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Rolt and Pinard

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Designing low-volume roads using the dynamic cone penetrometer

1 **John Rolt** DPhil, BSc, FICE, FCIHT, CEng
Freelance Consultant, Wokingham, UK
(corresponding author: jrolt@trl.co.uk)

2 **Michael Ian Pinard** BSc (Hons), MSc, FICE, FIHT, CEng
Managing Director, Infra Africa (Pty) Ltd, Gaborone, Botswana


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The paper describes an environmentally optimised approach to the design of low-volume roads (LVRs) in which the in situ strengths of the subgrade and pavement layers at the anticipated in-service moisture condition are used for design rather than soaked values. It describes how the assumptions and simplifications inherent in the more traditional California bearing ratio (CBR)-based methods of design tend to produce less-than-optimum solutions compared with the dynamic cone penetrometer (DCP) method. DCP measurements are much more reliable than CBR measurements and are also quick to perform; hence, a relatively large number of measurements of subgrade strengths (for new roads) and pavement layer strengths and thicknesses (for upgrading projects) can be obtained, thereby reducing risks of inadequate data for design purposes. Research has shown how material specifications for LVRs can be relaxed and the paper shows how this aspect is integrated into DCP design methods. The paper reviews the alternative methods of DCP design, summarises the advantages of these methods and recommends some improvements.

1. Introduction

1.1 Background

Low-volume roads (LVRs) are defined by different road authorities in various ways. However, it is generally agreed that the principles on which the design method is based apply to roads for which the cumulative traffic loading over the design life does not exceed about 1·0 million equivalent standard axles which, depending on the prevailing vehicle equivalence factors and proportion of commercial vehicles, equates to about 300 motorised vehicles per day. For such roads, which are generally constructed from naturally occurring, often 'non-standard' materials, it is not appropriate to use the same pavement design methods that are used for roads carrying high volumes of traffic and providing a higher level of service. Simpler design methods are required for LVRs that can take account of the various environmental factors that critically affect their performance. One such method is based on the use of the dynamic cone penetrometer (DCP), which uses the concepts of environmentally optimised design whereby specifications are adapted to suit the local road environment, thereby facilitating the greater use of local, more abundant, and therefore less expensive, materials.

1.2 Purpose and scope

The purpose of this paper is to describe the advantages of using the DCP to design LVRs. From the outset, it is important to separate the operation of the DCP itself from all the other aspects of the design process. The operation of the DCP is relatively simple, but the design process introduces concepts that must be clearly understood by the user. Some of the questions that the engineer may ask are as follows.

- Do the layer strength requirements and the pavement layer thicknesses obtained using the DCP design method generally match up with the expectations of engineers who are experienced in LVR design and performance?
- If the requirements appear to be more or less stringent than expected, are the variations in the specifications nonetheless acceptable in relation to the local road environment?
- Are there omissions, assumptions or other deficiencies in the method that are likely to lead to errors in design?
- What are the advantages of the method and do they outweigh any perceived disadvantages?
- Can the method be improved?

The purpose of this paper is to answer these questions.

2. Developments in DCP design technology

2.1 General

The DCP has been used for over 30 years by many road authorities to measure the in situ strength and layer thicknesses of existing pavements (De Beer, 1991; Jordaan, 1994; Kleyn and Savage, 1981; Livneh, 1987; Paige-Green and Pinard, 2012; Samuel and Done, 2005; TRL, 1993, 1999). It was shown that the DCP could be used to evaluate a wide range of materials with relatively good correlations between the in situ California bearing ratio (CBR) and DCP measurements (in terms of millimetres of penetration per blow (DN)) for granular as well as for fine-grained materials. Such correlations are shown in Figure 1.

It is not the purpose of this paper to discuss the operation of the DCP and limitations of its use in detail. The DCP cannot, for example, penetrate strong cemented layers (they need to be drilled first if underlying layers are to be tested) and a small percentage of tests may have to be discarded because of oversize material in a pavement layer. These and other issues have been discussed in many manuals (Kleyn and Steyn, 2010; Paige-Green, 2011; Paige-Green *et al.*, 1999; Samuel and Done, 2005; TRL, 1993, 1999, 2004).

