



ReCAP
Research for Community Access Partnership



Evaluation of Cost-Effectiveness and Value-for-Money of DCP-DN Pavement Design Method for Low-Volume Roads in Comparison with Conventional Designs

Final Workshop Report



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RESEARCH FOR COMMUNITY ACCESS PARTNERSHIP (ReCAP) *Safe and sustainable transport for rural communities*

ReCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa and Asia. ReCAP comprises the Africa Community Access Partnership (AfCAP) and the Asia Community Access Partnership (AsCAP). These partnerships support knowledge sharing between participating countries in order to enhance the uptake of low cost, proven solutions for rural access that maximise the use of local resources. The ReCAP programme is managed by Cardno Emerging Markets (UK) Ltd.

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Acronyms, Units and Currencies

AASHTO	American Association of State and Highway Transport Officials
AfCAP	Africa Community Access Partnership
CBA	Cost-Benefit Analysis
CBR	California Bearing Ratio
DCP	Dynamic Cone Penetrometer
DN	The average penetration rate in mm/blow of the DCP in a pavement layer
EMC	Equilibrium Moisture Content
EOD	Environmentally Optimised Design
FAQ	Frequently Asked Question
LCC	Life-cycle costs
MESA	Million Equivalent Standard Axles
MISA	Million Standard Axles
OMC	Optimum Moisture Content
PI	Plasticity Index
PM	Plasticity Modulus
PMU	Project Management Unit
ReCAP	Research for Community Access Partnership
TLC	Traffic Loading Class
ToR	Terms of Reference
TPA	Transvaal Provincial Administration
TRL	Transport Research Laboratory
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development, UK)
VFM	Value for Money
VOC	Vehicle Operating Costs

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Executive summary

A workshop was arranged by the Project Management Unit (PMU) of the Research for Community Access Partnership (ReCAP) to discuss the outcome of the Draft Final Report on the *Evaluation of Cost Effectiveness and Value-for-Money of the DCP-DN Pavement Design Method for Low Volume Roads in Comparison with Conventional Designs* (hereinafter referred to as “the Cost Evaluation Report”), as well as a companion report on the *Development of the DCP-DN Method*.

The workshop was held in Durban at the end of the SARF/IRF/PIARC conference on Friday 12th October, 2018. The workshop was attended by 23 persons representing roads agencies in 3 ReCAP partner countries, academia, the ReCAP Technical Panel, the Cardno Project Management Unit, Independent Consultants and the project consultants.

Although not stated specifically in the introductory remarks, a principal purpose of the workshop and the documents provided was to demonstrate that the DCP-DN method was founded on sound scientific principles and could be used with confidence albeit within defined limits. In addition, the workshop was expected to provide guidance on further research work necessary to improve the efficacy and applicability of the DCP-DN design method for LVRs.

The workshop presentations triggered a number of comments and clarifications from participants, the main outcomes of which may be summarised as follows:

Development of DCP-DN method

General outcomes:

- The science behind the development of the DCP-DN method is well documented, sound and credible.
- The use of the DN value only to select road materials needs to be elaborated upon in the paper on the Background to the Development of the DCP-DN Method.
- The limits of the application of the DCP-DN method to be clearly stated in terms of absolute limits, possible limits and no limits at all.
- The Malawi DCP-DN design manual to be updated on the basis of the outcomes/agreements reached at the workshop and converted to a generic DCP-DN design manual.
- Need to consider the level of risk when applying the DCP-DN method outside the South African environment.

Further Research outcomes:

- The precision limits/variability of the DCP test to be determined for comparison with ditto for the CBR test.
- The effect of confinement on the laboratory DN test to be investigated.
- A review to be undertaken of the DN-CBR relationship including the Standard Error and Coefficient of Variation.
- The failure criteria for LVRs to be investigated and redefined through additional research aimed at producing pavement structures for LVRs that resist subgrade failure with smaller margins than current design methods.

Cost evaluation report

General outcomes:

- Within the context of the ToR, it was not possible to undertake a traditional CBA based on life-cycle costs of the roads designed under ReCAP as they were all relatively recently constructed and had no significant performance history.
- The assumption that maintenance and vehicle operating costs (VOCs) on the different pavement structures were broadly similar, based on the assumption that they possessed similar structural capacities, was an over-simplification.
- The outcome of the Cost Benefit Analysis (CBA) was based essentially on a comparison of initial construction costs.
- At design traffic loading up to about 0.7 MESA, and for a wide range of subgrade strengths and climatic zones, the DCP-DN design method will, in the majority of cases, provide pavement cost savings in the range of USD 10,000 -20,000 per km, and in many cases in excess of USD20,000/km when compared against all other methods.
- The pavement cost savings offered by the DCP-DN method occur to a lesser extent in the higher TLCs (0.7 MESA and above) when, in some cases, other design methods, particularly ORN31, are more cost-effective in this higher traffic range.
- Consideration to be given to better supporting the key evaluation assumptions made in the CBA by possible obtaining roughness measurements and typical maintenance costs on similar roads to those evaluated in the project.
- The project cost per design method for the 0.1 MESA traffic loading to be checked.
- The Overseas Road Note 31 design method to be retained as one of the LVR design methods evaluated in the report as it is still used in a number of countries in Asia and Africa.
- More emphasis to be placed on the differences in pavement cost ratios rather than differences in project cost ratios.
- Zero haulage distance should be incorporated in the cost evaluations for comparison with the other short, medium and long haulage distance scenarios considered.
- When discussing Value-for-Money, need to separate the general benefits of road upgrading from those related specifically to the use of the DCP-DN method.

Overall summary

Based on feedback from participants, the workshop appears to have achieved its main objectives. One of the key outcomes, based on recent research undertaken through SEACAP and ReCAP, plus comments from workshop participants, is that additional research is required that will possibly lead to even greater cost reductions for the DCP-DN and other methods of LVR design. The motivation for undertaking such research is presented in **Annex F** of the report.

Evaluation of workshop by participants

A summary of the responses to the workshop questionnaire, based on the 12 completed evaluation forms submitted by the participants, is presented below.

- The majority of participants (75%) at least partially agreed that the time available to review the workshop documents was adequate.
- All the participants agreed that the workshop process and methodology were satisfactory.
- All the participants agreed that the workshop objectives were achieved.
- Half of the participants agreed that the workshop had clarified many of their concerns relating to the DCP-DN method of design and the other half did not.

- The majority of participants (58.4%) agreed that many of their concerns relating to the findings of the Cost Evaluation report had been clarified.
- All the participants agreed that the workshop presentations were adequately made.
- All the participants agreed that there was adequate time for presentations and discussions.
- The majority of participants (83.3%) agreed that the project team's responses to the issues raised and clarifications sought were satisfactory.

1 Background

1.1 General

The Research for Community Access Partnership (ReCAP) is supporting research and capacity building activities in Africa (Africa Community Access Partnership – AfCAP) and Asia (Asia Community Access Partnership – AsCAP). One of the objectives of the ReCAP initiative is to assist partner countries in providing low volume sealed roads in a cost-effective and sustainable manner through research. To this end, it has supported the enhancement of a method of pavement design based on the use of the Dynamic Cone Penetrometer (DCP) as an alternative to the more traditional California Bearing Ratio (CBR)-based design methods.

Following the development of a *Design Manual for Low Volume Roads Using the DCP Design Method* in 2013 (Min. of Transport and Public Works, Malawi, 2013), road sections have been designed on the basis of the DCP-DN method and constructed in a number of African countries dating back to 2012. Prior to that, over 2500 km of low volume roads have also been designed (and constructed) on a similar basis in a variety of road environments in South Africa dating back to the early 1980s (van Zyl and Burger, 2008).

1.2 Cost Evaluation Project

Despite the perceived advantages by some practitioners of the DCP-DN method of design over other, more traditional, CBR-based methods, they are yet to be fully quantified. This has prompted the ReCAP Project Management Unit (PMU) to commission a project to evaluate road sections designed in a number of African countries, dating back to 2012, using the DCP-DN method in terms of cost-effectiveness and value-for-money. The aim of the project was to collect and compile construction costs of these pavements in order to determine up-front cost savings, as well as life-cycle costs, arising from the design approach, and to compare them with those pavements upgraded to a similar paved standard based on traditional, CBR-based design methods (DCP-CBR, TRH4, ORN31).

Following the completion of the draft final report on the *Evaluation of Cost Effectiveness and Value-for-Money of DCP-DN Pavement Design Method for Low Volume Roads in Comparison with Conventional Designs (hereinafter referred to as “the Cost Evaluation Report”)*, it was submitted to ReCAP PMU for review, updated on the basis of their comments and, subsequently, sent to external experts for independent peer review.

In addition, and for completeness, ReCAP also engaged a team of two experts with intimate knowledge of, and significant involvement in, the earlier development of the DCP-DN method to prepare a comprehensive, fully-referenced paper on the *Background to the Development of the DCP-DN Design Method*.

