SEMINAR: SUSTAINABLE ACCESS
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TITLE: DCP analysis and design of low volume roads by new TRL software UK DCP

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Abstract

Low volume sealed roads in developing countries often deteriorate because of poor material properties, poor construction or most commonly a combination of these. The most effective way of resolving such problems is by carrying out repair to the pavement, this often being necessary over only a short length and referred to as spot improvements. Design of the repairs can be based on information obtained using simple, low cost techniques, the most suitable of which is the Dynamic Cone Penetrometer (DCP). The DCP is a labour intensive, non-destructive testing instrument designed for the rapid measurement of the in-situ strength of existing flexible pavements constructed with unbound materials.

In 1990, Transport Research Laboratory (TRL) produced Overseas Road Note 8 with a software package to analyse DCP test data. However, the evolution of alternative methods of using the results and developments in software application dictated an urgent need to upgrade the software. The Department for International Development (DFID), in support of its Knowledge and Research Programme, commissioned TRL to translate DCP test data into simple design procedures with the development of a data analysis program.

This paper presents an overview of the DCP test procedure and the various features of UK DCP data analysis package highlighting its use in structural evaluation of pavement.

1. Introduction

To rehabilitate a road it is often necessary to know as much as possible about the thicknesses of the existing pavement layers and their condition. This is vital when roads begin to fail prematurely indicating that there are inherent problems with the structure. The quickest and easiest way to assess the thickness and condition of the pavement is to inspect the design to which the pavement was originally built and perhaps also the as-built records compiled during construction. However, designs indicate only an intended construction and as-built records are often only indicative of the construction work carried out and neither give any information as to what has happened to the pavement since construction.

It is therefore necessary to investigate the current pavement condition using some form of destructive or non destructive testing. The usual method of destructive testing is to dig test pits at suitable intervals along the road. These are very useful as pavement thicknesses can be measured and material removed for testing in a laboratory. However, test pits are expensive to dig and reinstate and are rarely dug at a spacing of less than 2-3 kilometres. Non destructive testing is cheaper, quicker and can be carried out at closer spacing. A type of non destructive testing which has proved to be successful in many countries is the Dynamic Cone Penetrometer (DCP).

Software has recently been produced to analyse the data which is produced during a DCP test. This software is called UK DCP and has been commissioned for free download. This paper briefly introduces the DCP and then describes various features of the UK DCP software.

UK DCP has two main sections. The first concerns the analysis of penetration data to determine the strength of the existing road. However, this is not sufficient to allow improvements to be designed; it is also necessary to have information relating to the environment in which the road is located, in particular the presence of water. The second section therefore concerns the use of additional information and the design of the improvements.

The first section of UK DCP software is currently available for free download at the following website: www.transport-links.org/ukdcp/index.htm. The second section is not yet available, although the intention is to release it in the near future.

2. The DCP

The DCP consists of a cone fixed to the bottom of a tall vertical rod. A weight is repeatedly lifted and dropped onto a coupling at the mid-height of the rod to deliver a standard impact, or ‘blow’, to the cone and drive it into the pavement. A vertical scale alongside the rod is used to measure the depth of penetration of the cone. Figure 1 shows an assembled DCP instrument, which uses an 8 kg hammer dropping through a height of 575 mm and a 60° cone of 20 mm diameter.

The DCP is a simple piece of equipment and easy to transport, maintain and operate.

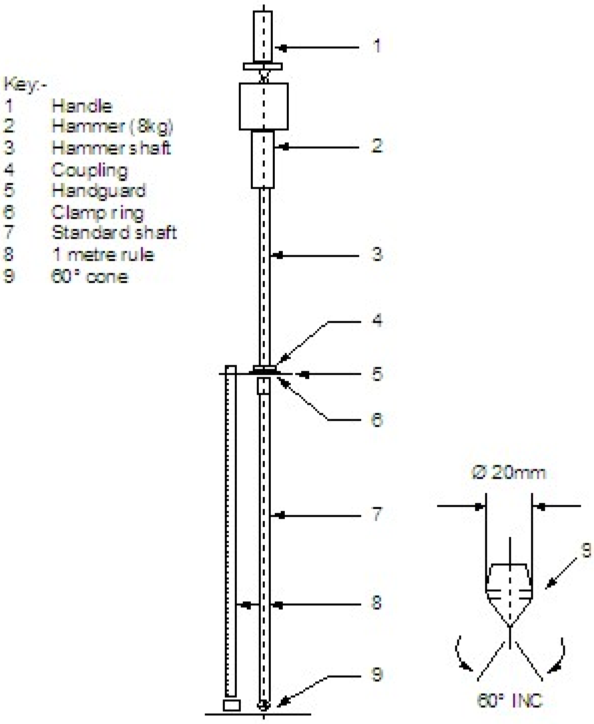


Figure 1 DCP instrument

3. The DCP test procedure

Using the DCP instrument to collect penetration data is straightforward. After recording the ‘zero error’, the reading on the vertical scale when the cone is resting on a flat level surface, the DCP is held vertically at the test point and the hammer is repeatedly raised and dropped onto the coupling. As the cone penetrates into the pavement, the number of blows and the penetration depth are recorded onto a Test data sheet and then plotted onto a penetration graph.