Undertaking in situ CBR tests in the layers of a pavement can be difficult and very time consuming and, as a result, they are rarely attempted. Instead, material samples are usually extracted from test pits dug along the road and tested in the laboratory at different densities and moisture contents to determine their strength characteristics. The DCP has considerable advantages over test pit-based methods for assessing the in situ strength and layer thicknesses of existing pavements. The DCP, by its very nature, measures strength at every blow, expressed as a DN value in mm/blow. For selecting borrow pit material, the laboratory DCP test (carried out in a CBR mould) provides a strength profile throughout the depth of each layer, whereas a CBR test is naturally biased towards the material near to the top or bottom of the mould. The CBR test typically exhibits poor repeatability and reproducibility compared with the DCP test (Smith and Pratt, 1983). Moreover, in the DCP test, the material is tested in an undisturbed state, whereas the CBR test is carried out on a disturbed sample, which must then be remoulded in the laboratory; hence the possibility for introducing a number of sources of error.

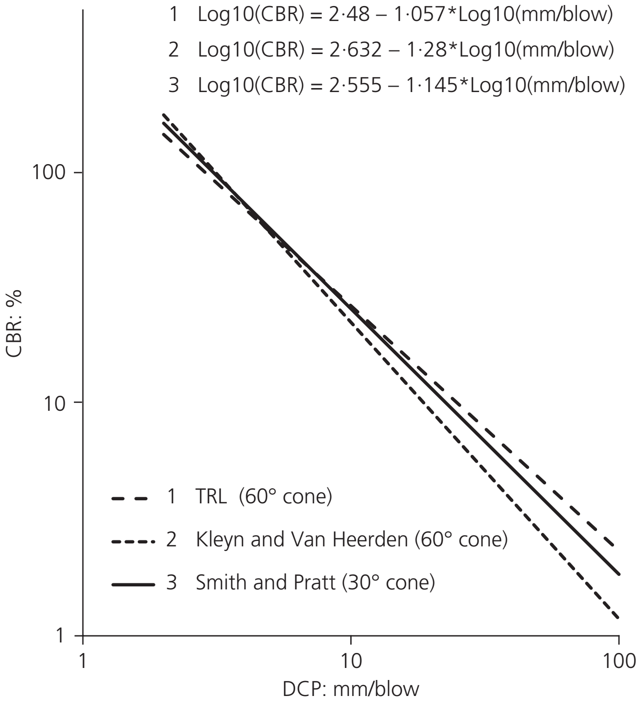

Figure 1. Relationships between CBR (%) and DCP (mm/blow)

Finally, and most importantly, a DCP measurement can be done relatively quickly (less than 30 min per test) and a DCP survey can therefore provide many more results of layer thicknesses and strengths than could ever be obtained solely from a test pit-based method. Thus a very good statistical distribution of subgrade (and layer) strengths can be obtained. This is absolutely invaluable because it provides a means of ensuring that very little of the road is at risk of under- or over-design. The weakest 5th, 10th or 20th percentiles of field measurements can be used for design rather than the simple averages of the small amounts of data available from a test pit-based approach.

2.2 Pavement structural design

There are essentially three principal DCP-based approaches that may be used for the upgrading of unpaved roads to a paved standard. These are

- DCP-CBR (TRL)
- DCP-DN (CSIR)
- DCP-DN (AFCAP).

The methods adopt a similar approach to determining the in situ strength of the existing road. However, the approach to the design of the pavement layers and selection of borrow pit materials differs in various ways. There are differences in the detail of the assumptions that the methods make, in the simplifications that they embody, in the way that they analyse the DCP data and in the way that they arrive at the pavement design solution.

2.2.1 DCP-CBR method

In the DCP-CBR method developed by TRL (Samuel and Done, 2005), the analysis program determines where pavement layer boundaries occur in the basic plot of total number of blows against depth (or millimetres per blow against depth). The strength of each layer is then computed by converting the penetration rate (DN value in mm per blow) to a CBR value based on the TRL-derived relationship between penetration rate and CBR (Figure 1). No correction for moisture condition is made automatically in the program at this stage because it is assumed that the DCP testing is done at the wettest time

Traffic class	0·01	0·1	0·3	0·5	1·0
Traffic range (10^6 standard axles)	< 0·01	0·01–0·1	0·1–0·3	0·3–0·5	0·5–1·0
Subgrade class					
S1 (<3%)	Special subgrade treatment required				
S2 (3–4%)	150 G45 150 G15	150 G65 125 G30 125 G15	150 G80 150 G30 175 G15	175 G80 150 G30 200 G15	200 G80 175 G30 200 G15
S3 (5–7%)	150 G45 100 G15	150 G65 100 G30 100 G15	150 G65 125 G30 150 G15	175 G65 150 G30 125 G15	200 G80 150 G30 150 G15
S4 (8–14%)	200 G45	150 G65 125 G30	175 G65 150 G30	175 G65 200 G30	200 G80 200 G30
S5 (15–29%)	175 G45	125 G65 100 G30	150 G65 125 G30	150 G65 150 G30	175 G80 150 G30
S6 (>30%)	150 G45	150 G65	175 G65	200 G65	200 G80