1.3 Durban Workshop

1.3.1 General

In order to fully debate the outcomes of the DCP-DN background development paper and the final draft evaluation report as submitted to the external peer reviewers, a workshop was arranged by the ReCAP PMU in Durban at the end of the SARF/IRF/PIARC conference on Friday 12th October, 2018. The intention was that the discussions and outcomes would feed into the finalisation of both reports to serve as future reference documents.

In addition to the above, the workshop was expected to provide guidance on further research work necessary to enhance the efficacy and applicability of the DCP-DN design method for LVRs.

1.3.2 Workshop programme and attendance

The workshop programme is presented in **Annex A**.

The workshop was attended by 22 persons representing roads agencies in 3 ReCAP partner states, academia, the ReCAP Technical Panel, the Cardno Project Management Unit, Independent Consultants and the project consultants. The attendance list is presented in **Annex B**.

1.3.3 Workshop outcomes and report

The outcomes of the workshop are summarised in subsequent sections of this Workshop Report which is based, in part, on the facilitator's Review of the Workshop (see **Annex C**) as well as on the rapporteurs' Record of Workshop Discussion (see **Annex D**) that was presented at the end of the workshop. In addition, for completeness, a number of Frequently Asked Questions (FAQs) on the DCP-DN method of design that were not/could not be fully explained/discussed in a workshop setting with limited time, are included in **Annex E** of the report. The responses to these FAQs are solely the views of the project consultants and do not in any way purport to reflect the views of the workshop participants.

The Workshop Report is structured as follows:

Section 1: (This section). Provides the background to the workshop including the motivation for holding it.

Section 2: Presents the workshop preliminaries including the opening remarks by the ReCAP Deputy Team Leader - Infrastructure Research Manager and the workshop facilitator.

Section 3: Provides a summary of the presentations made by the project team and presents their response to the comments made, or clarifications sought, by the workshop participants.

Section 4: Summarizes the main outcomes of the workshop and the way forward for completing the project reports.

2 Workshop Preliminaries

2.1 Opening Remarks

The opening remarks were made by Mr. Nkululeko Leta, the ReCAP Deputy Team Leader - Infrastructure Research Manager, who provided the background to, and purpose of, the workshop. As regards the background to the workshop, he mentioned that:

- The bringing together of a cross-section of stakeholders with an intimate knowledge of low volume road (LVR) design methods has been long planned by the ReCAP PMU and the attendance of these stakeholders at the Durban conference has provided a golden opportunity for inviting them to participate in the workshop.
- The main purpose of the workshop is to discuss the outcome of the Draft Final Report on the Evaluation of Cost Effectiveness and Value-for Money of the DCP-DN Pavement Design Method for Low Volume Roads in Comparison with Conventional Designs, as well as a related paper on the background to the Development of the DCP-DN method.
- There is representation at the workshop from a wide range of organizations including academia, roads agencies, the ReCAP Technical Panel and independent consultants who were carefully selected to share ideas and to contribute to the discussions on the two presentations being made at the workshop as a basis for finding common ground on the way forward.

In terms of the background to the DCP-DN method, the ReCAP Deputy Team Leader mentioned that:

- In 2010, the Roads Authority in Malawi approached AfCAP to assist with a review of the performance of their LVRs, including the prevailing prescribed standards and specifications. The output was a report on the *Performance Review of Design Standards and Technical Specifications for Low Volume Sealed Roads in Malawi (2011)*, which concluded that the then current design standards and specifications were overly conservative and that a new manual should be prepared based on previous investigations and research carried out in Malawi and in other countries in the region. This led to the development of the *Design Manual for Low Volume Sealed Roads Using the DCP Design Method (2013)*.
- The Malawi DCP manual had been used to design a number of roads in Malawi. There has also been interest in other AfCAP countries in the DCP design method which has led to the design and construction of a number of trial/experimental sections.
- Many different views have been expressed about the DCP-DN method of design and its cost-effectiveness but these have never been coordinated and collectively discussed in an appropriate forum. Accordingly, as a demand-driven organization, ReCAP has commissioned a study to evaluate the cost-effectiveness of the DCP-DN method against alternative methods of LVR pavement design.

In terms of the workshop process and outputs, the ReCAP Deputy Team Leader mentioned that:

- The focus of the workshop is on the review of the *Draft Cost Evaluation Report* based on scientific, credible evidence. For completeness, a presentation will first be made on the background to the *Development of the DCP-DN Method*.
- During the course of presentation of the two reports, participants were encouraged to make comments or seek clarifications on any aspects of them through the workshop facilitator.
- There should be clear outputs emanating from the deliberations on the technical and cost aspects of the presentations. The outcomes of these deliberations should hopefully provide a better understanding of each other's viewpoints as a result of which there might be agreement on some issues and not on others.

- Ultimately, there is a need to seek a mutually agreeable way forward with the two reports. The first output of the workshop will be a Workshop Report which will take account of the workshop summary prepared by the rapporteurs.
- The second output of the workshop will be a revised DCP background paper and a revised *Cost Evaluation Report* both of which will incorporate the outputs of the workshop.
- An evaluation questionnaire will be circulated to all delegates at the end of the workshop which should be filled in and handed back to the ReCAP Deputy Team Leader.
- The workshop outputs will provide an important input to the development of a generic Rural Road Note on LVR Design which will provide clear guidance and understanding of the limits of application of all the design methods.

The ReCAP Deputy Team Leader then introduced the three workshop rapporteurs Dr. Patrick Bekoe of Ghana, Ms. Leah Musenero of Uganda and Mr. Joseph Chibwe of Zambia who, he mentioned were the first three AfCAP-certified DCP-DN trainers.

2.2 Role of the ReCAP Technical Panel (TP)

Dr Jasper Cook as the ReCAP Chief Technical Adviser (CTA) briefly summarised the role of the TP. The TP works independently within ReCAP alongside and closely allied with the PMU with the objective on ensuring the quality of the research outputs as well as advising the Steering Committees and DFID, through the Executive Committee, on scientific and strategic issues. The TP is coordinated by the CTA. In the context of the workshop, the TP and the CTA's role is to assess the scientific quality of the work and the associated value for money. From their point of view therefore the key issues for assessment are;

- Scientific background to the DCP being established
- Sound methodology demonstrated by the project
- The value for money
- Defining limits of use for the DCP-DN approach.

The CTA and TP understood that the above points referred only to the DCP-DN method and not to the use of the DCP itself, which has been in general use now for more than 25 years

2.3 Facilitator's Introductory Remarks

After introducing himself, the workshop facilitator, Dr. David Hughes, from Queens University, Belfast, Northern Ireland, stated that his main task was to:

- Ensure that the workshop process was carried out in an orderly manner with a view to eliciting comments from delegates on key aspects of the two reports that were circulated to them in advance of the workshop and were to be presented at the workshop.
- Achieve consensus, as far as possible, on issues which had triggered divergent views from delegates.
- Agree the way forward to the finalisation of the two reports based on the outcomes of the workshop.

Dr. Hughes then requested all the delegates to introduce themselves, including their organisation affiliation.

3 Workshop Presentations, Discussions and Outcomes

3.1 General

Two PowerPoint presentations were made at the workshop, viz:

- (1) A paper on the *Development of the DCP-DN Method* by Messrs. Paige-Green and van Zyl, and
- (2) A report on the *Evaluation of Cost Effectiveness and Value-for-Money of DCP-DN Pavement Design Method for Low Volume Roads in Comparison with Conventional Designs* by Messrs. Pinard, Van Zyl, Paige-Green, Hongve and Mukandila.

During the course of the above presentations, comments were made by delegates and the ensuing discussions led to clarifications and explanations being made by the presenters, the outputs of which are summarized below. For completeness, some frequently asked questions (FAQs) about the DCP-DN design method, which were not specifically discussed at the workshop, are included in an annex to the Workshop Report.

3.2 DCP Background Paper

3.2.1 PowerPoint presentation

The key topics included in the PowerPoint presentation on the above paper may be summarized as follows:

- General Background
- Approach and Early Development
- CBR-DCP Correlation
- Advantages of DN Over CBR
- Principles of DCP Design Method
- DCP-CBR Design Method
- DCP-DN Design Method
- Risk and Mitigation

The key points emanating from the presentation may be summarized as follows:

- The original DCP-CBR/DN catalogue developed by Kleyn and van Zyl was based on back-analysis of some 1100 test sections located in a variety of road environments (traffic, material type, climate, etc.). This catalogue, including the DSN_{800} values (equivalent to the Structural Number concept embedded in the AASHTO design method), was subsequently corroborated by further detailed investigation of 57 LVRs also located in a variety of road environments.
- The back-analysis of the LVR investigations clearly showed a very poor correlation between road performance and strength (CBR), plasticity (PI or PM) and grading). This has been corroborated subsequently by back-analysis investigations of LVRs undertaken in Mozambique (Rolt et al, 2013) and elsewhere in the region.
- The pavement strength/balance concept, defined as the change in the strength of the pavement layers with depth, is a unique feature of the DCP-DN method in terms of differentiating between deep, shallow and inverted pavements that could be well balanced or poorly balanced. The catalogue layer-strength requirements are based on achieving a deep, well-balanced pavement in practice.

