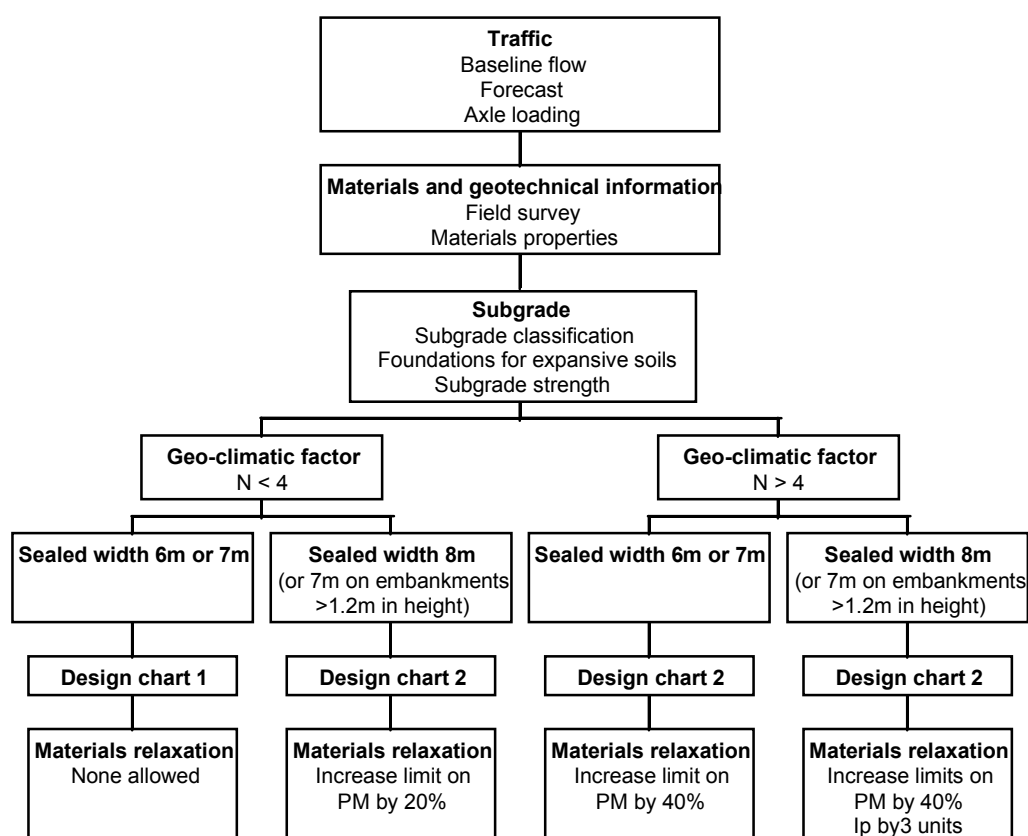### 2.2 Design Guidelines for Low Volume Roads

In developing design guidance for the region a number of key issues emerged which were observed to significantly affect performance and cost effectiveness including -

- The need for a greater number of subgrade design classes to take advantage of the strong subgrade materials which predominate over extensive parts of the region. This lead to two new subgrade classes, an SG15 and SG30.

- A greater number of design traffic classes (0.01M, 0.50M and 3M) with respect to the Zimbabwe standards, and which add 3 additional classes in the low volume range (< 0.3M) when compared to international standards, eg. Road Note 31.

- Selection criteria for quality of road base materials based on traffic, subgrade design class, crown height, sealed surface design, including the benefits of sealing road shoulders, and geo-climatic zone.

By incorporating a recognised climatic variable, the geographical transferability of the findings can be undertaken with confidence. The new criteria also recognise the importance of managing the impact of water on pavement layers and the road foundation.

