Developments in Low Volume Roads Technology: Challenging Conventional Paradigms

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***Abstract*—Low volume roads are an essential and integral component of the road system in all, particularly developing, countries where their importance extends to all aspects of the economic and social development of rural communities. Most of the current investment in new road projects involves upgrading these unsealed rural roads to a sealed standard. However, the design of this type of road is a challenging task in that:**

- **Pavements may be constructed using non-standard materials which may, nevertheless, be "fit for purpose";**
- **Geometric design standards may need to be "relaxed" in appropriate circumstances without undue increase in risk to road users;**
- **The deterioration of these roads is primarily driven by environmental factors wit traffic load being a lesser factor;**
- **Environmental issues often result in increased costs;**
- **Conventional economic analysis often cannot justify the investment of public funds in the construction and maintenance of these roads.**

The above characteristics challenge conventional engineering in a variety of ways which require a delicate balance to be struck between controlling both traffic and environmental deterioration at the least life cycle cost and with finely balanced risk factors whose complete removal would be too costly. In so doing, it has become necessary to adopt an "environmentally optimized" approach to design in which a variety of road environment factors must be addressed in an appropriate manner.

This paper provides examples of relatively recent developments in low volume roads technology that allow such roads to be provided in a more affordable and sustainable manner than hitherto, and without incurring unmanageable risk for road users or the agencies that provide them.

The paper concludes that a paradigm shift in thinking is required to move away from the conservative, and often inappropriate, approaches of the past to more progressive approaches informed by research-based evidence.

Keywords*—*Low volume, research, environmentally optimized, DCP, materials, specifications.

I. INTRODUCTION

A. Background

The sustainable provision of road infrastructure to rural communities in Africa is essential for their livelihoods and may be viewed as a universal human right in terms of facilitating poverty reduction, food security, access to markets, healthcare, education and social and economic opportunities of every kind. In most of these countries, almost the entire rural road network is unsurfaced and the cost of maintaining it to provide all year passability has generally proved to be insurmountable. The resulting poor road conditions have impacted adversely on the welfare of rural communities by reducing their growth opportunities and negating the benefits in other sectors designed to improve their livelihoods. Significant excess vehicle operating costs, which many rural communities can ill afford, are also a major consequence of such poor roads.

The effects of global climate change with increased precipitation and temperatures are likely to accelerate the deterioration of the road network in the years to come. The unsurfaced rural road network is particularly vulnerable to increased rainfall, which is forecast to affect large parts of the Sub Saharan region [1]. A proactive approach by the road authorities will be required to limit the adverse effects of climate change, but even then, substantial additional funding will be required to improve and maintain the rural road network to ensure all year passability to rural areas. More rural roads will need to be surfaced and it is thus imperative that upgrading of earth and gravel roads is done in the most cost effective manner

Whilst there are potentially significant life-cycle benefits to be achieved from upgrading unsurfaced rural roads to a paved standard, the cost of doing so following traditional standards and specifications is prohibitive. This is because these approaches tend to be overly conservative and ill-matched to the dictates of the local road environment. As a result, they are generally far too costly for application to most rural road networks in Africa.

Fortunately, there is a wealth of invaluable research and investigation that has been carried out into the performance of low volume roads (LVRs) in the African region in the past 25 years. Examples include: [2,3, 4,5]. This has not only identified many anomalies in our previous understanding of the mechanisms of performance of such roads, but has also questioned many of the accepted paradigms associated with their design. These findings have prompted a need to re-think many aspects of the provision of LVRs in the African region.

There is also a history of successful performance of relatively lightly trafficked roads in a number of African countries that have been constructed to less costly standards than dictated by many current design manuals [6,7,8,9]. However, despite their good performance, there is still a widespread concern that these LVRs are sub-standard and present a high risk undertaking. Part of the reason for these concerns is because there has been inadequate dissemination of the outcome of the research work undertaken in the region that has led to the development of performance-based standards and technical specifications that reflect successful, historical experience. These developments are increasingly being utilized in the region, and are gradually changing traditional practices and thinking through the development of new manuals and guidelines on LVRs [10,11, 12]. By so doing, they are leading to the adoption of more cost-effective interventions that can deliver an appropriate level of service necessary to promote and sustain the development of rural communities.

Even with the significant research findings referred to above, the cost of upgrading an earth or gravel road to paved standard is still quite high and upgrading large parts of the rural road network is beyond the financial capacity of most SSA countries. Research into alternative methods must therefore continue and at the same time increased efforts must be made to disseminate the research findings to the political leadership in order to foster the necessary policy adaptations.

In large parts of the SSA region, traditional gravel resources are rapidly dwindling or have already been depleted. An increasing share of the upgrading costs is therefore going towards haulage of gravel for the pavement layer(s) over long distances. An interesting area of research would therefore be to make better use of the in situ subgrades for the road pavement without importation of gravel for the base layer. This has the potential to drastically reduce the upgrading costs and enable road authorities to expand the paved rural road network at a much faster pace than hitherto.