- A comparison of the structural capacity of the DCP-DN method with the other CBR-based methods (DCP-CBR, ORN31 and TRH4) showed that they are all broadly similar up to about 0.1 MESA, after which the former becomes more conservative.
- Based on the experience with the use of the original (Klein) DCP-CBR method, the DCP-DN method has been refined as follows:
 - Minor revision of the design catalogue which has been extended to 1 MESA.
 - Moving away from converting DN to CBR due to poor correlations and material dependence and using DN values only in the field and the laboratory.
 - Using DN and DSN_{800} for delimitation of uniform sections.
 - Moving to the use of the DN values for proving the suitability of borrow pit samples (together with conventional classification testing initially), including limits on the Grading Modulus of the material for routine testing.
 - Laboratory DCP evaluation of borrow pit materials as structural layers.
 - Moving away from the percentile moisture conversion approach to determine the representative DN value under the expected moisture and density conditions to an approach based on laboratory investigation of samples taken from uniform road sections which allow a much better interpretation and understanding of the fundamental material properties, including the grading, compactability, moisture sensitivity (related to plasticity) etc. based on DCP-DN testing.
 - Development of the AfCAP LVR DCP Software

3.2.2 Comments/observations arising from presentation

Comment: The use of the DCP per se is well established, and is not in question.

- **Observation:** The original data on which the DCP-CBR/DN design method has been developed is extensive and most of it (8 of the 12 volumes, so far) is available in hard copy for further analysis, if required. It covers investigation of some 1100 road sections in a variety of road environments and material types. The information collected on each road section includes:
 - Road elevation/configuration (fill/side fill/cut)
 - Surface drainage
 - Slope erosion
 - Road condition (several distress types including rut depth > 20 mm as a failure criterion).
 - Surface condition
 - Material type
 - Moisture condition in pavement
 - Bulk samples obtained for materials classification and CBR and DCP determinations
 - DCP DN/depth plot

<ul style="list-style-type: none">○ Outcome: The science behind the development of the DCP-CBR/DN has been adequately demonstrated. However, the design catalogue may be further optimized through additional research (see Annex F).
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- **Comment:** The variability of the CBR is well known. Is there any literature on the variability of the DCP?
 - **Project team response:** The variability of the CBR test in relation to the DCP test has been reported by some researchers, e.g. Smith and Pratt (1983), Rallings (2014). In summary, the coefficient of variation of the CBR test is of the order of 60% and that for the DCP of the order of 40%. Whatever the case, because of the larger number of DCP test points normally taken to characterize subgrade strength, typically 5 – 10

times the number of CBR points, the DCP values provide a good statistical distribution of subgrade strengths for all methods using the DCP to evaluate the subgrade strength and, by so doing, ensures that very little of the road is at risk of under- or over-design.

- **Outcome:** Need for the authors to take cognisance of the fact that there may be issues around the repeatability of the DCP test and that precision limits of the DCP laboratory test could be **an area of further research** for comparison with the CBR test.

- **Comment:** Is there not an issue related to confinement in the laboratory DCP test as compared to the field DCP test and does this not affect the design method?

- **Project team response:** Confinement is not an issue with either the DCP-DN design method or the use of the DCP for quality control purposes. In the former case, the subgrade strength is characterized on the basis of at least 2 bulk samples taken from a uniform section along the road under design for laboratory DN testing at varying densities and moisture contents. The resulting lab DN values are then compared with the DCP catalogue which is also based on lab DN values, i.e. the comparison is between lab vs lab DN values and not lab vs field DN values.

As regards the latter case, the DCP is used in the field during a compaction trial only to determine when the maximum density has been obtained (no further increase in DN value) for the given compaction plant being used on site. The material in the layer being tested has, prior to construction, been approved through the laboratory DN test and consideration of the output of the Classification testing in a similar manner as the material would be approved based on laboratory CBR values for other methods.

- **Outcome:** A potential **area of research** could be to establish the effect of confinement on laboratory DCP tests.

- **Comment:** A log-log scale always provides a good relationship. It may be better to look at a Normal scale to determine the DN-CBR relationship. There is also a need to look at the Standard Error and Coefficient of Variation of the DN-CBR relationship. This would be the same for both the Kleyn and the TRL DN-CBR relationship.

- **Outcome:** A potential **area of research** could be to have a second look at the DCP/CBR data from the Burrow investigation to review the DN-CBR relationship and to determine the Standard Error and Coefficient of Variation.

- **Comment:** The failure criterion used in the Burrow investigation is a rut depth > 20mm. This appears to be too conservative for LVRs.

- **Delegates response:**
 - Failure has also been defined by visual assessments in terms of various types of distress, e.g. cracking, fretting, potholing, etc. However, these defects are symptoms of a road reaching a failed state but are not the cause of failure which may be due to poor drainage, lack of maintenance, etc.
 - The environment, rather than traffic loading, is often the predominant influence on performance of LVRs (traffic loadings < 1 MESA).
 - At an extreme, failure could be deemed to occur on a surfaced road when road users prefer to use a gravel road in preference to a badly deteriorated paved road.

- **Outcome:** The definition of failure in a LVR is currently poorly defined and should probably be related more to serviceability than to assessment of the strength or stiffness of the pavement layers. This is an **area of further research** that could lead to reduced costs when subgrade failure is properly defined in monitoring and back analysis.

- **Comment:** Isn't there a danger with "compaction to refusal" in terms of material breakdown?
 - **Project team response:** The term "compaction to refusal" is always qualified with the caveat "without breakdown of the material". This is a key feature of the DCP-DN method which seeks to compact the subgrade, particularly, to the maximum density attainable in the field, typically in excess of the traditional 93% BS Light Compaction, so as to maximize the stiffness of the subgrade and minimize the pavement layer strength requirements. Breakdown and degradation of the material could also be identified in the laboratory DN test.
- **Comment:** The DCP-DN values used for design purposes do not take account of the durability of the material.
 - **Project team response:** Both the CBR and DCP tests are mechanical in nature and cannot be used for detecting potential durability problems with, particularly, materials derived from weathering of basic igneous rocks like basalt and dolerite. Appropriate durability testing, e.g. Durability Mill or soundness testing (sulphate or magnesium) would need to be separately carried out.

From back-analysis of numerous projects in South Africa, material durability has generally not been an issue for LVRs. Durability Mill Index (DMI) values in excess of 2000 have been measured, compared with values of 150 – 200 recommended for roads in general, and this has generally not had any adverse impact on the performance of the LVRs investigated. However, warning on the use of these types of materials is included in the LVR manuals, Care, however, needs to be taken when using mudrocks and shales that are susceptible to slaking and tests such as the COLTO "Venter test" or the slake durability test should be used in such cases.

- **Comment:** The use of the DN value only for selecting materials is dangerous and misleading.
 - **Project team response:** The statement in the background paper on the development of the DCP-DN that the DN value is the sole criterion for selecting materials is, without the normal explanations given in other documents, potentially misleading and will be corrected.

By way of explanation, in the DCP-DN design method, the selection of a material is based on the following:

- The DN value of the material at a selected density and moisture condition
- A minimum grading modulus (typically > 1 to exclude very fine-grained materials and < 2.25 to exclude materials that are too coarse).
- A knowledge of the properties of the soils in terms of Atterberg Limits and grading determined from at least 2 bulk samples selected from within a uniform section of the subgrade of the road under design or from the borrow pit materials being considered for use in the pavement layers.

The rationale behind the above approach is that:

- The DN value (resistance to material penetration) measured over the full depth of a CBR mould, is a composite measure of the mechanical properties of a material that affect its strength as influenced by the material's plasticity (PI and PM) and grading, and in relation to the density and moisture of the material. Thus, the DN value is crucially influenced by the PI and grading of the material at a particular density and moisture content.
 - For design purposes, the material's strength, as indicated by its DN value, is determined in a CBR mould at 3 densities and 3 moisture contents. This array of information provides the designer with a sound basis for assessing the suitability of the material for incorporation in the road subgrade or pavement in terms of the anticipated field density and long-term equilibrium moisture content.
 - The specification of the material is based on its DN value without the traditionally specified grading and plasticity requirements as well. This is because the influence of these properties is reflected in the DN value at various densities and moisture contents. Moreover, research evidence shows clearly that the specification of a strength requirement (DN or CBR value), with a requirement to simultaneously satisfy both PI/PM and grading requirements does not provide any greater degree of assurance that suitable materials were being selected than had these requirements not been specified. For example, as shown in the presentation, the inclusion of both plasticity and grading requirements would have excluded between 30 and 63% of base materials used in the 57 roads investigated in South Africa, results that are corroborated by the roads that were investigated as a basis for developing the DCP-CBR catalogue as well as from back-analysis of LVRs in Mozambique (Root et al 2013).
- **Comment:** There are limitations to using the DCP-DN method along alignments where there is significant cut or fill or possibly in areas with significant widening.
 - **Project Team's Response:** The DCP-DN method, just like the DCP-CBR method, can also be used along alignments where there is significant cut or fill or possibly in areas with significant widening.
 - In fill areas, the approach would be to determine the laboratory DN value of the borrow material that will be used for the fill/capping layer (subgrade) of the road being upgraded.
 - In cut areas, the approach would be to undertake the DCP testing after the cut had been made to formation level (future subgrade of the road). Depending on the depth of the cut, samples from the subgrade at the designed formation level can also be taken for testing in the laboratory to get an initial indication of the subgrade strength/class on which to base the pavement design.
 - In areas of significant widening, the approach would be similar to the above, depending on where the widening would involve a cut or fill situation.