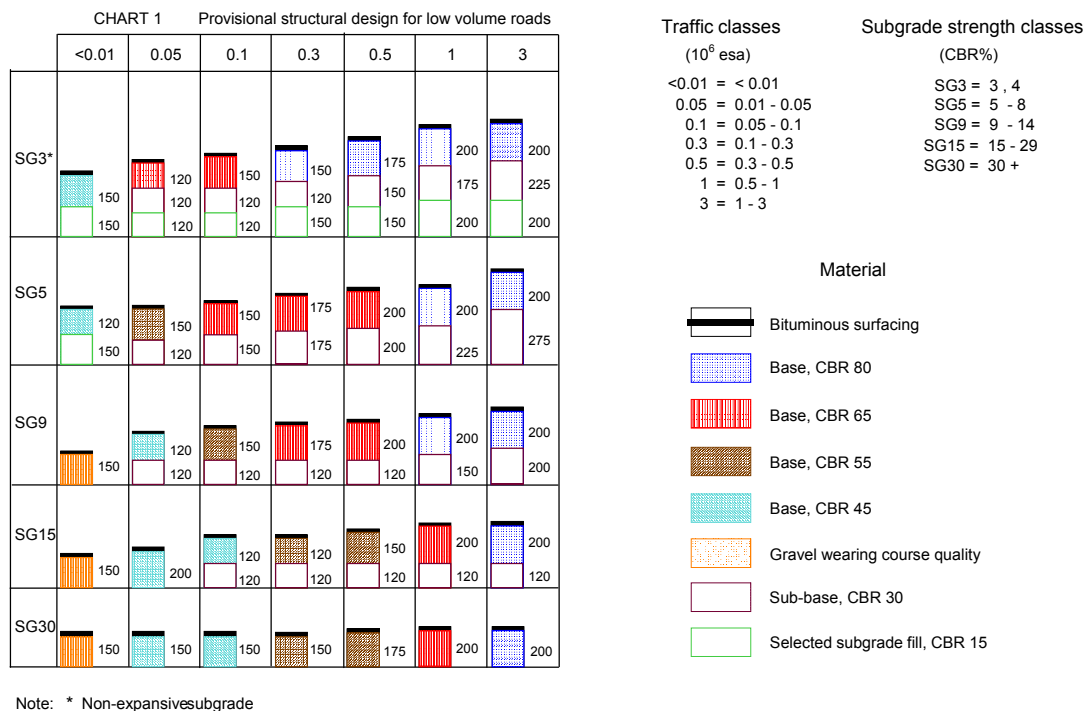### 2.2.1   Pavement Thickness Design

The approach developed for pavement design is summarised in Figure 1. Comments on the key factors are given below.

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                        ┌─────────────────────────┐
                        │         Traffic         │
                        │      Baseline flow      │
                        │        Forecast         │
                        │      Axle loading       │
                        └─────────────────────────┘
                        ┌─────────────────────────────┐
                        │ Materials and geotechnical   │
                        │         information          │
                        │        Field survey          │
                        │     Materials properties     │
                        └─────────────────────────────┘
                        ┌─────────────────────────────┐
                        │          Subgrade            │
                        │   Subgrade classification    │
                        │ Foundations for expansive soils│
                        │      Subgrade strength       │
                        └─────────────────────────────┘
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Geo-climatic factor N < 4		Geo-climatic factor N > 4	
Sealed width 6m or 7m	**Sealed width 8m** (or 7m on embankments >1.2m in height)	**Sealed width 6m or 7m**	**Sealed width 8m** (or 7m on embankments >1.2m in height)
Design chart 1	**Design chart 2**	**Design chart 2**	**Design chart 2**
Materials relaxation None allowed	**Materials relaxation** Increase limit on PM by 20%	**Materials relaxation** Increase limit on PM by 40%	**Materials relaxation** Increase limits on PM by 40% Ip by 3 units

Figure 1 Flow chart for sealed road design process

Climate: Climatic zones are characterised by the Weinert N-values (Weinert, 1974). N-values less than 4 imply a seasonally wet tropical or sub tropical climate. Values greater than 4 indicate a tropical or sub tropical arid or semi-arid climate. The pavement design chart for N < 4 for sealed widths less than 7 m (Chart 1) is reproduced in Figure 2