G45 is a granular material of soaked CBR > 45% and so on for the other symbols

Table 1. CBR design catalogue for different traffic classes (wet climate)

Traffic class	0·01	0·03	0·1	0·3	0·7	1·0
Traffic range (10^6 standard axles)	< 0·01	0·01–0·03	0·03–0·1	0·1–0·3	0·3–0·7	0·7–1·0
Pavement layer	DN values					
0–150 mm base ≥ 98% Mod. AASHTO	DN ≤ 8	DN ≤ 5·9	DN ≤ 4	DN ≤ 3·2	DN ≤ 2·6	DN ≤ 2·5
150–300 mm sub-base ≥ 95% Mod. AASHTO	DN ≤ 19	DN ≤ 14	DN ≤ 9	DN ≤ 6	DN ≤ 4·6	DN ≤ 4·0
300–450 mm subgrade ≥ 95% Mod. AASHTO	DN ≤ 33	DN ≤ 25	DN ≤ 19	DN ≤ 12	DN ≤ 8	DN ≤ 6
450–600 mm In situ material	DN ≤ 40	DN ≤ 33	DN ≤ 25	DN ≤ 19	DN ≤ 14	DN ≤ 13
600–800 mm In situ material	DN ≤ 50	DN ≤ 40	DN ≤ 39	DN ≤ 25	DN ≤ 24	DN ≤ 23
DSN 800	≥ 39	≥ 52	≥ 73	≥ 100	≥ 128	≥ 143

DSN is the total number of blows to reach a depth of 800 mm

Table 2. DN design catalogue for different traffic classes

of the year. However, the designer can apply a correction by adjusting the CBR of the pavement layers (see below) or by applying a 'drainage factor' to modify the structural number (AASHTO, 1993; Samuel and Done, 2005).

Uniform sections along a road are determined by the analysis software to produce a subgrade design class for pavement design purposes. The design of the upgrading of the pavement is based on a CBR catalogue of pavement structures for different traffic levels, subgrade strength values and layer strengths. The design chart for a specific climatic zone (wet, Weinert *N*-value < 4) is shown in Table 1.

2.2.2 DCP-DN method

In the DCP-DN method, developed originally by Kleyn (1984), the existing pavement or subgrade at each DCP test point is divided into 150 mm layers for analysis purposes. Naturally each layer of the existing structure is unlikely to be 150 mm thick and so the program computes the weighted average strength of each 150 mm layer in terms of a DN value. All the DCP measurements of the layers at each 150 mm incremental depth are then combined to yield the median and the 20th and 80th percentile values for each 150 mm layer along a uniform section of road. Depending on the anticipated moisture conditions (three choices) one of the three values for each 150 mm layer is selected for the in situ condition. The program then compares these results to the catalogue of structures that is, itself, based on 150 mm layers, to see where the existing structure fails to meet the requirements. The catalogue is shown in Table 2.

If any 150 mm layer is not of adequate strength (or DN value) mechanical stabilisation of the existing layer is carried out to achieve the required pavement strength, or an additional layer (or layers) of the necessary strength (DN value) is added at the top.

2.2.3 The DCP-DN (AFCAP) method

The AFCAP method is essentially the same as the CSIR method except that the selection of borrow pit material is based on a DN rather than CBR value and further relaxation of several other material specifications is allowed. In addition, relaxation of basic strength parameters has been incorporated thereby allowing a wider range of materials to be used in the pavement structure (see Section 3.3 on the selection of pavement materials).

3. Key features of DCP design methods

3.1 Establishing subgrade strength for design

All methods of pavement design require four main design activities, namely

- assessing the strength of the subgrade or of the layers of an existing old road prior to improvement or upgrading
- assessing the design traffic loading
- selecting materials for the pavement layers
- determining the thicknesses of the pavement layers.

The environmentally optimised approaches to pavement design are based on the actual subgrade strengths exhibited under the pavement. In other words, the structure of the pavement will be correct for the in situ subgrade strength at any location along the road. In practice the subgrade strength usually varies with the season and from year to year, hence the appropriate subgrade strength value for design may require a weighted average over time.