3.3 Draft Cost Evaluation Report

3.3.1 PowerPoint presentation

The key topics included in the PowerPoint presentation on the above report may be summarized as follows:

- Background
- Approach and Methodology
- LCC Evaluation Procedure
- Pavement Designs
- Cost Comparisons
- Evaluation of Value for Money
- Summary

The key points emanating from the presentation may be summarized as follows:

- The main purpose of the project was “To carry out an evaluation of the cost-effectiveness and value-for-money of the DCP-DN pavement design method with a view to assess the benefits/cost savings accruing to the Road Authorities, in terms of both the upfront cost savings and life-cycle costs, as a result of adopting the method in comparison with conventional designs”.
- The project is also required to highlight the cost-effectiveness and value-for-money aspects of the DCP-DN design method;
- The design methods to be compared were:
 - DCP-DN
 - DCP-CBR
 - ORN31
 - TRH4
- The 10 roads/trial sections that were evaluated were located in 6 African countries and ranged in age from zero years (3 sections not yet constructed) to over 17 years. These roads/trial sections are located in a variety of road environments and offer a total of 36 design scenarios (4 design methods x 1 traffic design class x 1 subgrade strength x 1 climatic zone x 3 material types x 3 borrow haulage distances).
- In order to extend the number of design scenarios likely to be encountered in practice, a total of 1728 hypothetical designs were also undertaken (4 design methods x 3 x traffic classes x 4 x subgrade strengths x 2 x climatic zones x 6 x material types x 3 x borrow pit haulage distances)
- The pavement structures for the 10 roads/sections evaluated (the in-situ designs) were determined from actual input data pertaining to the design traffic loading, in-situ subgrade strength and climatic environment prevailing in the various countries where the roads were located.
- The pavement structures for the hypothetical road sections being evaluated were determined from application of the 4 design methods as applied to a relatively wide range of input factors in terms of traffic loading, in-situ subgrade strength and climatic environment.

- The unit construction costs applied to the different pavement structures were determined for both the in-situ and hypothetical designs included the following:
 - Cost of material, stockpiled at borrow pits and crushers, ready for loading.
 - Load plus free haul of 1km.
 - Haulage costs per three range distances (as would be the case in practice)
 - In-situ rip and recompact costs.
 - Plant and labour costs to construct different layer thicknesses.
- Ideally, a Cost benefit Analysis (CBA) would include all life-cycle costs anticipated over the life or analysis period of a road with the main components being:
 - Agency costs
 - Initial construction/rehabilitation costs
 - Future maintenance costs
 - Benefits due to savings in user costs over the analysis period
 - Salvage costs

A discounted cash flow technique would then be used to determine the Net Present Value (NPV) of each option on which basis the preferred option would be determined.

- A typical life-cycle cost analysis would only have been possible if all the 10 roads/trial sections being designed by the four design methods were:
 - founded on a similar strength subgrade
 - located in the same road environment with replication of the trials in a variety of road environments.
 - properly constructed and adequately maintained over their design life
 - monitored at least at the end of their design life in terms of the total traffic carried since construction (in MESAs), roughness cracking, rutting, etc. so as to be able to determine relative benefits due to savings in user costs over the analysis period and their relative salvage values.
- In the absence of the idealised scenario described above, it was necessary to make a number of pragmatic assumptions for undertaking an indicative, hypothetical LCC analysis – assumptions which were considered to be not unreasonable in the circumstances, viz:
 - The structural capacities (based on DSN_{800}) of the pavement structures produced by the four design methods are broadly similar (in fact, the structural capacity of the DCP-DN method was determined to be very similar to all of the other design catalogues up to about 0.1 MESA, after which it became slightly more conservative).
 - Drainage was adequate for all the road/trial sections.
 - Drainage and surface maintenance which are key factors affecting performance, were adequate for all the roads/trial sections.
 - The road environment in terms of climate, rather than traffic loading, exerts a predominant influence on road deterioration.
 - As a result of the above, it was assumed that:
 - the pavement structures would be expected to deteriorate in a broadly similar manner under a given traffic loading and road environment. In other words, there would be little significant differential performance between them.

- the cost of the periodic maintenance interventions for the roads/trial sections would be broadly similar and, when discounted to the base year, would be relatively small in comparison with the construction costs (the non-traffic related routine maintenance costs are assumed to be the same for all the roads/trial sections).
- the roughness generated by a relatively small number of commercial vehicles on the roads/trial sections, and hence the related VOCs, would be broadly similar and, when discounted to the base year, the difference in VOC savings would be relatively small in comparison with the construction costs. Most roughness variations on new LVRs are built-in during construction and are not traffic related.
- Based on the above necessary assumptions, the CBA would, in the final analysis, be related primarily to the initial construction costs of the road trials/sections. For the reasons explained above, this outcome is considered to be at least reflective of the idealized scenario described above.
- Based on the above assumptions, global cost trends were evaluated for the four design methods in terms of:
 - Pavement cost ratios
 - Total project cost ratios
 - Total project cost differences/km (this parameter being considered to be of most interest to road financiers and roads agencies).
- The outcome of the LCC analysis, essentially related to initial construction costs, may be summarized as follows:
 - At design traffic loading up to about 0.7 MESA, and for a wide range of subgrade strengths and climatic zones, the DCP-DN design method will, in the majority of cases, provide pavement cost savings in the range of USD 10,000 -20,000 per km, and in many cases in excess of USD20,000/km when compared against all other methods.
 - The pavement cost savings offered by the DCP-DN method occur to a lesser extent in the higher TLCs (0.7 MESA and above) when, in some cases, other design methods, particularly ORN31, are more cost-effective in this higher traffic range.
- In general terms, the difference in pavement costs per km for the various design methods, and the pavement cost efficiency of the DCP-DN design method, relative to the other design methods, decreases with higher quality subgrades and higher TLCs. Also, for the specific set of environmental conditions considered, there is no major difference in the trends between Wet and Dry-Moderate environments.
- The global conclusion to be drawn from the very wide range of design evaluations is that the DCP-DN method is generally the most cost-effective design option at low TLCs, up to about 0.7 MESA and across all subgrade strengths. However, at TLCs above 0.7 MESA the method gradually becomes less cost effective than the other methods, particularly ORN31, which become more cost-effective in many situations.
- In terms of value-for-money (VFM), the use of the DCP-DN method and, indeed other methods such as ORN31 when applied to relatively high design traffic loadings (>0.7 MESA) in some road environments, is expected to provide Value for Money in terms of the following:

- Cost-effectiveness.
- Outcome (uptake) and knowledge.
- Potential impact on society.

3.3.2 Comments/observations arising from presentation

- **Comment:** The assumption that pavement deterioration was broadly similar for the road sections designed by the different design methods and that maintenance and VOCs, as related to roughness, are broadly similar was an over-simplification. The analysis undertaken was based essentially on a comparison of initial construction costs.

- **Project team response:** In the context of the terms of reference which stipulated the roads/trial sections to be evaluated, there was little alternative to the approach adopted given that the roads are all relatively new and without a performance history that would allow end of design life roughness values, and hence VOCs to be determined, as well as maintenance cost interventions and residual values. In any case, there are serious reservations over the applicability of current deterioration models for application to CBA of LVRs for which environment-related distress generally dominates overall pavement deterioration. Such distress typically results in some form of surface deterioration which is not necessarily related to inadequate structural capacity (SN or DSN₈₀₀) which is the premise on which pavement failure is predicated in these deterioration models.

As shown in the DCP-DN Background Paper, the structural capacities for all pavement designs are broadly similar up to about 0.1 MESA, after which the DCP-DN method becomes more conservative. For this reason, it was not considered unreasonable to assume that VOC and maintenance cost would also be broadly similar for all the road sections/trials. Moreover, if these costs were to be slightly higher for the DCP-DN designs, the discounted maintenance and VOC costs would be minimal, especially as the contribution of VOCs to total life-cycle costs on LVRs is small due to the low traffic volumes.

Notwithstanding the above, in order to better quantify the qualitative assumptions made in the CBA analysis, it would be possible to incorporate some evidence-based performance models of the different pavement structures to produce a more rigorous LCC analysis. This could be done by measuring the roughness on a selection of existing LVRs, similar to the ones being evaluated, to get some indication of the generation of roughness since construction for determining differential VOCs. Typical maintenance costs on similar LVRs could also be obtained for inclusion in the LCC analysis.

- **Outcome (1):** Within the context of the Terms of Reference, it was not possible to undertake a traditional LCC analysis. **(2)** The outcome of the CBA analysis was based essentially on a comparison of initial construction costs. **(3)** Consideration to be given to better supporting the key evaluation assumptions made in the CBA analysis by, for example, obtaining roughness measurements and maintenance costs on similar LVRs.