Traffic and environmental effects: For a correctly constructed pavement carrying low levels of traffic, there is a low risk of a pavement failure being induced by traffic, and deterioration is controlled mainly by environmental factors. This is consistent with the finding that materials that are of marginal quality, in the traditional sense, perform well at low traffic levels. However, as traffic levels increase, the specification for road bases should approach those of traditional design charts. Experience suggests that this transition is in the range of design traffic classes of 0.3M to 0.5M.

CHART 1   Provisional structural design for low volume roads

	<0.01	0.05	0.1	0.3	0.5	1	3
SG3*	150 / 150	120 / 120 / 120	150 / 120 / 120	150 / 120 / 150	175 / 150 / 150	200 / 175 / 200	200 / 225 / 200
SG5	120 / 150	150 / 120	150 / 175	175 / 200	200 / 200	200 / 225	200 / 275
SG9	150	120 / 120	150 / 120	175 / 120	200 / 120	200 / 150	200 / 200
SG15	150	120 / 200	120 / 120	120 / 120	150 / 120	200 / 120	200 / 120
SG30	150	150	150	150	175	200	200

Traffic classes
(10^6 esa)

<0.01 = < 0.01
0.05 = 0.01 - 0.05
0.1 = 0.05 - 0.1
0.3 = 0.1 - 0.3
0.5 = 0.3 - 0.5
1 = 0.5 - 1
3 = 1 - 3

Subgrade strength classes
(CBR%)

SG3 = 3 , 4
SG5 = 5 - 8
SG9 = 9 - 14
SG15 = 15 - 29
SG30 = 30 +

Material

- Bituminous surfacing
- Base, CBR 80
- Base, CBR 65
- Base, CBR 55
- Base, CBR 45
- Gravel wearing course quality
- Sub-base, CBR 30
- Selected subgrade fill, CBR 15

Note: * Non-expansive subgrade

Figure 2 Pavement design chart for sealed widths less than 7 m (N<4)

Sealed width: On total sealed widths of 7 metres or less, the outer wheelpath is within one metre of the edge of the seal. This affects pavement performance adversely, so relatively stronger pavements are necessary in these situations. If the road width is sufficient for the outer wheelpath to be more than 1.5 metres from the pavement edge, and good drainage is ensured by maintaining the crown height at least 700 mm above the ditch, a further improvement in performance results which is reflected in the charts. The different sealed surface widths are, therefore, treated separately in the design charts.

Embankments: When a road is on an embankment of more than 1.2 m in height, the material in the road base and sub-base stays relatively dry, even in the wet season. In this case, the design category can be relaxed, and a pavement with a 7 m total sealed width can be designed to the same criteria as an 8 m seal.

2.2.2   Materials Design

The specification is based on the following principles:

- The strength, plasticity and grading requirement varies depending on the traffic level and climate, as shown in Table 1.   For designs in dry environments and where sealed shoulders are employed, relaxation of the plasticity index and plasticity modulus is allowed.

- The soaked CBR test has been used to specify the minimum base material strength, with a compaction requirement for the test of 98% mod AASHTO, and with a minimum soaking time of four days or to zero swell.

- Four grading envelopes (A, B, C and D) for road bases are used, which depend on the traffic and subgrade design class. Envelopes A, B and C are illustrated in Figure 3. Envelope D is specified in terms of Grading Modulus (GM). In the guidelines, Envelope A is sub divided into 3 sub divisions based on nominal maximum size.

3. EXPERIMENTAL STUDIES IN ZIMBABWE

3.1 Approach

In order to derive validated relationships for predicting the deterioration of low volume sealed roads, it was necessary to select and monitor the performance of a wide spectrum of test sections over a period of time.