The gradient of the graph indicates the strength of the material through which the cone is passing and a change in gradient indicates a boundary between layers of different strength material. Layer strengths can be calculated from the gradients, using known relationships, and layer thicknesses can be determined from where boundaries are indicated.

The DCP cannot penetrate strong or very coarse granular layers such as hot mix asphalt, water bound macadam or cement treated bases. These layers must be removed by coring or drilling and their strength is assessed using other means.

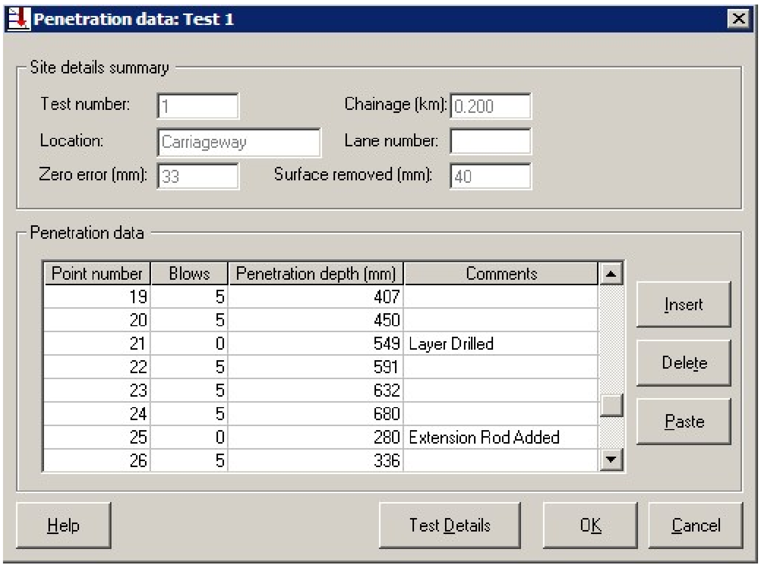
If, during the test, the DCP leans away from the vertical no attempt should be made to correct it, although if the lean becomes too severe and the hammer slides down the hammer shaft, rather than dropping freely, the test should be abandoned and repeated close by.

4. Key features of UK DCP software

UK DCP is able to analyse penetration data from a single test, collate the results from many tests in order to identify uniform sections along a road and allow improvements to those sections to be designed. The following paragraphs describe some of the key features of the software.

4.1 Data input

The input screens are designed so that data is input from the Test data sheet in a logical sequence. This includes the site details, upper layer details and penetration data. The software triggers suitable messages for valid data input to all mandatory fields. The software allows the user to record that one or two impenetrable surface layers were cored at the start of the test, and then to input the strength of these layers later in the process. When an extension rod is added or a layer is drilled, the software automatically adjusts the data for the sudden reduction or increase in recorded penetration depth. It is also possible to copy the penetration data from a spreadsheet into UK DCP. A maximum of 999 tests can be entered for a project. If as-built or test pit information is available, it is possible to record the thicknesses of the surface, base and sub-base layers and then display them to assist layer identification. Figure 2 shows how site details and penetration data are entered into UK DCP and how drilled layers and the use of an extension rod are identified.



Test number: 1
Chainage (km): 0.200
Location: Carriageway
Lane number:
Zero error (mm): 33
Surface removed (mm): 40

Point number	Blows	Penetration depth (mm)	Comments
19	5	407	
20	5	450	
21	0	549	Layer Drilled
22	5	591	
23	5	632	
24	5	680	
25	0	280	Extension Rod Added
26	5	336	