- **Comment:** The inclusion of 3 haulage scenarios, short, medium and long, with some cost scenarios assuming better quality materials would have a greater haulage distance would seem to favour the DCP-DN method which allows for the use of lower “strength” materials in the structural layers that are available at shorter haulage distances than the other designs methods. Given the uncertainty of the location of borrow pits on any particular project, it would be more prudent to assume that the same haulage rates apply for all the design methods.

- **Project team response:** It is a reality that there is an increasing scarcity of good quality gravel for road construction in many countries which is precisely the reason why the move to sealing of LVRs has become a necessity, hence the choice to analyse the three different haulage scenarios which provide a realistic estimate of pavement costs under varying circumstances.

The cost table used for the analyses shows four cost elements:

- a) costs for clearing, excavating and stockpiling in the borrow pit
- b) costs for free haul within 1 km
- c) costs for levelling and compacting the materials in various layer thicknesses, and
- d) costs for hauling beyond the 1 km free haul distance.

The zero-haulage scenario only eliminates cost element d) and does not alter the general trend of the pavement cost differences between the different pavement designs since cost elements a), b) and c) are dominant and haulage costs contribute less to the overall pavement costs at short hauling distances. In the zero-haulage scenario the cost differences therefore remain, in most cases, more or less the same as in the 5 km average haulage scenario for all material qualities, which in our view is a more realistic option than zero-haulage.

- **Outcome:** The zero-haulage scenario to be included in the revised report with a comment on the implications of considering the other haulage distances already considered in the report.

- **Comment:** In relation to the project cost per design method for 0.1 MESA, the same pavement cost is achieved in both dry and wet climates for the DCP-CBR method. The initial suggestion was that the subgrade may have been very weak and the impact of the operating climate could have been insignificant.

- **Outcome:** The authors of the report to check and confirm why this is so.

- **Comment:** Cost evaluations should be related to the pavement only and not to the project which is too complicated.

- **Outcome:** (1) More emphasis to be placed on the comparison of pavement cost differences. (2) Fig. 6 – 11 to be replaced with pavement costs.

- **Comment:** Value-for-Money (VFM) should be discussed in terms of the cost-effectiveness of the DCP-DN method and not in terms of the general benefits of upgrading gravel to paved roads which apply to all methods.

- **Project team response:** In terms of VFM as defined by DFID, the DCP-DN method has been evaluated in terms of:
 - Cost-effectiveness
 - Outcome (uptake) and knowledge
 - Sustainability
 - Uptake
 - Quality of DCP-DN research
 - Knowledge of the DCP-DN method

- Potential impact

As stated in the report, “The use of the DCP-DN method and, indeed, other methods such as ORN31, is expected to provide VFM in terms of:

- Cost-effectiveness
- Outcome (uptake) and knowledge
- Potential impact”.

○ **Outcome:** The report should be revised to indicate that the potential impacts, as currently stated, apply to all the design methods.

- **Comment:** The limitations and risks of the DCP-DN method need to be clearly stated and a table is required that defines the limits of its application.

- **Project team response:** In principle, the limits of application of the DCP-DN method would be very similar to the other methods of design, such as DCP-CBR and ORN31, that commonly require a DCP survey to be undertaken to characterise the future subgrade of an existing unpaved road that is to be upgraded to a paved standard.

○ **Outcome:** The report on the Background to the Development of the DCP-DN report to be revised to include the limits of effective application of the DCP-DN method in various geographic road environments.

- **Comment:** Since ORN31 is no longer used for the design of LVRs, why has it been included as one of the design methods to be evaluated.

- **Project team response:** ORN31 is commonly used for the design of LVRs in many countries in both Africa and Asia and, in fact, is integral to the new Kenya pavement design manual.

○ **Outcome:** ORN31 to be retained as one of the LVR design methods evaluated in the Cost Evaluation report.

- **Miscellaneous comments:**

- The outcomes/agreements of the discussions from the workshop to be included in the final version of the two reports presented.
- The Malawi DCP-DN design manual to be updated on the basis of the outcomes/agreements reached at the workshop and converted to a generic DCP-DN design manual.

4 Summary of Workshop Outcomes

4.1 General

The main outcomes emanating from the discussions held at the workshop may be summarized as follows:

4.1.1 Background paper on Development of DCP-DN method

General outcomes

The general outcomes emanating from the discussion on the Background to the Development of the DCP-DN method may be summarized as follows:

- The science behind the development of the DCP-DN method is well documented and credible but could be refined through additional research.
- The background data referred to in section 3.2 to be made available on request
- The limits of the application of the DCP-DN method need to be stated.
- The report to be revised to include the limits of application of the DCP-DN method.
- The Malawi DCP-DN design manual to be updated on the basis of the outcomes/agreements reached at the workshop and converted to a generic DCP-DN design manual.

Research outcomes

The outcomes of the discussions which offer scope for further research work may be summarized as follows:

- The precision limits of the DCP test for comparison with the CBR test.
- The effect of confinement on the laboratory DN test.
- A review of the DN-CBR relationship including the Standard Error and Coefficient of Variation.
- A better definition of failure as it applies to LVRs.

In addition to the above, the view of many workshop participants is that further research should be carried out to determine structures for LVRs that resist subgrade failure with smaller margins than any of the design methods considered in the Evaluation Report. This is possible because failures used to determine the catalogues stemming from these methods did not depend on recognising subgrade failure, but from failures dependent on other factors. This could lead to even larger savings than indicated in the report. The motivation for undertaking such research is presented in Annex F.

4.1.2 Cost evaluation report

General outcomes

The general outcomes emanating from the discussion on the Cost Evaluation report may be summarized as follows:

- Within the context of the ToR, it was not possible to undertake a traditional CBA based on life-cycle costs of the 10 roads that were designed on the basis of the DCP-DN method.
- The assumption that maintenance and VOCs on the different pavement structures were broadly similar, because they possessed similar structural capacities, was an over-simplification.
- Consideration to be given to better supporting the key evaluation assumptions made in the CBA by obtaining roughness measurements and typical maintenance costs on similar roads to those evaluated in the project.

- The outcome of the CBA analysis was based essentially on a comparison of initial construction costs.
- The zero-haulage scenario to be included in the revised Cost Evaluation report.
- The project cost per design method for the 0.1 MESA traffic loading to be checked.
- The Cost Evaluation report to be revised to indicate that the potential impacts of upgrading unpaved roads to a paved standard based on the DCP-DN method also apply to all the other design methods.
- ORN31 to be retained as one of the LVR design methods evaluated in the report.

4.2 Closing Remarks

4.2.1 Workshop facilitator – Dr. David Hughes

Dr. Hughes' closing remarks may be summarized as follows:

- The variability of the DCP test should be the subject of further research work.
- As a future area of research, the failure criteria for LVRs need to be investigated and redefined.
- The use of the DN value only to select road materials needs to be elaborated upon in the DCP-DN Development report.
- More emphasis should be placed on the differences in pavement cost ratios rather than differences in project cost ratios which may be overly complicated.
- Zero haulage distance should be incorporated in the cost evaluations for comparison with the other short, medium and long haulage distance scenarios considered.
- When discussing Value-for-Money, need to separate the general benefits of road upgrading from those related to the use of the DCP-DN method.
- Need to consider the level of risk when applying the DCP-DN method outside the South African environment.

4.2.2 ReCAP Technical Panel - Dr. Jasper Cook

Dr. Cook's closing remarks may be summarized as follows:

- As the ReCAP Technical Adviser, his responsibility is to advise DFID on technical issues of all ReCAP projects. As such, he must be able to defend the outputs of any project, including those being discussed at the workshop.
- The science behind the development of the DCP-DN method is sound.
- The variability of the DCP test should be the subject of further research work.
- The methodology for undertaking the CBA in terms of the assumptions made is a concern. The cost comparisons were made on the basis of initial construction costs only. Need to make clear the limitations of the CBA analysis
- Zero haulage costs should be considered in the cost comparisons with a sensitivity analysis
- Need to provide VFM aspects as they relate specifically to the DCP-DN method.
- Confidence limits required on the use of the DCP-DN method in terms of:
 - Absolute limits; geotechnical/physical areas where the DCP-DN has proven history
 - Possible limits; similar to the above; the use may be possible but required to be proven
 - No use: geotechnical/physical areas not similar to the above and where DCP-DN unlikely to be of use.

4.2.3 ReCAP Dep. Team Leader - Infrastructure Research Mgr, Mr. Nkululeko Leta

Mr. Leta's closing remarks may be summarised as follows:

- Thanks to all the workshop participants for their constructive contributions to the workshop proceedings.
- Hope that many of the issues surrounding the development and use of the DCP-DN method had been clarified.
- Thanks to the workshop facilitator for his even-handed management of the workshop.
- Thanks to the rapporteurs for their workshop summary.
- Thanks to the project consultants for their presentations at the workshop and responses to the comments made and clarifications sought by the workshop participants.
- Reminded all workshop participants to fill in the workshop evaluation forms.
- Wished all participants a safe journey back to their homes.