The required activities involved desk studies, field reconnaissance and visits to Provincial Road Engineer's offices, followed by network surveys. The purpose of the network survey was to quantify the surface, structural and drainage conditions of a representative selection of low volume sealed roads, and to aid the selection process for establishing test sections representative of the low volume sealed road network.

The road network survey comprised a general surface condition survey of 50 metre lengths of road at 0.5 km spacings along each selected road link; a roughness survey with readings recorded every 0.5 km; and a FWD survey with measurements taken in the centre of each 50 metre block.

The performance of the selected test sections of road was then monitored, the performance data analysed and compared with the deterioration rates predicted by HDM-4, enabling appropriate calibration factors for local conditions to be derived for the HDM-4 relationships. Road user costs and economic factors were collated and used in determining life cycle costs of a wide range of alternative pavements with the aim of identifying optimum engineering standards for different design traffic levels.
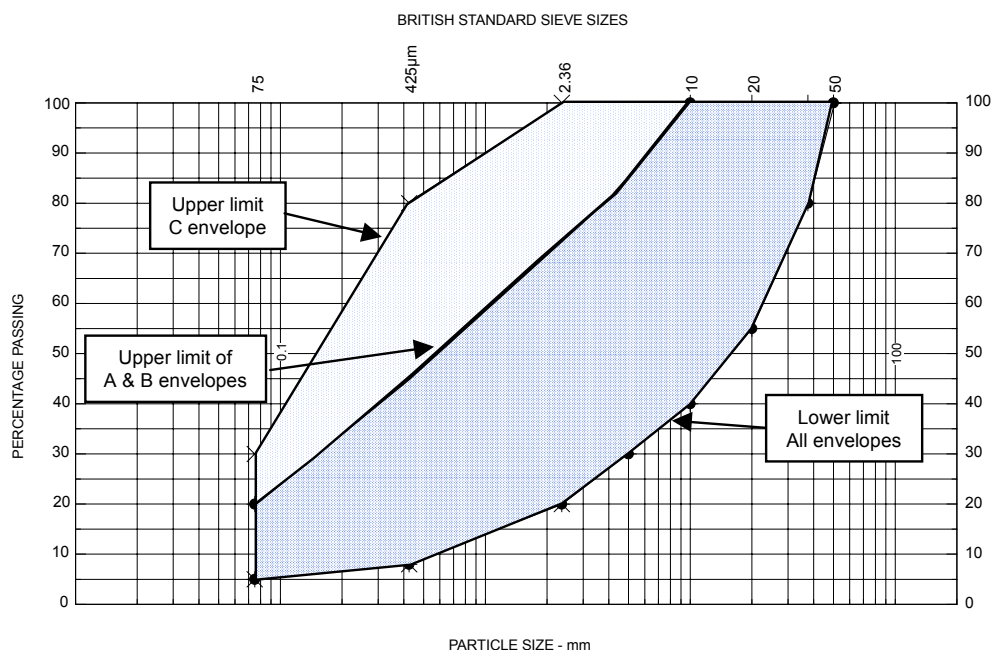
Figure 3 Particle size distributions for natural gravel road bases

Table 1
Selection of natural gravel road base materials

Subgrade class	Material property	Upper limit of design traffic class						
		0.01M	0.05M	0.1M	0.3M	0.5M	1M	3M
SG3	Ip	≤12	≤12	≤9	≤6	≤6	≤6	≤6
	PM	400	250	150	120	90	90	90
	Grading	B	B	B	A	A	A	A
SG5	Ip	≤15	≤12	≤12	≤9	≤6	≤6	≤6
	PM	550	320	250	180	90	90	90
	Grading	C[1]	B	B	B	A	A	A
SG9	Ip	Note (2)	≤15	≤12	≤12	≤9	≤9	≤6
	PM	800	450	320	300	200	90	90
	Grading	D[3]	B	B	B	B	A	A
SG15	Ip	Note (2)	≤15	≤15	≤12	≤12	≤9	≤6
	PM	n/s	550	400	350	250	150	90
	Grading	D[3]	C[1]	B	B	B	A	A
SG30	Ip	Note (2)	≤18	≤15	≤15	≤12	≤9	≤6
	PM	n/s	650	550	500	300	180	90
	Grading	D[3]	C[1]	C[1]	B	B	A	A
			Road base CBR	Max swell (%)				
			45	0.5				
			55	0.3				
			65-80	0.2				