When the subgrade is relatively weak, the required pavement thickness is very sensitive to the subgrade strength. It is therefore usually best to base the structural design on a measure of the weakest likely long-term strength of the subgrade in any defined uniform section of road. A low percentile (10% or 20%) is usually used. This provides a measure of safety because 80 or 90% of the section of road will always be stronger. When the subgrade is strong, the pavement design is less sensitive to the subgrade strength and a higher percentile may be used for selecting the design strength.

If the subgrade is likely to be soaked and very weak at some time it is prudent to base the design on a soaked strength test. Such design methods must not be confused with methods that are based on always testing the subgrade in the soaked condition. Design charts should ideally be based on actual performance data and it is very unlikely that most subgrades would be actually soaked for any length of time.

Assessing the strength of subgrades was, traditionally, based on predicting the moisture content in the subgrade. The methods for predicting the moisture content were quite advanced and somewhat more reliable than attempting to predict subgrade strength directly. Furthermore, there was no easy method available for measuring subgrade strength in situ. Therefore the first step was to estimate the likely moisture content in the subgrade of the completed road. This could be done from knowledge of the minimum depth of water table and the properties of the subgrade material (e.g. TRL, 1993). Samples of subgrade were extracted from the road alignment and their compaction and strength properties measured in a series of standard laboratory tests. This involved compaction to different density levels and at different moisture contents plus CBR testing to determine strength at a particular density and moisture content. From these tests and knowledge of the specified compaction level and estimated moisture content, the likely strength of the subgrade could be determined. The disadvantage of this method is that the testing is time consuming and hence the number of tests carried out was usually quite small and statistically unsound.

It will also be appreciated that estimating subgrade strength in this way includes several assumptions, specifically about the likely moisture content of the subgrade and the density likely to be achieved. It also ignores the fact that these properties vary with depth. Most importantly, it does not deal directly with variability. The measured strength of subgrades under existing roads show high variability along an alignment; therefore, to obtain reliable data, a correspondingly large number of tests need to be performed. As a result of these difficulties, a certain level of safety was built into the design manuals in order for road design engineers to be confident in their designs.

Finally, as in situ strength was difficult to measure directly, there was almost no feedback after construction as to whether the assumptions and calculations had yielded an accurate answer. The 'traditional' design method therefore included numerous assumptions and gave opportunities for considerable errors to occur.

Thus the challenge, which is common to all pavement design methods, is to identify the likely worst subgrade conditions. In the past the simple solution was to assume that the worst condition would be a soaked condition. However, many well-researched design methods did not advocate this since, most of the time, it would result in over-design. With the advent of the DCP the simplest solution is to measure the in situ subgrade strength directly under the existing pavement (if it is a rehabilitation or upgrading project) or under a nearby paved area on the same subgrade at the time of year when the subgrade is likely to be at its weakest. This does not account for differences between one year and the next, but it is better than measuring at a time when the subgrade is at its strongest. However, in normal situations this may not be possible; measurements must be made according to the client or designer's programme of work. Therefore the option of estimating subgrade strength at different times of the year becomes necessary.

3.2 Estimating subgrade strength at a different time of the year

Any method that requires estimates of strength or moisture content at a different time of the year, and this includes most methods of design, cannot be based on precise data; some degree of engineering judgement is required. This is partly because the relationships between strength and moisture content for different materials can show wide variation depending on the material properties, particularly the plasticity and fines content (see Section 4.1 'Pavement layer strengths'). It is usually impractical to determine this relationship for the materials in individual pavements.

Under a DCP design method the engineer assesses the in situ moisture conditions at the time of the DCP testing and adjusts the measured DN values to the anticipated, long-term, in-service moisture content. This solution must be pragmatic, but relies on engineering judgement and experience. There are two principal methods.

- Method A: Subgrades are normally classified into five or six strength classes, each covering a range of strength, in terms of CBRs, varying by a factor of about two. The method is simply to increase or decrease the subgrade class by one class up or down if the in situ worst case long-term conditions are expected to be drier or wetter (Gourley and Greening, 1999).
- Method B: If the engineer judges that the in situ DCP measurements were taken when the conditions were much wetter than they are likely to be in the finished new road, the assumption is made that the CBRs in the finished road will be similar to the 80th percentile value (or the 20th percentile if using DN values directly). Similarly, if the conditions are expected to be wetter, the 20th percentile CBR is used (or 80th percentile if DN values are used directly).