4.2.4 Outcome of Workshop Evaluation

The outcome of the workshop evaluation, which was responded to by 12 of the participants, is presented in Table 1 and may be summarised as follows:

- The majority of participants (75%) at least partially agreed that the time available to review the workshop documents was adequate.
- All the participants agreed that the workshop process and methodology were satisfactory.
- All the participants agreed that the workshop objectives were achieved.
- Half of the participants agreed that the workshop had clarified many of their concerns relating to the DCP-DN method of design and the other half did not.
- The majority of participants (58.4%) agreed that many of their concerns relating to the findings of the Cost Evaluation report had been clarified.
- All the participants agreed that the workshop presentations were adequately made.
- All the participants agreed that there was adequate time for presentations and discussions.
- The majority of participants (83.3%) agreed that the project team's responses to the issues raised and clarifications sought were satisfactory.

Table 1 – Outcome of workshop evaluation questionnaire

1. Overall objective and Outcomes

Item	Strongly Agree	Agree	Partially Agree	Disagree	Strongly disagree
1. The time available for reviewing the workshop documents was adequate.	16.7%	25.0%	33.3	25.0	0%
2. The workshop process and methodology were satisfactory.	33.3%	66.2%	0%	0%	0%
3. The objectives of the workshop were generally achieved.	50.0%	50.0%	0%	0%	0%
4. The workshop has clarified many of my concerns relating to the DCP-DN method of pavement design.	33.3%	16.7%	41.7%	8.3%	0%
5. The workshop has clarified many of my concerns relating to the findings of the report on the Evaluation of Cost-Effectiveness and Value-For-Money of the DCP-DN Method for Low Volume Roads in Comparison with Conventional Designs.	16.7%	41.7%	25.0%	16.7%	0%

2. Presentations

Item	Strongly Agree	Agree	Partially Agree	Disagree	Strongly disagree
1. The workshop presentations were adequately made.	75.0%	25.0%	0%	0%	0%
2. There was adequate time for presentations and discussion.	75.0%	25.0%	0%	0%	0%
3. The Project Team’s responses to the issues raised, and clarifications sought, by workshop participants were satisfactory.	33.3%	50.0%	8.3%	8.3%	0%

3. Other Comments

Please list any further comments that you wish to bring to make on the workshop.

1. The workshop was well chaired.
- 2
- 3

References

- Done S, Cook J, Meksavanh B and S Manodham (2009). **Low Volume Rural Road Environmentally Optimised Design Manual**. SEACAP 03.02 project, TRL Ltd in association with Lao Transport Engineering Consultant (LTEC) and OtB Engineering (International Ltd).
- Hongve J and Pinard M I (2015). **Guideline for Quality Control on Low Volume Roads Using the Dynamic Cone Penetrometer**. ReCAP Project MAL2007B.
- Livneh M and Livneh N (2013). **The use of the Dynamic Cone Penetrometer for Quality Control of Compaction Operations**. International Journal of Engineering Research in Africa Vol. 10 (2013) pp 49-64.
- Rallings R. 2014. **CBR Test- A Case for Change?** Australian Geomechanics Vol49, No.1 2014.
- Root J, Mukura K, Dangare F and A Otto (2013). **Back Analysis of Previous Low Volume Roads in Mozambique**. AFCAP project MOZ/001/G, TRL Report No. 2585.
- Roy, B K (2007). **New look at the DCP Test with a Link to the AASHTO SN Concept**. Journal of Transportation Engineering, April 2007.
- Sampson L R. 1984. **Investigation of the correlation between CBR and DCP**. Pretoria: National Institute for Transport and Road Research, CSIR. (Technical Note TS/33/84).
- Siekmeier J A, Pinta C, Merth S, Jemsen J, Davich P, Camargo F and M Beyer. **Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance**, Minnesota Department of Transportation, Minnesota 55109, U.S.A, 2009-12.
- Van Zyl G and R Burger (2009). **A Review of Experience on 2600 Km of Low Volume Surfaced Roads in South Africa**. Association of Southern African National Roads Agencies (ASANRA) Conference, Maputo, Mozambique.

Annex A – Workshop Programme

Venue: Conference Room, Hilton Hotel, Durban, South Africa

Date: Friday 12th October, 2018

Item	Time	Topic	Lead person
1	8:30 (10 mins)	Introductions and purpose of the meeting	ReCAP/Chair
2	8:40 (20 mins)	Presentation of programme and <i>rules of engagement</i>	Facilitator
3	9.00 (40 mins)	Presentation of background paper on development of the DCP-DN method, including underlying research.	P Paige-Green/Gerrie van Zyl
4	9.40 (20 mins)	Questions, clarifications	ALL
5	10.00 (30 mins)	Presentation of reviewed final draft of the study report: (a) Approach and methodology*	Project Team (M Pinard)
6	10.30 (20 mins)	Questions, clarifications	ALL
	11:00 (30 mins)	Tea/Coffee	
7	11:30 (30 mins)	Discuss Presentation of reviewed final draft of the study report (cont'd): (b) Pavement designs: alternative methods*	Project Team (J Hongve and E Mukandila)
8	12:00 (20 mins)	Questions, clarifications	ALL
	13:00 (60 mins)	Lunch	
9	14:00 (30 mins)	Presentation of reviewed final draft of the study report (cont'd): (c) Cost comparisons*	Project Team (G van Zyl)
10	14.30 (20 mins)	Questions, clarifications	ALL
11	15:00 (30 mins)	Key issues emanating from the discussions on draft evaluation report DCP-DN method	Facilitator/Rappoteurs
12	15:30 (30 mins)	Key recommendations for: i) issues to be addressed and aspects to be incorporated into the final study report; ii) further research to enhance DCP-DN pavement design method as a viable and cost-effective option for design of LVR.	ALL
	16:30	Tea/Coffee	
12	17.00	Wrap-up and final remarks	ReCAP

Annex B – Workshop Attendance List

Name	Organisation	Country of residence
1. Dave Runganaikaloo	Cardno Emerging Markets	United Kingdom
2. Gerrie Van Zyl	MyCube (Project Consultant)	South Africa
3. Morris De Beer	CSIR	South Africa
4. Edouard Kleyn	Retired (DCP-DN method developer)	South Africa
5. Michael Burrow	University of Birmingham	United Kingdom
6. David Hughes	Queens University Belfast	United Kingdom
7. Mark Henry Rubarenzya	UNRA	Uganda
8. John Rolt	Independent Consultant	United Kingdom
9. Annabel Bradbury	ReCAP PMU	United Kingdom
10. Nkululeko Leta	ReCAP PMU	South Africa
11. Jasper Cook	ReCAP Technical Panel	United Kingdom
12. Tony Greening	ReCAP Technical Panel	United Kingdom
13. Phil Paige Green	Paige-Green Consult (Project Team)	South Africa
14. Michael Pinard	InfraAfrica Consultants (Project Team)	Botswana
15. Jon Hongve	Independent Consultant (Project Team)	Norway
16. Estimé Mukandila	IX Engineers (Project Team)	South Africa
17. Les Sampson	Independent Consultant	South Africa
18. Leah Musenero	Rapporteur	Uganda
19. Joseph Chibwe	Rapporteur	Zambia
20. Patrick Bekoe	Rapporteur	Ghana
21. Edison Madeira	Cardno Emerging Markets	United Kingdom
22. Liam Bloundele	Cardno Emerging Markets	United Kingdom

Annex C – Facilitator’s Workshop Review Report

**Chair’s review of Workshop held on 12th October 2018 on:
‘Evaluation of cost-effectiveness and value-for-money of DCP-DN pavement design
method for low-volume roads in comparison with conventional designs’
Research for Community Access Partnership (ReCAP)**

**Submitted by: Dr David Hughes FIHT MIEI MICE CEng
14th October 2018**

1. Introduction

I chaired a workshop, held in Durban on the 12th October 2018, to review the draft Report ‘Evaluation of cost-effectiveness and value-for-money of DCP-DN pavement design method for low-volume roads in comparison with conventional designs’, (Project Reference: RAF2128A) for Cardno Emerging Markets (UK) Ltd. The attendees are listed in Appendix 1 of this Report. The authors of the Report presented their findings and detailed discussions were held with those present on the DCP-DN design approach and technical details in the above Report. The following paragraphs summarises my understanding of the modifications and caveats that were discussed and agreed at this meeting and that were recommended to be incorporated into this Report and into the DCP-DN design documentation. Three rapporteurs also made notes during the meeting, and a review of their understanding of the way forward was presented, discussed and agreed at the conclusion of the meeting.

2. Variability of both CBR and DCP data

The authors presented data on the variability of CBR data and on various correlations between DCP penetration rates and CBR values. Data was presented that showed the poor repeatability of the CBR test and the high variability that can occur. The authors believe that the DCP test method has better repeatability (and therefore reliability) than the CBR test method, particularly in the laboratory, and are using a non-standard DCP laboratory test method to assess the ‘strength’ of soils rather than the CBR test. The advantages of this DCP test method were outlined but it was agreed there was limited published peer reviewed data on the variability and repeatability of DCP strength testing, both insitu and in the laboratory. While detailed further data on the repeatability of DCP testing is outside the immediate scope of the ToR, the authors agreed to take cognisance of the fact that there may be issues around the repeatability of DCP data in the design approach, despite the likelihood that many more DCP data points and tests are likely to be available to the Engineer than CBR values.