Figure 2 Test data input

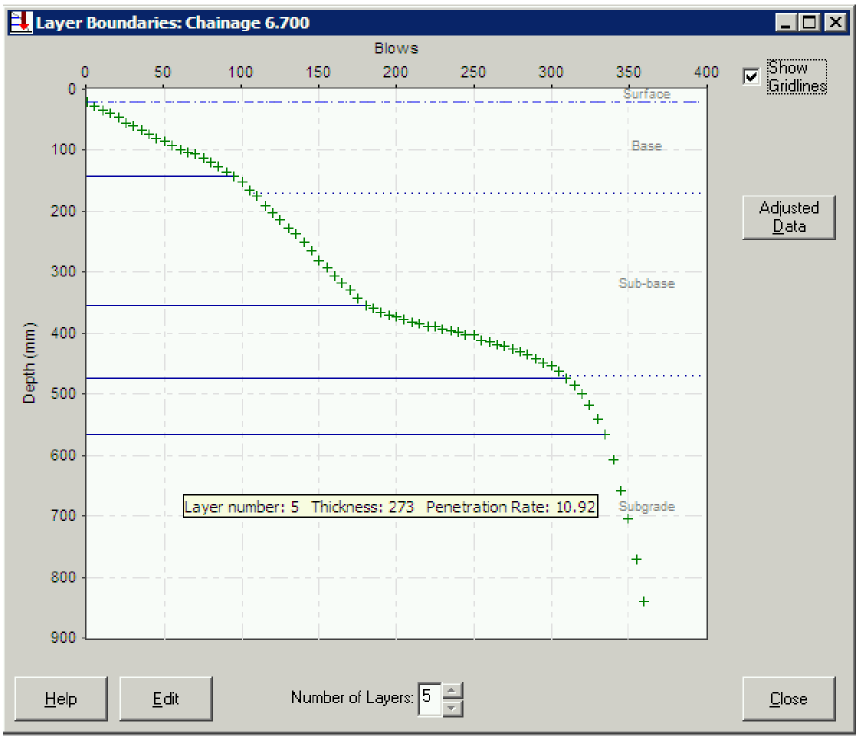
4.2 Layer analysis

Penetration data entered for a test can be analysed and layers identified in two different ways: automatically and manually.

Automatic layer analysis identifies layer boundaries using the cumulative sum technique, a process which finds the points at which the graph deviates from a straight line. The only option for the user is to decide the point at which the pavement has been adequately divided into layers and it is not necessary for further boundaries to be identified where they may not actually exist. An automatically analysed penetration plot is shown in **Error! Reference source not found.**3.

Manual layer analysis allows the user to represent the penetration graph as a series of straight lines. UK DCP then generates a boundary wherever these straight lines intersect. A manually analysed penetration plot is shown in Figure 4.

Both methods have advantages and disadvantages. Automatic analysis is quicker than manual analysis but the user has no control over where layer boundaries are located. It also can give inappropriate results on complex graphs, for example a strong layer overlaid by weaker layers or where a layer has been drilled. Manual analysis is slower but the user has more control over layer boundaries, drilled layers, strong lower layers and so on. Automatic analysis is recommended for simple graphs; manual analysis for complex graphs.

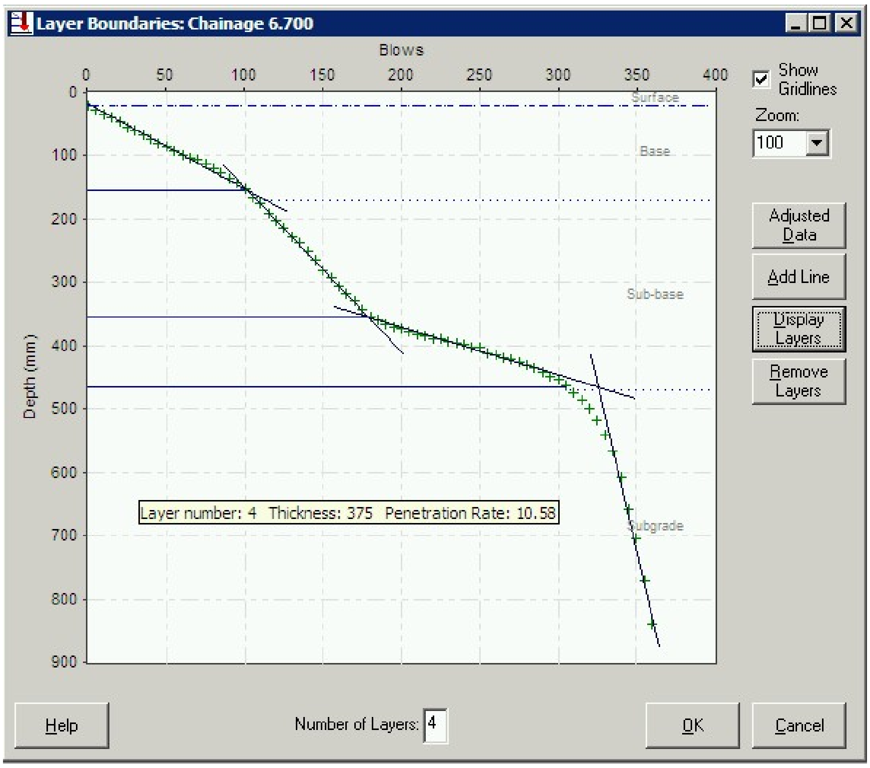


☑ Show Gridlines

Layer number: 5 Thickness: 273 Penetration Rate: 10.92

Number of Layers: 5

Figure 3 Automatic layer analysis



☑ Show Gridlines

Zoom: 100

Layer number: 4 Thickness: 375 Penetration Rate: 10.58

Number of Layers: 4

Figure 4 Manual layer analysis

4.3 CBR calculation

The strengths of each of the layers are calculated automatically by converting the penetration rate (mm per blow) to a California Bearing Ratio (CBR) value. A number of relationships between penetration rate and CBR value have been derived for 60° and 30°cones and are given in Table 1.