Notes:
(1) Grading 'C' is not permitted in wet climates; grading 'B' is the minimum requirement
(2) Maximum Ip = 8 x GM
(3) Grading 'D' is based on the grading modulus 1.65 < GM < 2.65
- All base materials are natural gravels
- Subgrades are non-expansive
- Further relaxation applicable for the use of laterites and calcretes
- Ip   Plasticity index
- PM   Plasticity modulus = % passing 0.425 mm sieve x Ip
- n/s   Not specified

3.2 Experimental Design

The experimental matrix for the sealed roads covered narrow mats (NM), Otta seals, Low Cost Seals (LCS) which were applied by Provincial authorities in upgrading gravel roads and standard MoTE designed roads with single (SST) and double (DST) seals. Pavements constructed using both natural gravel bases (GB) and chemically stabilised gravels (SB) in the roadbase were selected. Other information considered during the final site selection process included traffic volumes, pavement structural design, age of the road and surfacing, type of shoulder (i.e. gravel or sealed), condition of the surfacing and prevailing drainage condition. A total of 34 homogeneous lengths, mostly 300 metres in length, were finally selected as test sections for detailed monitoring.

3.3 Monitoring

Monitoring of the test sections comprised the following activities at regular intervals:
- Sampling and Testing of pavement and subgrade layers.
- Surface Condition Assessment (by visual means)
- Roughness using a TRL profile beam.
- Deflections using a Falling Weight Deflectometer
- Layer strength using a Dynamic Cone Penetrometer

3.4 Pavement Strength and Material Properties

In comparison with design requirements, the in situ strength of the sections were relatively high. Average annual modified structural number (SNC) of the test sections, as determined from DCP tests conducted at the start and end of the wet season, ranged between 2.6 and 4.1.

Materials testing of the roadbase indicated that of the samples tested, 43% conformed to the MoTE grading specifications and 77% conformed to the plasticity specifications. As shown in earlier studies, the in situ CBR values were significantly higher than the soaked values. Approximately 80% of the subgrade soils were of residual origin, bearing a close relationship to the underlying granitic geology. The range of subgrade design CBR's for the sites reflected the generally strong nature of the road formation soils in the country.

3.5 Road Performance

Road performance was assessed in terms of structural cracking, rutting (ie. permanent deformation) and roughness. Observed values were compared with those predicted from the HDM-4 relationships (Morosiuk, et al, 2000) to derive appropriate calibration factors for local conditions. The conclusions drawn are given below.

Structural Cracking
Cracking was classified as the total amount of cracking (ACA) affecting each section. Of the 34 test sections, 21 had less than 10% cracking, with only three sections having more than 30% cracking.
- Crack initiation occurred between 4 years and 8 years after construction, whereas default predictions were of the order of 13 years.
- The time to crack initiation was shown to increase by a factor of two as the design standard increased from 0.05M to 1.0M.
- A reseal on a double seal inhibits the initiation of cracking, giving an extra 3 to 4 years compared with an original double seal.
- The rates of crack progression on the DSR standard low volume roads were generally similar to that predicted by HDM-4.
- For single seals on 0.05M low cost roads, the observed rates were 1.5 times greater than the rate predicted by HDM-4.
- On the reseals on the 1.0M designed trunk roads, the observed rates were half the rate predicted by HDM-4.