3. The definition of road failure in LVRs

There was discussion around the definition of ‘failure’ in LVRs. This appears to have been defined as a 20mm rut depth in many cases (particularly in the derivation of the DCP v CBR relationships and the production of the structural design catalogue for pavements in South Africa), but has also variously been defined by visual assessment of cracking, fretting and pothole frequency. It was agreed that rutting and cracking etc are symptoms of a road reaching a failed state but are not the cause of failure, which may be due to poor drainage or degradation of one or more layers in the pavement structure, amongst other things. There should be a recognition that, for LVRs, low pavement strength (or low Structural Number) does not necessarily lead to failure of the pavement and environment alone can be a major factor in deterioration, particularly at low traffic volumes (<1 MESA). The general opinion

was that the definition of failure in LVRs is currently poorly defined and should probably be related more to serviceability than to any assessment of the strength or thickness of the pavement layers. This is an area for further research, beyond the scope of the current DCP-DN Design Guide, although there may be an opportunity to raise the issue in the revised version of the Design Guide.

4. Clarification of the importance of characterising the material properties of pavement materials.

The authors of the Design Guide agreed that the current version of the document does not highlight the importance of ensuring that the materials used in the pavement are of a suitable quality and durability, and that they should be tested and examined using traditional test methods. The impression mistakenly given in the current version is that pavement materials can be approved for use solely using DCP data. The authors agreed that this was not their intention and that the Guide would be revised to reflect the necessity of initial testing of materials for suitability of inclusion in the pavement before DCP data can further be used to rapidly assess the 'strength' of approved material.

5. Cost Benefit Analysis (CBA) and road deterioration models

The panel was of the view that the current methodology of comparing the cost saving of roads designed using the DCP-DN and other design approaches was misleading in that an assumption has been made by the authors that roads designed using different methods, giving different pavement structures, would all deteriorate at the same rate and have the same maintenance regimes. There is currently insufficient evidence to suggest this, and it was suggested that the authors should either simply compare construction costs of the pavements only, using the different design methods, making it clear no CBA was carried out, or incorporate some evidence-based deterioration models of the different pavement structures into a more rigorous CBA. It was recognised that there is little data currently available on deterioration of roads designed using the DCP-DN method so at this stage it may be more prudent to simply compare pavement construction costs and not to carry out a full cost benefit analysis.

6. Pavement costs, haulage rates and project costs

The authors had carried out an exhaustive analysis of pavement construction costs, with some cost scenarios assuming that better quality materials would have a greater haulage distance.

(The DCP-DN design method often allows for the use of lower 'strength' materials in the structural layers than other designs, particularly at low traffic levels.) Whilst the panel felt this might be the case in some or even most projects it is not always the case. Given the uncertainty of the location of borrow pits on any particular project it was felt it was more prudent to compare pavement costs using the same haulage distances with perhaps a note to the effect that in many cases a further cost saving could be accrued as it was likely that haulage distances would be greater if better quality materials needed to be specified in the pavement structure.

The report states that these are included to show the relative differences between projects depending on pavement design method and that this is primarily what potential clients will be interested in. The authors do therefore not agree that this is irrelevant.

7. The comparison of ORN 31 and DCP-DN pavement design methods.

There was some discussion around the current use of ORN 31 in the design of LVRs in Southern Africa. It was generally accepted that at lower traffic volumes (around 0.7MESA) the DCP-DN method generally recommends a lighter (more cost effective) pavement than ORN 31, and at traffic loading around 0.7MESA and above this tendency is reversed with the DCP-DN design outputting a heavier (less cost effective) design.

8. Off alignment design

There should be more clarity in the DCP-DN design method around the assessment of subgrade conditions where the pavement is to be constructed off the existing alignment or in cut or fill situations where the DCP cannot be used to assess the existing pavement structure or subgrade.

9. Conclusions

The DCP-DN design approach is empirical in nature and the findings are currently based on measurements and observations on limited soil types, in limited environmental conditions and in only the Southern African geographical region. Consequently, it was felt that the authors should be cautious about extrapolating or extending the method to other soil types and across different environmental conditions and geographical regions without further verification and performance monitoring.

Furthermore, whilst the particular advantages of using the DCP to assess pavement materials in this simplified empirical design approach for LVRs was recognised (where there is limited or no access to sophisticated modern laboratory and field testing equipment) we should recognise that the DCP does not measure any fundamental properties of pavement materials. It cannot assess mineralogy or soil type or the likely durability properties of pavement materials. Also, the design approach does not take any cognisance of current thinking on mechanistic design of pavements or measurable fundamental physical properties of pavement materials such as stiffness (resilient modulus) or strength, effective insitu stresses or partially saturated soil properties.

Dr David Hughes
14th October 2018

Annex D – Rapporteurs Record of Workshop Discussions

S/N	Item/Issue	Discussion	Way Forward	Future Research
1.	Shift from CBR to DCP based design	DCP is a useful tool and its use is not questionable. Limitations of CBR against DCP are well understood	Agreed	
2.	DCP Variability	Variability of CBR method is well documented and understood. Further understanding of the DCP Laboratory Test Method required.	Need to look into the variability of DCP, including precision limits, reproducibility, etc. Need to confirm whether DCP has better precision limits.	Variability, precision limits & reproducibility of DCP Laboratory Test Method
3.	Correlation	Log-log relationship for DCP-CBR	Need to have a second look at the available original data	
4.	Failure Criteria	The 20 mm rut depth criterion adopted appears to be too conservative for defining failure of LVRs.	Need to further look at failure criteria for LVRs vis-à-vis structural & functional	Research aimed at defining the appropriate failure criteria for LVRs
5.	Laboratory DCP test	Effect of confinement in laboratory DCP tests		Research required to establish the effect of confinement on Lab DCP Tests.
6.	Materials selection using the DCP-DN method	Due to large variability in materials, materials selection should not be limited to DN measurement. Compaction to refusal needs to be qualified with the fact that it should only be done if there is no materials degradation	DN should not be the only criterion used for selecting materials. Report to be revised to indicate the other tests undertaken for the purpose of understanding material characteristics.	
7.	Assumption that for a given traffic loading &	The assumption that the DCP-CBR and	More supporting information to be	Validation of assumption through

S/N	Item/Issue	Discussion	Way Forward	Future Research
	road environment, pavements with similar capacity & surfacing would deteriorate in a broadly similar manner	DCP-DN methods performance is similar over the lifetime of the pavement is overly simplified. The assumption was in itself a risk	incorporated in the report as presented in the workshop	LTPP monitoring, starting with on-going projects
8.	Naming of project (CBA or cost comparison?)	Report compares construction costs and not life cycle cost. This is not a cost benefit analysis	Argument for the assumption that the construction costs are representative enough to be strengthened in line with action in item 7 above.	
9.	Haulage costs	The inclusion of haulage costs favours the design methods that emphasise the use of in-situ material	Conclusion on the cost comparison to be revised to focus on no-haul scenario and thereafter discuss the implications of long-haul distances.	
10.	Cost benefit of DCP-CBR	For 0.1 MISA, same pavement cost is achieved in both dry & wet climate for the DCP-CBR method. This is quite abstract. Initial suggestion was that the subgrade may have been very weak and the impact of the operating climate could have been insignificant.	Authors of report to check and confirm why that is so.	
11.	Value for Money (VFM)	VFM should be discussed in line with only the DCP-DN	Authors to revise the report accordingly	
12.	Limitations/Risks	Limitations and risks of the DCP-DN need to be clearly documented. Definition of	Authors to consider specifying the circumstances under which the DCP DN	

S/N	Item/Issue	Discussion	Way Forward	Future Research
		Envelope limits of application of the DCP-DN method	method should be applied	
13.	ORN31		Appropriate circumstance for the use of ORN31 to be indicated	Redefinition of traffic classes

Other comments:

- Additional background information presented in the workshop on the DCP DN Method to be incorporated into the report.
- Update of the current Malawi DCP-DN design manual and convert to a generic manual – ReCAP required

Annex E – Frequently Asked Questions on the DCP-DN Method of Design

FAQ 1: What are the main advantages and disadvantages of the DCP method of design?