Thus the estimation of subgrade strength for design is an imprecise exercise, but is certainly better than the estimations of likely strength using the traditional methods described in the above Section 3.1 'Establishing subgrade strength for design'. There is no exact method and it is worth reminding ourselves that if the measurements are done when the subgrade is at its weakest, normally towards the end of the rainy season, then most of these complications do not arise.

3.3 Selection of pavement materials

During the last 30 years or so the use of materials in LVRs that do not meet the traditional specifications for high volume roads has been the subject of considerable research (Gourley and Greening, 1999; Infra Africa (Pty) Ltd and CSIR, 2010; Paige-Green, 1991, 1999, 2015; Pinard, 2011; Rolt *et al.*, 2013; Scott Wilson Kirkpatrick and Partners *et al.*, 1988). The research has shown that materials that do not meet traditional standards can be used successfully in the base and sub-base and specifications have been amended accordingly, depending on traffic level and climate. Research has also demonstrated that when roads fail, many of the traditionally controlled properties of the pavement layers (e.g. plasticity index (PI), plasticity modulus (PM) and grading) do not correlate well with the observed performance. Materials that are deemed sub-standard have frequently performed well and some, apparently good materials, have not performed well under comparable environmental conditions.

There are two main reasons for the lack of apparent correlation between traditional specifications for materials and performance. First of all, the reasons for poor performance are most often associated with the poor performance of the surfacing rather than the individual pavement layers (Gourley and Greening, 1999; Paige-Green, 1991, 1999; Rolt *et al.*, 2013; TRL, 1993, 1999). Secondly, if water becomes a serious problem within the pavement (e.g. because the surfacing is allowing water to penetrate) the fact that the soaked CBR of one material is higher than another is no guarantee of sufficiently better performance, especially if positive pore pressures are able to occur, even for a relatively short time. Positive pore pressures are extremely destructive and mitigating measures should be adopted including, for example, the use of impermeable surfacings, sealed shoulders and, where possible, avoidance of permeability inversion within the layers of the pavement.

Nevertheless, laboratory testing to determine the relationship between DN, moisture content, plasticity and density is often required, thereby enabling materials of high sensitivity to moisture to be rejected. These tests eliminate some materials with high plasticity and materials with poor grading that have poor inter particle 'interlock'. Other tests that are usually required such as durability tests for aggregates, bitumen affinity and expansivity of fine-grained soils are sometimes required, as in most pavement design methods.

The strength of the roadbase is not normally a design parameter, but in LVR design methods it has become so, based on the expected moisture conditions and traffic level. Thus once the critical strength for each traffic level and for each pavement layer has been determined from the research, it is only necessary to ensure that the materials meet these strength criteria at the expected moisture conditions.

These considerations are primarily part of the pavement design philosophy and are not inherently wedded to a DCP design approach. However, for the reasons mentioned above, the DCP methods are superior to the traditional approaches in assessing the in situ strength of materials.

4. Comparison of design methods

4.1 Pavement layer strengths

The DCP-DN design catalogue is published in terms of maximum DN values derived from testing trial pavements with a heavy vehicle simulator (Table 2) and from a study of the performance of a wide range of LVRs in South Africa. The equivalent CBR values obtained from Figure 1 are given in Table 3. These are the strengths required at the anticipated, long-term, in-service moisture condition selected from three basic situations for roadbases, sub-bases and subgrades namely at 0·75 of optimum moisture content (OMC), at OMC, or in the soaked condition. To convert from the in situ DN or CBR values to the equivalent value if the material were to be at a different moisture content requires knowledge of the appropriate relationship. Figure 2 is just an example of the relationship between the CBRs of different materials compacted to normally specified densities and at OMC with CBRs in the soaked condition (Pinard, 2011). The scatter is correspondingly greater between 0·75 × OMC and soaked CBR.

Thus if DCP readings are made in the wet season, estimating values in the dry season is imprecise, and vice versa. Using such a relationship based on extensive data (Paige-Green, 2003; Paige-Green *et al.*, 1999) Table 4 shows the required soaked CBR values for roadbase materials based on the three assumptions about the design moisture content. These comparisons also depend on the relationship between DN and CBR (Figure 1) and this also shows considerable variability. For very strong free-draining material the sensitivity to moisture content can be lower and the differences in CBR correspondingly smaller, but for relatively fine-grained, plastic materials the differences can be quite large.