B. Purpose and Scope

The main purpose of this paper is to highlight the significant developments that have taken place in LVR technology in the past 25 years that have led to the more cost-effective provision of paved LVRs than hitherto. The paper draws on the outputs of a number of important research and investigation projects that have been carried out in the region since the 1990s. The corroborative findings of these projects provide a wealth of performance-based information that has advanced previous knowledge on various aspects of LVR technology. This has allowed state-of-the-art guidance to be provided in this paper on a number of key aspects of LVR provision which, when collectively and correctly applied, provide the potential to significantly reduce the cost of such roads.

II. CHARACTERISTICS OF LOW VOLUME ROADS

A. Definition

A common understanding of the definition of a LVR is crucially important as it will dictate the approach to undertaking the design of such roads in relation to their characteristics and the related criteria to be used in providing them at an appropriate level of service and minimum life cycle cost.

There is no internationally accepted definition of a LVR. In developed countries such as the USA, roads carrying about 400 vehicles per day (vpd) are defined as very low volume roads. In the African region, the figure that is currently, typically, used is about 300 vpd PLUS a design traffic loading not exceeding about 1 million equivalent standard axles (MESA). However, neither of these definitions provides a complete picture of the unique characteristics of a LVR in that there are a number of other characteristics that need to be considered in their design as discussed below.

B. Defining Characteristics

There following specific characteristics of LVRs affect the manner of their provision and need to be fully appreciated in that:

- They are constructed mostly from naturally-occurring, often "non-standard", moisture-sensitive materials.
- Pavement deterioration is driven primarily by environmental factors, particularly moisture, with traffic loading being a relatively lesser influential factor, and drainage being of paramount importance.
- The alignment may not necessarily be fully "engineered", especially at very low traffic levels, with most sections following the existing alignment.
- A need to cater for a significant amount of non-motorized traffic, especially in urban/peri-urban areas, coupled with a focus on the adoption of a range of low-cost road safety measures.
- Variable travelling speeds that will seldom exceed about 80 km/h, as dictated by local topography.
- An appreciation that conventional economic analysis often cannot justify the investment of public funds in the provision of such roads in which it can be relatively difficult to quantify the many benefits of a broad socio-economic and environmental nature.
- Environmental and sustainability inputs as important components of economic analyses and whole life-cycle costing.

Based on the above typical characteristics of LVRs, it should be readily apparent that certain types of roads that fulfil just some of the above attributes will not fall under the heading of LVRs as defined above. For example:

- A trunk road carrying less than 300 vpd and less than 1 million MESA over its design life would not necessarily be classified a LVR, as the level of serviceability that it would be expected to provide would be dictated by its function which would be characterized by a relatively high design speed and matching geometrics, low risk of failure, etc.
- A haul road serving, for example, an industrial, mining, agricultural or quarry area, in which heavy loads are transported for a few months of the year during the rainy season even though the design traffic loading may be less than 1 MESA.

A holistic appreciation of the attributes that characterize LVRs will guide designers in producing more appropriate designs with an emphasis on using a fit-for-purpose, context sensitive, environmentally optimized approach to their design and construction. This will place an onus on the design engineer to provide a road that meets the expected level of service at least life-cycle cost based on a full understanding of the local environment and its demands, and to turn these to a design advantage.

The unique characteristics of LVRs as described above challenge conventional engineering practice in a number of aspects, including materials and pavement design, geometric design, drainage, road safety and maintenance, for which particular attention should be paid in the development of new guidelines and manuals.

III. DESIGN PHILOSOPHY

A. General Approach

The general approach to the design of a LVR will be guided by the client and will build on information and data collected during the project pre-feasibility and feasibility stages. The client will have a budget in mind for the works, the location and route will be known in outline, and the preferred approach to the works will also be known, for example labour or equipment based. The client may also have views and guidance on apportioning works and contract size, technical issues, social, environmental and time constraints. The job of the road design engineer will then be to develop the project within and around these boundaries and limitations, whilst at the same time alerting the client to issues and problems that may limit or require adjustment of expectations.

The approach to the design of LVRs follows the general principles of any good road design practice. There are, however, important differences from the traditional road design practice which the designer must be fully cognizant of if he is to provide the client with an optimised design based on the financial, technical and other constraints that define the project.

Optimising a LVR design requires a multi-dimensional understanding of all of the project elements and in this respect all design elements become context specific. The designer therefore needs to be able to work outside their normal areas of his expertise and to understand implications of his recommendations or decisions on all other elements of the design. Thus, the successful design of LVR will rely on:

- A full understanding by the design engineer of the local environment (natural and social).
- An ability to work within the demands of the local environment and to turn these to a design advantage.
- Recognition and management of risk.
- Innovative and flexible thinking through the application of appropriate engineering solutions rather than following traditional thinking related to road design.
- A client who is open and responsive to innovation.
- Assured routine and periodic maintenance.

There is an onus on the design engineer to provide a road that meets the expected level of service. Many design engineers tend to be conservative and to build in factors of safety that cater for their perceptions of risk and extremes of caution. This approach prevents the application of innovation, uses scarce or inappropriate resources and results in high financial costs for the client and the country. There is also often a temptation to provide or upgrade roads to a future level of service not justified by the economic or other project projections; or road user requirements. This type of approach absorbs available resources and prevents extension of access. It is the role of the design engineer to properly represent the clients and country’s interests.