Answer:

Main advantages (DCP in General):

- Involves the use of relatively low cost, robust apparatus that is quick and simple to use (approx. 30 minutes per test). This allows many measurements to be made on existing unpaved (subgrade) or paved roads to provide a comprehensive characterization of the road conditions (strengths and layer thickness at prevailing moisture and density conditions. This information provides a strong statistical basis for design, minimizing the risks of under- or over-design inherent in any method that does not provide sufficient information for a proper statistical analysis (applies to all methods using the DCP for characterising the subgrade).
- Provides improved precision limits compared to the CBR test (Smith and Pratt, 1983). The strength (DN) values obtained in the field or the laboratory are inherently more accurate because the DCP provides a virtually continuous strength profile throughout the layer being tested (+/- 150 mm) whereas a CBR test is naturally biased towards the ends of the test mould at a penetration depth of 2.5 or 5.0 mm. Moreover, it has been shown that with reasonable care taken to control testing errors, DCP data can be treated as representative of in-situ materials characteristics (Roy, 2007) (applies to the DCP-DN method only).
- Involves testing actual subgrade strength using the DCP at multiple points along the road at the time of the year when subgrades are weakest as well as under multiple seasonal scenarios in contrast to CBR-testing which is relatively costly and time consuming to carry out, requiring large samples for laboratory testing. Moreover, the entire subgrade to a depth of 800 mm is assessed in-situ in 150 mm layers as opposed to the traditional testing of a composite, generally disturbed sample extracted from a specified depth (seldom 800 mm) within the subgrade (applies to all methods using the DCP for characterising the subgrade).

Main advantages (DCP -DN):

- Avoids the need to convert the DCP-DN values to equivalent CBR values at any stage of the design process which would incur errors due to the relatively poor correlation between DCP and CBR measurements (material specific correlation coefficients ranging from 0.67 – 0.79 (Sampson, 1984) (applies to DCP-DN method only).
- Provides a standalone means of improving the quality control of compacted materials from density-based methods, which tend to be slow, potentially hazardous (nuclear gauges) and of uncertain accuracy, particularly where there is a variation in site materials along any tested section (Livneh and Livneh, 2013; Hongve and Pinard, 2016) to stiffness/strength-based methods which allow direct comparison to be made between design and achieved strengths on site (Siekmeier et al, 2009).
- Offers a more holistic approach to the provision of LVRs in that the DCP test can be used for field investigations, pavement design, laboratory testing and compaction quality and layer thickness control (applies to the DCP-DN method only).

Disadvantages

- 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 resulting in incorrect readings. Therefore, some DCP tests may need to be abandoned or repeated (applies to all methods using the DCP for characterising the subgrade).
- 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 (applies to all methods using the DCP for characterising the subgrade).

- 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. However, the DCP test is less operator susceptible than many other tests thus reducing the risk of measurement error (applies to all methods using the DCP for characterising the subgrade).

FAQ 2: What are the limitations of the use of the DCP-DN method?

Answer:

The DCP-DN method is based on testing of a wide variety of materials (igneous, sedimentary and metamorphic rocks as well as pedogenic and transported soils) under a range of traffic and loading conditions and in a variety of climatic and drainage environments in South Africa. The method caters for soaked or unsoaked conditions in environments subjected to high rainfalls or periodic flooding. Such environmental conditions are found in almost all tropical and sub-tropical regions of the world. Thus, the DCP-DN method, just like other design methods, such as the DCP-CBR and ORN31 design methods, if appropriately applied, in line with the stipulated design procedure, could be applicable to most design situations found in practice in tropical and sub-tropical regions of the world following initial assessment.

It should be noted, however, that the method cannot be used directly if the proposed road is in deep cut or on a high fill, where the final formation level (selected subgrade or capping layer) is either below or above the currently exposed soil surface. In such cases, the cutting or embankment must be constructed to the formation height before testing of the support for the pavement design. However, in the case of elevated roads, the material to be used for the embankment can be tested using the DCP in the laboratory to understand its properties at varying densities and moisture contents: this material will provide the formation level on which the capping layer would be placed and tested with the DCP as part of the pavement design process.

FAQ 3: Is it not inappropriate to use the DCP-DN method of design in low-lying, deltaic areas with high water tables and monsoon-type rains.

Answer:

1. The challenge of constructing an embankment (if it doesn't already exist) on soils having low undrained shear strength and high compressibility (e.g. the Gangetic Plains in India or the low-lying deltaic areas of Myanmar) is **geotechnical** in nature and has nothing to do with the DCP in terms of assessing the subgrade strength of the road to be upgraded to a paved standard pavement as an input to its design.

2. Having constructed a stable embankment that will hopefully not settle, a capping layer would then be placed over the embankment, possibly in conjunction with the use of geogrids or capillary cut-off layers at the interface of the embankment with the capping layer. Only thereafter would the **DCP** be used to undertake a DCP survey to say 500 mm below the top of the capping layer to obtain information for the design of the road pavement.

3. Issues such as high-intensity or monsoon type rains are **climate adaptation** challenges which require attention to be paid to such issues as:

- Cut and fill slope protection using appropriate bio-engineering measures
- Shoulder sealing to the edge of front slope of the drain.
- Adequate drainage capacity
- Use of equalizing culverts in low lying areas

- Scour protection in side and mitre drains
- Culvert and bridge abutment protection
- River/stream erosion protection
- Etc, etc.

None of the above measures have anything to do with the use of the DCP *per se* but, rather, with good engineering practice

FAQ 4: *Since the DCP-DN catalogue was developed on the basis of soil types and environmental conditions prevailing in South Africa, can it be used in other geographical and environmental regions of the world, for example, where LVRs may be susceptible to periodic flooding or overtopping, without further verification and performance testing.*

Answer:

The wide range of soil types found in South Africa are similar to those found in many other tropical and sub-tropical regions of the world. For example, the typical soil types found in Laos (and elsewhere in South East Asia), are as follows (Done et al, 2009):

- Type 1 - Hard Rock: Igneous (granite, basalt); sedimentary (crystalline limestone); metamorphic (schist).
- Type II - Weak rock: Shale, mudstone, non-crystalline limestone, weathered Type 1 rock.
- Type III - Hill gravels (colluvium) derived from a combination of hard rock weathering and down-slope accumulation.
- Type IV - Laterite gravel.
- Type V - Residual soil (laterite soil)
- Type VI - Alluvial soils.

Since the above material types are all found in South Africa, there should be little, if any, risk in using the DCP-DN method or, indeed, other design methods such as the DCP-CBR or ORN31 methods, in other tropical and sub-tropical regions of the world to determine the DN/CBR values that are used as a proxy for the shear strength of a soil. By way of a very simplistic explanation, the DCP device does not “see” what type of material is being tested. Rather, it just “feels” the material’s resistance to penetration by the DCP or CBR plunger as influenced by its basic properties of plasticity and grading at a particular moisture and density. However, neither the DCP-DN nor CBR tests can detect potential durability problems that need to be separately determined via appropriate durability testing.

As regards roads that may be susceptible to periodic flooding or overtopping, it should be noted that the materials to be used in the pavement structure would need to be tested in the soaked condition, but the required penetration rates remain unchanged. In other words, a much higher quality material will be necessary to provide the same strength (equivalent to the soaked CBR that would conventionally be used in such a situation).

FAQ 5: **Why did the design method change from using the percentiles of DN for moisture assessment in the field to the laboratory assessment at various densities and moisture contents?**

Answer: The percentile method worked well on numerous roads for many years but when testing highly moisture sensitive silty sand subgrades more recently, it was found that the strength changes were significantly higher than anticipated. By carrying out the simple, laboratory investigation, assumptions as to the strength/moisture content relationship were eliminated and the output allows a much better interpretation and understanding of the fundamental material properties, including such issues as the grading, compactability, moisture sensitivity (related to plasticity) etc.

FAQ 6: What impact does the confinement of a material within a CBR mould in the laboratory DN test have on the road design and testing after construction?

Answer: Although confinement within a CBR mould has been indicated as having an effect on the laboratory versus field DN value, the DCP-DN design method is based on laboratory testing of field samples (from the roads investigated or from borrow pits with potential pavement quality materials), i.e. laboratory vs laboratory DN values and not laboratory vs field DN values. Thus, the confinement of a material within a CBR mould has no impact on the validity of the DN values used for design purposes.

In terms of testing materials after construction for quality control purposes, it is clearly stated that the acceptance value must be determined during compaction trials carried out in the field on the accepted materials at the specified OMC and compaction level. This then is used for quality control purposes.

Annex F – Motivation for further research on low volume roads (additional contribution by Workshop Report reviewer, Dr. John. Rolt.

In the original research on the DCP-DN design method, the terminal condition of a road was defined as a rut depth of 20mm at which structural failure was assumed to be occurring. In other words, the protection of the subgrade by the pavement layers for the particular traffic level was inadequate. This was a reasonable assumption, but recent research is showing that subgrade failure is rather rare in LVRs and that this assumption is conservative. This is not surprising because research data of the type recorded in the original studies by J Burrow and E Kleyn always show wide variations.

Ideally, roads need to be monitored until a structural failure *resulting from inadequate protection for the subgrade actually occurs*. If the roads deteriorate and reach a terminal serviceability level for some other reason, then all that can be said about the structural design is that it was adequate and nothing about how much thicker or stronger the pavement needs to be for a different traffic level. In other words, the relationship between DN₈₀₀ and traffic carrying capacity cannot be deduced very precisely.

However, some additional testing was carried out using the Heavy Vehicle Simulator. Although heavy vehicle simulator testing does not allow time for environmental effects to have an effect, it can help to identify structural limits. More complete details of these data should also have also been included in the workshop or in the pre-workshop papers or as an appendix to this report.