The above results suggest that a wider range of parameters than those currently included in the HDM-4 relationships affect behaviour. These additional variables include pavement materials quality (these are generally lower for lower traffic), the type and durability of the surface seals and road drainage (lower design standards often imply poorer drainage conditions). The enhanced performance of reseals is a reflection of both the waterproofing characteristics of a new seal and the improved durability resulting from thicker binder films.

Rut Depths

The mean rut depths on the test sections were low, ranging between 5 mm and 10 mm, with only a few sections having a value in excess of 10 mm. Predicted values were also low, indicating that the pavement materials and road strengths were sufficient for the reasonably low axle loads carried by the low volume roads in Zimbabwe.

Roughness

Differences in the rate of roughness progression have been shown to be the most important means of discriminating between the performance of the test sections from a technical and economic viewpoint. Explanation of these differences first involved grouping the sections by design traffic, structural strength and quality of road drainage. Calibration of the HDM-4 roughness model was then carried out by adjusting the calibration factor for the environmental coefficient. As shown below in Figure 4, the environmental component is by far the most influential contributor to the roughness of a road for low volume roads.
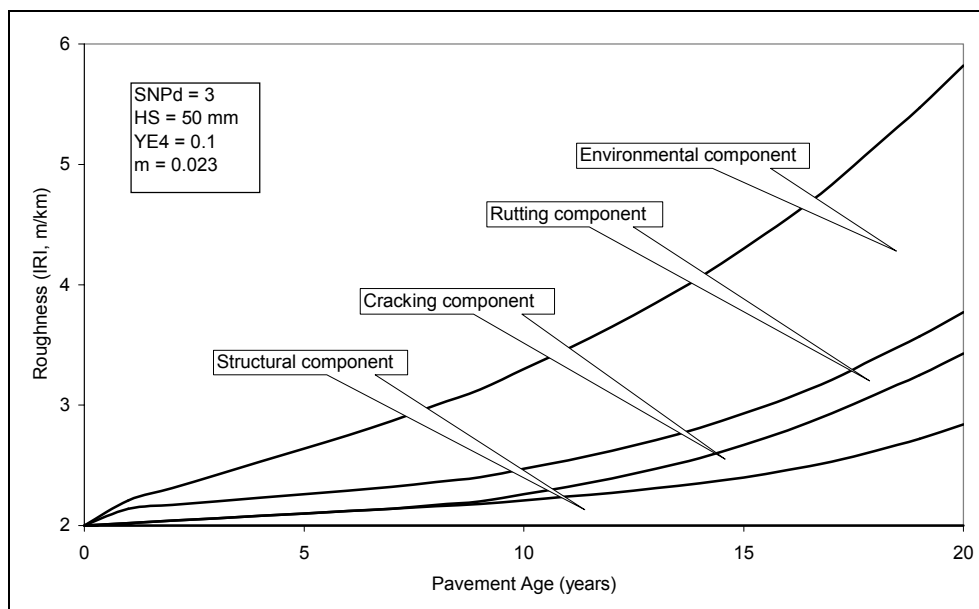
Figure 1
HDM-4 predicted rates of roughness progression – low traffic

The magnitude of the environmental coefficient, m, has been shown to vary by climate zone and ranges between 0.005 for tropical/arid climates to 0.070 for sub-tropical cool/per-humid climates. The appropriate climate zone for Zimbabwe using the HDM-4 classifications is sub-tropical hot/semi-arid. The value of 'm' for this climate zone is 0.015.

Roads in a region may be considered to have different 'environments'. For example, a road in a wet climate may perform as though it was located in an arid climate because of a high crown height, good drainage and strong free draining subgrade or embankment soils. Calibration of the roughness data in this study was achieved by adjusting the calibration factor (K_{gm}) for the environmental coefficient.

The average values of K_{gm} for the 0.05M and 0.3M designed sections monitored in this study, and the value derived for the 1.0M designed trunk roads from an earlier TRL-MoTE study (Hewitt et al, 1998), are given in Table 2.