Layer thickness: mm	Traffic class	TLC 0·01	TLC 0·03	TLC 0·1	TLC 0·3	TLC 0·7	TLC 1·0
	Layer	< 0·01	0·01–0·03	0·03–0·1	0·1–0·3	0·3–0·7	0·7–1·0
0–150	Base	29	43	70	94	122	128
150–300	Sub-base	10	14	25	42	59	70
300–450		5	7	10	18	29	42
450–600		4	5	7	10	14	16
600–800		3	4	4	7	7	8

Table 3. Approximate equivalent required in situ CBRs (DCP-DN method)

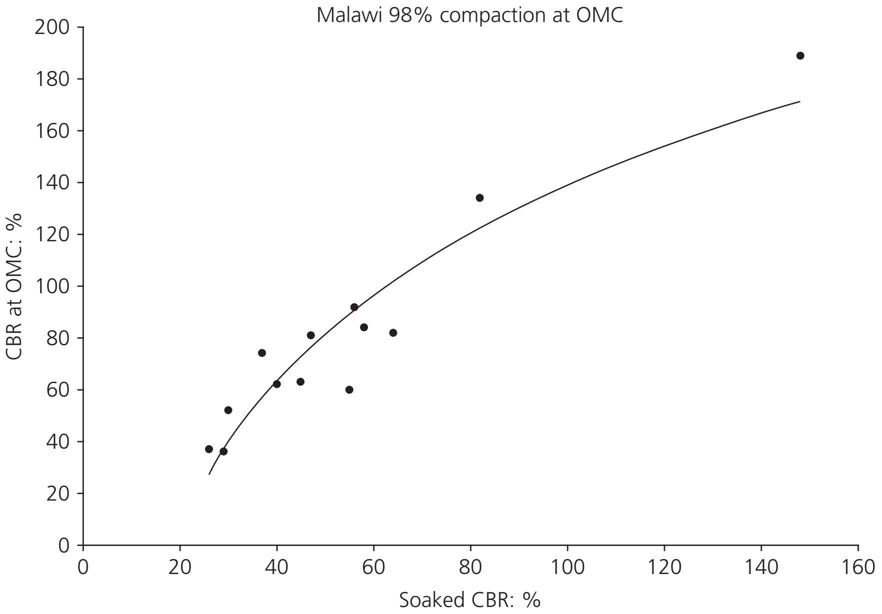

Figure 2. Example of soaked CBR against CBR at OMC

Traffic loading (mesa)	Results shown as required strengths in soaked test		
	Field moisture conditions		
	Soaked	OMC	0·75 OMC
1	128	94	59
0·7	122	90	53
0·3	94	80	32
0·1	70	53	16
0·03	43	16	7
0·01	29	8	5

Table 4. Equivalent soaked CBR requirements for roadbases at different design moisture conditions

When material of high quality is required for high and heavy traffic levels, a crushed stone will be required and this will normally exceed the minimum strengths required for LVRs.

It is important to note that under the DCP-DN method there is no need to convert the DN values to CBRs at any stage of the design process. DCP-DN values are both more reproducible than CBR measurements and more accurately represent the strength of a layer because the measurement is continuous (small increments of depth) throughout the depth of the layer.

4.2 Layer thicknesses

As a result of the differences between the DCP-DN design method and conventional methods a simple comparison of designs using the two methods is not straightforward. One constraint is that the DCP-DN method is based on DN values rather than CBRs, and hence any comparisons must make use of the correlation between CBR and DN (Figure 1) with all the variability that that entails. Comparisons can be made for specific conditions, but these require knowledge of the likely CBR and DN values at different moisture contents for the pavement materials. These also show wide variability (see Section 4.1 ‘Pavement layer strengths’). In short, a general comparison between the results obtained by the different methods is quite difficult to carry out. Nevertheless the data on which the DCP-CBR method for LVRs is based (Gourley and Greening, 1999) did not include many examples at the low end of the ranges (low subgrade strength and very low traffic) and so the designs are likely to be slightly more conservative in these areas.

5. Strengths, limitations and improvements

5.1 Strengths

The DCP is a relatively low-cost, robust device that is quick and simple to use, allowing many measurements of pavement layer thicknesses and strengths to be obtained to provide a comprehensive characterisation of the in situ road conditions. This provides a strong statistical base for design, minimising the risks of under-design or over-design inherent in any method that does not provide sufficient information for a proper statistical analysis.