Cone angle	**Name of relationship**	**Relationship**
60° cone	TRL	$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.48 - 1.057\ \mathrm{Log}_{10}(\text{pen rate})$
	Kleyn (pen rate > 2 mm/blow)	$\mathrm{CBR} = 410\ (\text{pen rate})^{-1.27}$
	Kleyn (pen rate ≤ 2 mm/blow)	$\mathrm{CBR} = 66.66\ (\text{pen rate})^2 - 330\ (\text{pen rate}) + 563.33$
	Expansive Clay Method	$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.315 - 0.858\ \mathrm{Log}_{10}(\text{pen rate})$
	100% Planings	$\mathrm{Log}_{10}(\mathrm{CBR}) = 1.83 - 0.95\ \mathrm{Log}_{10}(\text{pen rate})$
	50% Planings	$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.51 - 1.38\ \mathrm{Log}_{10}(\text{pen rate})$
	User-Defined	$\mathrm{Log}_{10}(\mathrm{CBR}) = [\text{constant}] - [\text{coefficient}]\ \mathrm{Log}_{10}(\text{pen rate})$ Constant and Coefficient can be defined by the user
30° cone	Smith and Pratt	$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.555 - 1.145\ \mathrm{Log}_{10}(\text{pen rate})$
	User-Defined	$\mathrm{Log}_{10}(\mathrm{CBR}) = [\text{constant}] - [\text{coefficient}]\ \mathrm{Log}_{10}(\text{pen rate})$ Constant and Coefficient can be defined by the user

Table 1 CBR – penetration rate relationships

4.4 Structural Number calculation

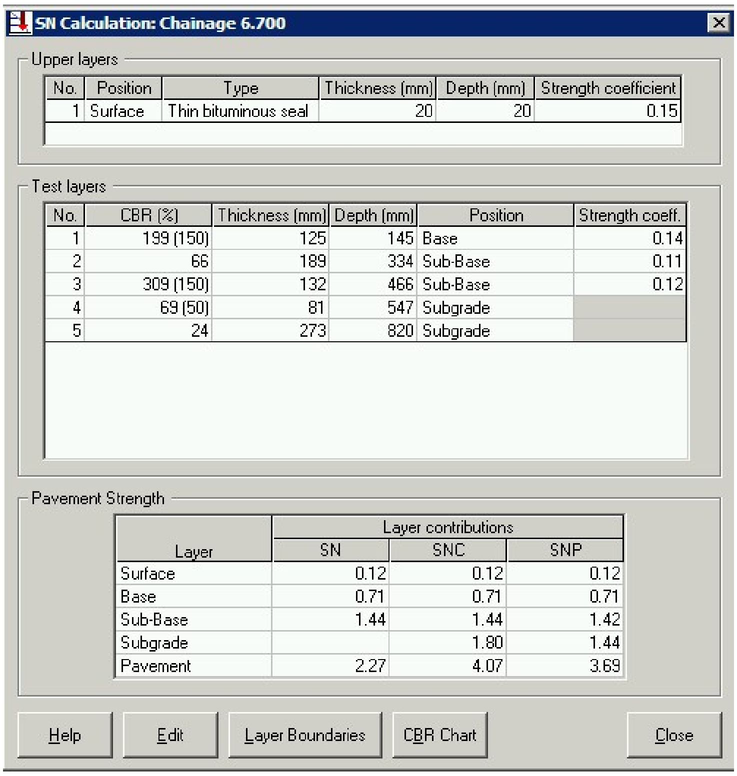
The concept of a Structural Number (SN) was developed during the AASHO Road Test research as a single number which indicates the strength and durability of an entire flexible pavement. A strength coefficient is calculated, from the CBR value using relationships given in Table 2, for each pavement layer. The SN of a pavement is the sum of the thickness multiplied by strength coefficient for all pavement layers.

Pavement Layer		**Relationship**
Base		$a = 0.0001\ [29.14\ (\mathrm{CBR}) - 0.1977\ (\mathrm{CBR})^2 + 0.00045\ (\mathrm{CBR})^3]$ This relationship is also used for a gravel or earth surface layer (10).
Cement treated base	CBR > 70%	$a = 0.00016\ [29.14\ (\mathrm{CBR}) - 0.1977\ (\mathrm{CBR})^2 + 0.00045\ (\mathrm{CBR})^3]$
	CBR < 70%	$a = 0$. Tests have shown that a cement treated base with a CBR less than 70 has minimal effective strength.
Sub-base		$a = 0.184\ \mathrm{Log}_{10}(\mathrm{CBR}) - 0.0444\ (\mathrm{Log}_{10}(\mathrm{CBR}))^2 - 0.075$

Table 2 Strength coefficient – CBR relationships

Over time, the concept has expanded. The original term, SN, is calculated from the imported surface, base and sub-base layers. The modified Structural Number (SNC) was then introduced to include the effect of the subgrade. However, it was realised that because the subgrade contribution to SNC is independent of its depth, redefining subgrade material as sub-base gives a higher SNC. The adjusted Structural Number (SNP) was therefore developed to adjust the contribution of the sub-base and subgrade according to the depth of the boundary and eliminate this potential source of error.