Table 2
HDM-4 calibration factors for the environmental component of roughness

Design Standard	K_{gm}
0.05M	1.25
0.3M	0.7
1.0M	0.3

The 0.05M designed sections can be described as low cost/SFRDP designed roads with an (initial) single seal and low crown height (< 0.7 m). The 0.3M designed sections were DoR standard designs with a double seal and moderate crown height (0.7 – 1.2 m). The 1.0M designed trunk roads have a double seal and a high crown height (> 1.2 m). The results clearly show that the higher the standard of road (and crown height), the lower the rate of roughness progression. On the other hand, maintaining a lower crown height either through design or as a result of poor maintenance of side drains gives rise to a substantially higher rate of roughness progression, by a factor of 4 or more. Whilst this is clearly significant in physical terms, it is important to investigate its importance in economic terms as described below.

4   ECONOMIC EVALUATION

Economic analysis was undertaken to determine the life-time costs of sealed roads built to different standards. The steps in the process were as follows:
i)   Collection of up-to-date engineering and vehicle operating cost information.
ii)   Calculation of construction costs for a range of design standards.
iii)   Prediction of road condition over a 20-year period using calibrated road deterioration relationships.
iv)   Determination of lifetime total transport costs.
v)   Calculation of discounted Net Present Values for different design options.

4.1 Economic costing

Engineering costs: All costs and benefits were adjusted to represent the real economic resource costs to the country as a whole, hence the taxation component of prices was deducted and subsidy components added back. For the analysis it was estimated that, for engineering activities, economic prices were on average 96% of market prices.

Government costings were not used because these often exclude significant elements of cost, including equipment depreciation and down time, supervisory expenses, office equipment, etc. The engineering costs used were derived from commercial full cost accounting rates, with additional elements added to cover contingencies and agency overheads.

To explain the effect of the environmental calibration factor on road performance, Table was drawn up. The costs in Table 3 were derived for a pavement with a modified structural number (SNC) of 3. However different thickness' of fill are used

to give a range of values for the calibration factor K_{gm} for the environmental coefficient, 'm'. In simple terms, the lower the calibration factor, (i.e. the lower the 'm' value), the greater the crown height of the road above the level of the drains and the less the road pavement will be sensitive to fluctuations in moisture.

Table 3
Sealed road construction costs

Design Traffic	ADT	Double Seal Construction Costs (Zw$ million /km)				Single Seal Construction Costs (Zw$ million /km)			
		Kgm							
		0.3	0.6	1.0	1.5	0.3	0.6	1.0	1.5
0.05M	50	1.66	1.46	1.26	1.06	1.62	1.42	1.22	1.02
0.1M	100	1.67	1.46	1.27	1.07	1.64	1.44	1.24	1.04
0.3M	300	1.82	1.62	1.45	1.22	1.79	1.59	1.39	1.19
1.0M	1000	1.83	1.63	1.43	1.23	1.79	1.59	1.40	1.20

Vehicle Operating Costs: The composite VOC formulae (in units of VOC's per vehicle, Zw$ per km) as a function of the road roughness IRI, used in the analysis are as follows:

$$\text{Unsealed VOC's} = 7.447 + 0.292\,(IRI) + 0.0175\,(IRI)^2$$

$$\text{Sealed VOC's} = 7.084 + 0.304\,(IRI) + 0.0177\,(IRI)^2$$

4.2 Life-time Costs

An analysis was carried out to estimate the combined total life-time costs of construction, maintenance sealing and vehicle operating costs for different construction designs and different traffic levels.

A twenty year planning time horizon was used in the analysis and traffic was assumed to grow at 4% per year. A discount rate of 12% was assumed. The analysis was undertaken for both single and double seals. Based on field observations, the analysis assumed that a single seal needed to be resealed every five years. For the double seal it was assumed that the initial seals on the 0.05M (50 ADT) and 0.1M (100 ADT) designs last 5 years, while on the stronger designs (0.3M and 1M) the initial seals lasted six years. For the double seals, subsequent reseals were assumed to take place every nine years.