The DCP can be used to test materials in the laboratory and can beneficially replace the CBR test if required. The repeatability and reproducibility of the DCP test is much better than that of a CBR test and the values obtained are inherently more accurate because the DCP provides a virtually continuous strength profile throughout each layer, whereas a CBR test is naturally biased towards the ends of the mould.

Very little damage is done to the pavement being tested. It is effectively a non-destructive test.

Since the DCP design method makes full use of the existing in situ pavement layers, no assumptions about whether design densities will be achieved are required for those layers. When additional layers are added, there is likely to be a small improvement in density of the existing layers, provided that they have not been disturbed – an important part of the rehabilitation/upgrading method.

Improved drainage, which should be a mandatory requirement when upgrading a gravel road to a paved standard, should reduce in-service moisture contents along the section affected and, by so doing, lower DN values.

5.2 Limitations

The main limitations that are likely to affect the results and their interpretation and that need to be considered when using the DCP design method include those outlined below.

(*a*) If the existing pavement contains material that is very coarse, the DCP probe may ‘hit’ a large stone or be deflected sideways, creating friction on the shaft, which results in incorrect readings. Some DCP tests will therefore need to be abandoned or repeated.
(*b*) If the pavement contains a cemented layer, the DCP will not be able to penetrate. To obtain information about the underlying structure, a suitable sized hole must be drilled through the cemented layer without using water for lubrication.
(*c*) Ideally the penetration readings should be recorded (i.e. number of blows) at between 10 mm and 20 mm depths of penetration. In practice most operators choose to keep the number of blows fixed at, say, 10 blows in the strong material and to reduce this to 5, 3, 2 and 1 as the material gets weaker. There is an obvious danger that the operator might forget to record where these changes take place, but in practice an error of one or two blows will not make any significant difference.
(*d*) The DCP tests may be performed poorly (e.g. hammer not falling the full distance, non-vertical DCP, excessive movement of the depth measuring rod, etc.). Any test can

be poorly executed and therefore this is not a particular limitation of the DCP test. In fact the DCP is less likely to be done badly than many other tests.

(*e*) As with all empirical methods, use outside the type of environment (materials, climate, traffic, etc.) in which it was developed is not recommended until local experience has been acquired to allow suitable and scientifically based adjustments and modifications.

There is now a large body of literature about the DCP-DN and DCP-CBR design methods and solutions to most problems encountered by users should be readily available.

5.3 Possible improvements

The improvements described below are not exhaustive and do not apply to all methods because they are already included in some.

5.3.1 Using a lower risk percentile of subgrade strength

In some design methods the subgrade strength value used for design is not based on the average (or median) of the measured values, but the 10th percentile. This is because the range of measured values is often quite wide, even though nominally uniformly behaving sections are selected for evaluation. Therefore there is a risk that if the average or median is used then a considerable proportion of the road could be founded on a subgrade that is much too weak and which requires a substantially thicker pavement to protect it. Results from a recent project showed that if the subgrade CBR strength for design is based on the 10th percentile rather than the median value, significant changes in subgrade class for design occur. The results are summarised in Table 5.

Only 10% of the road sections retained their original subgrade classification, but 7% were already in the lowest category (S1) and therefore could not be reduced further. Thus only one out of 27 retained its original classification (it was particularly uniform). Twenty (75%) changed their subgrade classification by one class and six (22%) changed by two classes. In this project the subgrades were particularly weak. Under these conditions the subgrade strength has the greatest impact on pavement thickness and it is therefore important to identify the weakest values. The results underline the importance of using 10th percentiles of distributions now that the tool is available (DCP) to enable enough measurements to be made to identify the distributions more accurately.

5.3.2 Point-by-point analysis

Point-by-point analysis is an improvement that could be used in all methods, and is made possible by the versatility and simplicity of the DCP. An important statistical aspect of pavement design is concerned with the very non-linear relationship between pavement design parameters (e.g. subgrade strength) and the design traffic and hence the required layer thicknesses. For example, the difference in pavement thickness required when the subgrade CBR strength decreases by 4% from, say, 9% to 5% is much greater than when the subgrade CBR strength decreases from 16% to 12%. Selecting any percentile from a subgrade strength distribution and using that for the pavement design is therefore not statistically correct. The correct method is to design on a point-by-point basis using measurements at each point separately. The level of risk that can be tolerated or desired is then applied by choosing a percentile of the distribution of the additional thickness or structural number requirements, usually the 90th percentile at the high-traffic end of the LVR scale and maybe the 75th percentile for lower traffic. This method is the only way that a true percentile and therefore an accurate risk can be applied. Such a method can be used in DCP analysis and may be found in various manuals for rehabilitation design (e.g. ERA, 2013; TRL, 1999).