Figure 5 shows the screen which is used to calculate SN, SNC and SNP in UK DCP. Penetration graphs showing information from as-built records or test pits can be used to allocate each identified layer to base, sub-base or subgrade, since the relationship between strength coefficient and CBR value is different for each layer type. The pavement shown in Figure 5 has five granular layers under a 20 mm bituminous seal. The first layer appears to be strong and it has been defined as base. The remaining four layers have been divided into sub-base and subgrade on the basis of as-built information. It will be noted that subgrade layers do not have a strength coefficient since subgrades have, in theory, infinite thickness; instead the contribution of the subgrade to SNC and SNP is calculated directly from the CBR value.



Upper layers

No.	Position	Type	Thickness (mm)	Depth (mm)	Strength coefficient
1	Surface	Thin bituminous seal	20	20	0.15

Test layers

No.	CBR (%)	Thickness (mm)	Depth (mm)	Position	Strength coeff.
1	199 (150)	125	145	Base	0.14
2	66	189	334	Sub-Base	0.11
3	309 (150)	132	466	Sub-Base	0.12
4	69 (50)	81	547	Subgrade	
5	24	273	820	Subgrade	

Pavement Strength

Layer	Layer contributions		
	SN	SNC	SNP
Surface	0.12	0.12	0.12
Base	0.71	0.71	0.71
Sub-Base	1.44	1.44	1.42
Subgrade		1.80	1.44
Pavement	2.27	4.07	3.69

Figure 5 SN calculation screen

4.5 Uniform sections, using penetration data

UK DCP has two functions which can divide a project into sections that are both reasonably uniform and different from adjacent sections. The first is based solely upon penetration data and is described here; the other is based upon additional design information and is described in the following section.

Sectioning is carried out using the same cumulative sum technique that is used in automatic layer analysis and can be based upon one or more of a number of parameters, including strengths, structural numbers and layer thicknesses. After sectioning has been carried out using each selected parameter, a bar chart can be generated which shows the sections derived from each parameter alongside each other. The user can then compare the sections and manually insert section boundaries to define the overall design sections of the project. These design sections can then be used to assess the performance of the pavement or to design improvement works. Figure 6 shows three parameters being used for sectioning, each one with a significant change at a similar chainage and the road therefore having two uniform sections.

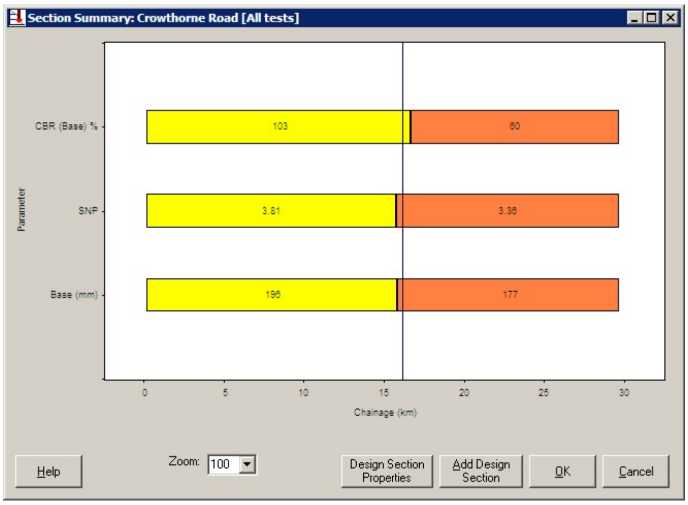
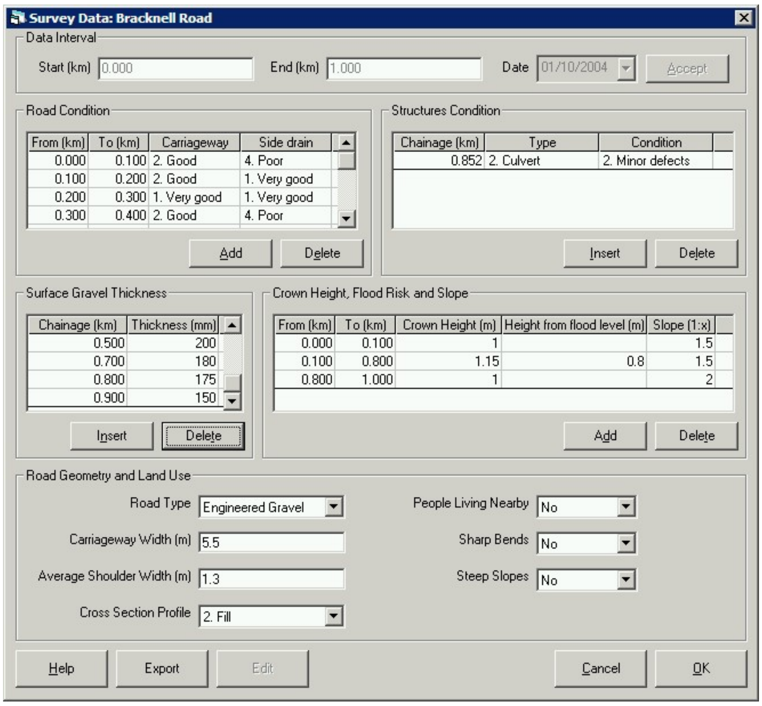


Figure 6 Uniform sections from DCP data

4.6 Input of additional design data

Unlike high volume roads, the performance of low volume roads depends not just on pavement design and traffic levels, but also very largely upon a wide variety of environmental factors, particularly those which relate to the effect of water on the pavement and the surface.