The results of the analysis are shown in Table 4. For the lower traffic levels (50 to 300 ADT), the overall minimum cost solution occurs for the cheaper construction designs with K_{gm} of 1.5. However for the 1M design with a 1000 ADT, the lowest cost solution occurs with the lowest K_{gm} value of 0.3. Because of the lower reseal frequency, double seals are shown to give lower discounted overall costs than single seals. This finding is reflected in practice by low cost upgrading strategies being applied to roads carrying 50-100 ADT and more conventional designs used at higher traffic levels (> 300 ADT).

Table 4
Life-time sealed road costs

Initial ADT	Mean Roughness IRI m/km				Single Seal Total Net Present Costs Zw$ million				Double Seal Total Net Present Costs Zw$ million			
	Kgm											
	0.3	0.6	1.0	1.5	0.3	0.6	1.0	1.5	0.3	0.6	1.0	1.5
50	3.83	4.02	4.34	4.68	3.56	3.37	3.20	3.02	3.51	3.32	3.14	2.96
100	3.83	4.03	4.34	4.69	5.25	5.08	4.92	4.77	5.203	5.02	4.87	4.72
300	3.86	4.06	4.38	4.73	12.12	12.00	11.93	11.88	12.04	11.92	11.85	11.80
1000	3.95	4.16	4.49	4.85	35.75	35.82	36.07	36.38	35.67	35.74	35.99	36.30

Table 5 gives the environmental calibration factors and total discounted transport costs for these two road designs based on actual observations in Zimbabwe. For this analysis construction costs were adjusted in line with the analysis presented in Table 4. Although care must be taken in extrapolating the results of the analysis, the findings suggest that use of low cost seal techniques and the 'design by eye' approach promulgated through the SFRDP can generate savings of the order of 10% of Total Life Cycle Costs (TLCC's) in comparison with standard design practice.

Table 5
Observed Zimbabwe pavement designs and total transport costs

Initital ADT	K_{gm}	Mean Roughness IRI m/km	Single Seal - Total Net Present Costs Zw$ million	Double Seal – Total Net Present Costs Zw$ million
50	1.25	4.46	3.14	3.06
300	0.7	4.11	11.99	11.91

5   CONCLUSIONS

1)   New pavement design charts are presented for application to low volume sealed roads which enable considerable cost savings to be achieved. Typical savings are of the order of 10% of total life cycle costs of construction, maintenance and vehicle operation. Construction savings alone are of the order of 40%. The findings reinforce the widely held belief that low cost upgrading of unsealed roads and the 'design by eye' approach promulgated by the SFRDP in Zimbabwe are extremely cost effective.

2)   The charts include additional traffic and subgrade design classes and criteria for crown height, sealed surface design and geo-climatic zone. Controlling the moisture environment both within and in the immediate vicinity of the road has been shown to be the most dominant factor in terms of future performance.

3)   The results of calibrating the HDM-4 cracking models showed a distinct relationship between crack initiation times and rates of progression and design traffic class. Crack initiation occurred significantly earlier at low traffic volumes, and the rate of progression was almost double that on more highly trafficked roads. Reseal lives were also shown to be considerably longer than original seals, a fact which needs recognition in current models.

4)   The environmental component of the roughness progression model was shown to be the most influential contributor to long term performance. It varied according to design traffic. Low cost roads with low crown height were found to deteriorate, in roughness terms, almost 4 times quicker than roads built to more conventional standards. Interestingly, the low cost design

options were found to minimise total life cycle costs at low traffic levels, whereas the higher costs of providing and maintaining increased crown height and foundation standards minimised life cycle costs at higher traffic levels.

5) The study has identified the need for further examination of the deterioration models within HDM-4, particularly with respect to their application to low volume roads where environment related distress dominates overall deterioration.

6 ACKNOWLEDGEMENTS

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