5.3.3 Substitution with material that is significantly stronger than the minimum requirement

In some design methods, if materials that are significantly stronger than the minimum are readily available and could be used in the new pavement, there is a corresponding reduction in the thickness requirements. In other words there is a recommended substitution ratio of strong for weaker material. For example, 100 mm of material of CBR 120% may be equivalent to 125 mm of material of CBR 80% (or the equivalent

Subgrade class (CBR %)	Number of road sections in subgrade class based on median	Number of road sections in subgrade class based on 10th percentile	Number differing by 1 class	Number differing by 2 classes
S1 (<3)	2	17	—	—
S2 (3–4)	12	7	12	—
S3 (5–8)	10	3	6	3
S4 (9–14)	1	0	0	1
S5 (15–29)	2	2	0	2
S6 (≥30)	2	0	2	0

Table 5. Effect of designing on the 10th percentile subgrade strength

expressed in DN terms). Substitution of stronger for weaker materials should cause no problem, but substitution of weaker for stronger material is not allowed. The American Association of State Highway and Transportation Officials (AASHTO) structural number concept can be used to determine the substitution ratios, but it is important that the pavement balance is not adversely affected. Such a refinement may be used where there is a choice of suitable materials and the relative costs are in favour of the substitution. The TRL rehabilitation design method (TRL, 1999) using a point-by-point SN design approach is a convenient DCP-CBR-based design method that deals with substitution, whereas in the DCP-DN method the use of 'user defined' design curves allows base layer thicknesses of less than 150 mm to be considered.

5.3.4 Combinations of properties

In the DCP-DN method, the DN value is used as the primary criterion for evaluating the suitability of the pavement layer material, on the assumption that this value provides a composite measure of the properties that ultimately affect performance; that is, grading, plasticity, moisture and density. The requirement to also meet a minimum grading modulus (GM) is to avoid the unnecessary testing of materials that are patently unsuitable for use in pavement layers in terms of their grading and/or plasticity; for example, very fine, plastic soils or very coarsely/poorly graded gravels.

Despite the available field evidence from a number of projects to support this assumption, there may be concerns that ignoring traditional grading and plasticity requirements and relying solely on the DN and GM parameters may prove risky. The risk is likely to be outweighed by the many benefits offered by the use of the DN criterion for selecting pavement materials and, when in doubt, the materials can be subjected to the same strength/moisture content/density testing in the laboratory that should be used in traditional CBR design methods to determine moisture sensitivity, for example, and to eliminate unsuitable materials. However, in this case the DCP is used for the strength measurements instead of the CBR test for the reasons explained above.

6. Conclusions

The performance of LVRs depends on many factors. Sufficient pavement thickness using materials of adequate strength are vital, but are not themselves sufficient to ensure good performance. Good drainage design, good surfacing, adequate maintenance and control of severely overloaded large vehicles are all important and compensation for inadequacies in these areas by means of additional pavement thickness and/or the use of stronger materials is not an appropriate solution.

The structural designs based on the design methods described herein have been endorsed by engineers experienced in LVR design and performance and the specifications have been underwritten by a considerable body of research.

Since the DCP first came into regular use by some road authorities, improvements in the device itself, methods of use and methods of data analysis have been made from time to time and continue to be made. For example, the latest versions of the DCP analysis programs have benefitted from advances in computer technology and are now easy to use and very comprehensive.

Nevertheless there are improvements that can be made. For example, the DCP is damaged mainly when it is being extracted from the road, after a test has been completed. The use of disposable cones is advocated by some users because it is the extra width of the cone that makes extraction a damaging operation.

The main advantage of DCP methods is that in situ information for design about material strengths and pavement layer thicknesses can be obtained very quickly and this allows the engineer to design a statistically very reliable pavement because of the amount of data that becomes available.

The main conclusion is that DCP methods of pavement design for LVRs, especially those that combine the concepts of environmentally optimised design with the use of in situ material conditions, are generally suitable for use in Africa and elsewhere and offer advantages over traditional CBR-based methods of pavement design. Improvements and further simplifications will evolve through use and experience. However, experience is needed before relatively new methods are more widely accepted. This is inevitable with engineering innovations and it is therefore recommended that the process of research and demonstration continues in order to provide the experience necessary for wider acceptance and adoption. Meanwhile, the design of LVRs using DCP-based methods can continue with confidence.

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