To properly design improvements, it is therefore necessary to have the following information: road condition, structure condition, surface gravel thickness, crown height, flood risk (in terms of the height of the road above flood levels), slope gradients, road geometry, land use information, national design standards, climatic data, traffic levels and traffic characteristics. UK DCP allows this information to be input using the screens in Figures 7 and 8. The presence of people living nearby, sharp bends and steep slopes is useful information since sites where gravel is a dust nuisance, loose or slippery may justify a sealed surface even if the pavement structure is sound.



Data Interval

Start (km) 0.000
End (km) 1.000
Date 01/10/2004

Road Condition

From (km)	To (km)	Carriageway	Side drain
0.000	0.100	2. Good	4. Poor
0.100	0.200	2. Good	1. Very good
0.200	0.300	1. Very good	1. Very good
0.300	0.400	2. Good	4. Poor

Structures Condition

Chainage (km)	Type	Condition
0.852	2. Culvert	2. Minor defects

Surface Gravel Thickness

Chainage (km)	Thickness (mm)
0.500	200
0.700	180
0.800	175
0.900	150

Crown Height, Flood Risk and Slope

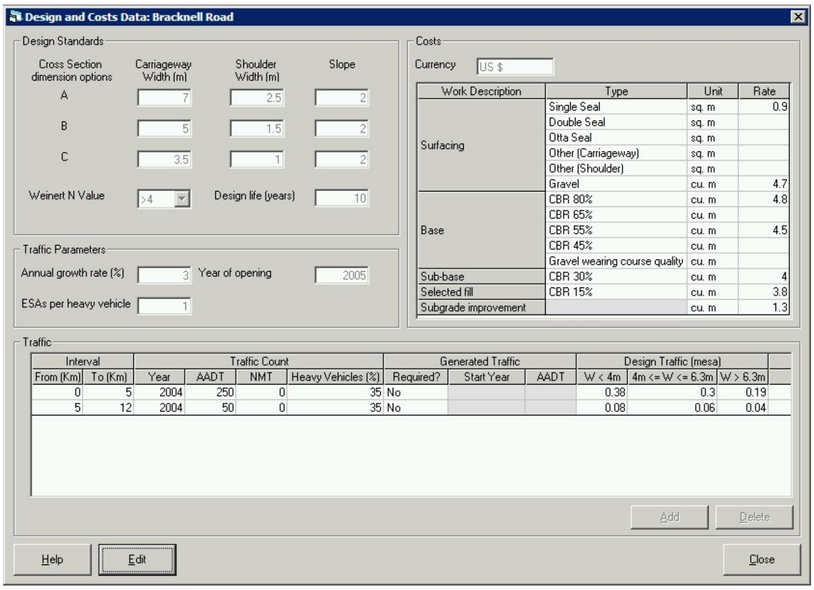
From (km)	To (km)	Crown Height (m)	Height from flood level (m)	Slope (1:x)
0.000	0.100	1		1.5
0.100	0.800	1.15	0.8	1.5
0.800	1.000	1		2

Road Geometry and Land Use

Road Type Engineered Gravel
Carriageway Width (m) 5.5
Average Shoulder Width (m) 1.3
Cross Section Profile 2. Fill
People Living Nearby No
Sharp Bends No
Steep Slopes No

Figure 7 Survey data input

UK DCP is also able to estimate the cost of the improvements. To do this, unit cost information is required. This is also input in the screen in Figure 8.



Design Standards

Cross Section dimension options	Carriageway Width (m)	Shoulder Width (m)	Slope
A	7	2.5	2
B	5	1.5	2
C	3.5	1	2

Weinert N Value: >4
Design life (years): 10

Traffic Parameters

Annual growth rate (%): 3
Year of opening: 2005
ESAs per heavy vehicle: 1

Costs

Currency: US $

Work Description	Type	Unit	Rate
Surfacing	Single Seal	sq. m	0.9
	Double Seal	sq. m	
	Otta Seal	sq. m	
	Other (Carriageway)	sq. m	
	Other (Shoulder)	sq. m	
	Gravel	cu. m	4.7
Base	CBR 80%	cu. m	4.8
	CBR 65%	cu. m	
	CBR 55%	cu. m	4.5
	CBR 45%	cu. m	
	Gravel wearing course quality	cu. m	
Sub-base	CBR 30%	cu. m	4
Selected fill	CBR 15%	cu. m	3.8
Subgrade improvement		cu. m	1.3

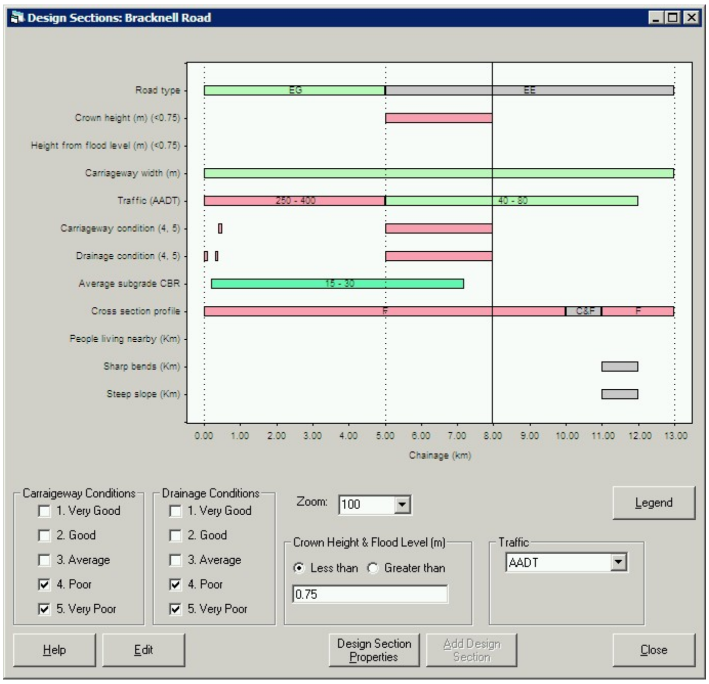
Traffic

Interval		Traffic Count				Generated Traffic			Design Traffic (mesa)		
From (Km)	To (Km)	Year	AADT	NMT	Heavy Vehicles (%)	Required?	Start Year	AADT	W < 4m	4m <= W <= 6.3m	W > 6.3m
0	5	2004	250	0	35	No			0.38	0.3	0.19
5	12	2004	50	0	35	No			0.08	0.06	0.04

Figure 8 Design and cost data input

4.7 Uniform sections, using additional design data

Whereas the sectioning using penetration data is carried out using the cumulative sum technique, the sectioning for design purposes is carried out visually. The wide variety of parameters listed in 4.6, as well as subgrade CBR from the penetration data (since this directly affects the design process), are shown in the bar chart in Figure 9. Parameters are represented in different ways according to the nature of the parameter and the possible variants. Some parameters can be filtered, for example to show only 'very poor' condition or 'poor' and 'very poor'. The software initially inserts a section boundary wherever the road type changes; it is then for the user to insert further section boundaries where the relevant parameters show significant variation over a significant length of road.



Carraigeway Conditions
☐ 1. Very Good
☐ 2. Good
☐ 3. Average
☑ 4. Poor
☑ 5. Very Poor

Drainage Conditions
☐ 1. Very Good
☐ 2. Good
☐ 3. Average
☑ 4. Poor
☑ 5. Very Poor

Zoom: 100

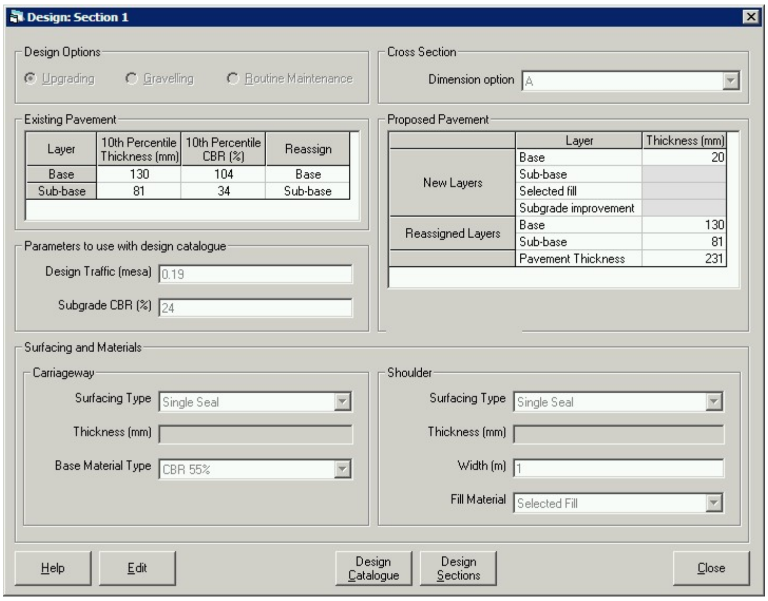
Crown Height & Flood Level (m)
● Less than ○ Greater than
0.75

Traffic: AADT

Figure 9 Uniform sections from design data

4.8 Design of improvements

UK DCP allows the user to design and cost improvements for each uniform section described in 4.7. Improvements can include pavement upgrading, regravelling and routine maintenance, depending upon condition, gravel thickness and other parameters. The design of the pavement upgrading is based on research carried out over many years in southern Africa and uses a catalogue of pavement structures for different traffic levels, subgrade CBR values, and layer strengths. The design screen for a uniform section is shown in Figure 10 and the catalogue for a specific climatic zone is shown in Figure 11. For each uniform section, the existing pavement layer thicknesses and strengths (calculated from the penetration data) are displayed and compared against the appropriate pavement structure from the catalogue. The user can then reassign existing layers into the new pavement and identify what new layers are required to match the catalogue structure.


Design: Section 1

Design Options

● Upgrading ○ Gravelling ○ Routine Maintenance

Cross Section

Dimension option: A

Existing Pavement

Layer	10th Percentile Thickness (mm)	10th Percentile CBR (%)	Reassign
Base	130	104	Base
Sub-base	81	34	Sub-base

Proposed Pavement

	Layer	Thickness (mm)
New Layers	Base	20
	Sub-base	
	Selected fill	
	Subgrade improvement	
Reassigned Layers	Base	130
	Sub-base	81
	Pavement Thickness	231

Parameters to use with design catalogue

Design Traffic (mesa): 0.19

Subgrade CBR (%): 24

Surfacing and Materials

Carriageway

Surfacing Type: Single Seal

Thickness (mm):

Base Material Type: CBR 55%

Shoulder

Surfacing Type: Single Seal

Thickness (mm):

Width (m): 1

Fill Material: Selected Fill

Figure 10 Design of improvements

After the appropriate improvement has been designed for each uniform section, UK DCP estimates the required quantities of each activity or material and then uses the previously entered unit costs to estimate the overall cost of the improvements.

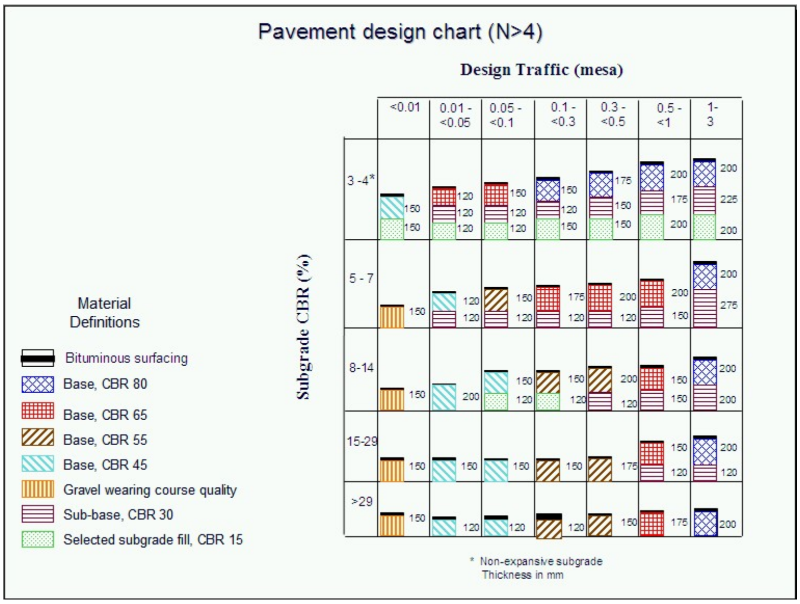


Figure 11
Pavement catalogue

4.9 Reporting

UK DCP can produce a variety of reports for printing or export. There are two types of report: test reports and project reports. Test reports contain information from a single penetration test and present penetration data and layer strength analysis. Project reports contain information from the entire project and present section summary, design section properties, project summary, condition data summary and the designed pavement improvements.

5. Limitations of the DCP and UK DCP software

The DCP is unable to penetrate coarse granular materials, material stabilised with a high percentage of cement and thick layers of bituminous material. In such cases, it is necessary to core or drill a hole through the impenetrable layer and then continue the penetration in the underlying material. Because penetration data cannot be recorded for the drilled layer, it is necessary to estimate and manually input the strength coefficient for the layer in order to include its contribution in the SN of the pavement.

Although thin bituminous layers, such as a surface dressing, can be penetrated by the DCP, the penetration data cannot be used to calculate the strength of such layers and the strength coefficient must be estimated and manually input.

UK DCP software is able to automatically adjust penetration data when a layer is drilled or an extension rod is added. However, it is unable to adjust for a second drilled layer or extension rod, although since these events are likely to either excessively disturb the material or generate excessive side friction along the rod, the data may be unreliable and the test ought to be repeated.

Currently all penetration data is either entered directly or copied from a spreadsheet. Once a project has been input into UK DCP and analysed, it is not possible to export a portion of the analysis into another file for further comparison or design. The next development of UK DCP is likely to address this issue and allow more flexibility when moving data, both before and after analysis.

6. Conclusion

UK DCP has taken the 1990 analysis software as a starting point and has added a long list of developments and enhancements to produce a tool for the rapid and accurate analysis of penetration data and design of improvements.

7. References

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