The level of attention and engineering judgement required for optimal provision of LVRs is no different and in most cases is higher than that required for the provision of other roads. The design engineer needs to draw on all of his engineering skills, judgement and local experience if appropriate designs are to be developed without incurring unacceptable levels of risk. The design of LVR is, in fact, a specialised Civil Engineering discipline and, with the current demand for upgrading of LVRs in Africa, offers good career opportunities for young African Civil Engineers. However, the training at universities does not currently include appropriate LVR curricula. Extensive post-graduate capacity building is therefore required.

B. Road Environment Factors

The term “road environment” is an all-encompassing one that includes both the natural or bio-physical environment and the human environment. It includes the interaction between the different environmental factors and the road structure. Some of these factors are uncontrollable, such as those attributable to the natural environment, including the interacting influence of climate (e.g. wind, rainfall and intensity), local soils, geology and hydrology, and drainage, terrain and gradient. Collectively, these will influence the performance of the road and the design approach needs to recognise such influence by providing options that minimise the negative effects. Others factors, such as the construction and maintenance regime; safety and environmental demands; and the extent and type of traffic are largely controllable and can be more readily built into the design approach.

Typical road environment factors are presented in Figure 1 and must all be carefully considered by the design engineer at the design stage of the project.

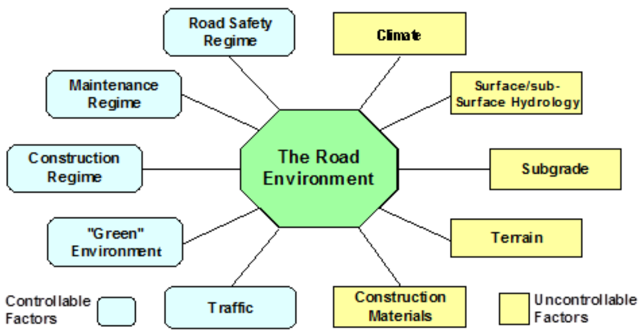

Figure 1 – Road environment factors

C. Environmentally Optimized Design

In order to obtain optimal results from investments in road infrastructure in any country, it is important to adopt an approach that is guided by appropriate local standards and conditions, in order to achieve a sustainable outcome. In this regard, international and regional research has highlighted the benefits of applying the principles of Environmentally Optimised Design (EOD) to the design and construction of low volume rural roads [13]. The various factors that influence the implementation of LVSR technology and that need to be considered in the context of EOD are illustrated in Figure 2.

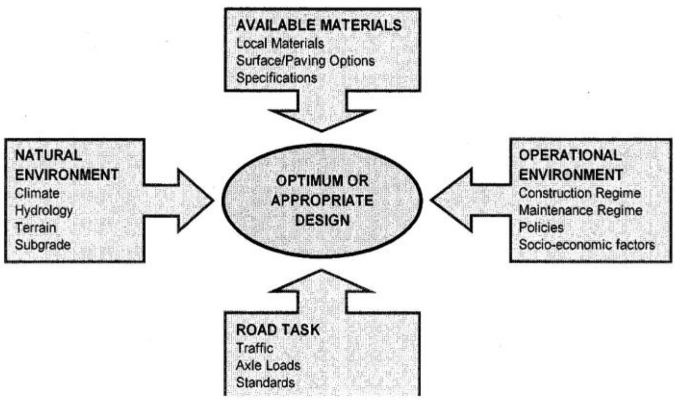

Fig. 2. LVR implementation with an EOD context

In essence, EOD can be described as a strategy for utilising the available resources of budget and materials in the most cost-effective manner to counter the variable factors of traffic, terrain, materials and subgrade that may exist along an alignment. To be successful and sustainable, LVR technology needs to be implemented within the framework of an EOD strategy. Moreover, if the LVR project is to be sustainable in the long run a number of strategic objectives should be satisfied, including:

- Maximum use of local labour and skills.
- Maximum use of locally available or produced materials.
- Use of appropriate design standards and materials specifications.
- Low capital investment (relatively simple equipment requirements).
- Socially and environmentally acceptable use of materials and construction practices.

The appropriate application of an EOD approach requires careful consideration of the variation of different road environments along the length of the road, such as steep gradients, wet and marshy areas as well as passage over easy terrain. This approach also requires consideration of a range of options for improving or creating LVR access – from dealing with individual critical areas on a road link (Spot Improvement Design (SID)), to providing a total whole link design, which in latter case, could comprise different design options along its length

The SID principle can be applied within the context of an EOD strategy with the overall aim of ensuring that each section of a road is provided with the most suitable pavement type for the specific circumstances to provide sustainable access along the road. This requires analysis of a broad spectrum of solutions to improve different road sections, depending on their individual requirements, ranging from engineered natural surfaces to bituminous pavements. The chosen solution must be achievable with materials, plant and contractors available locally.

The EOD/SID approach ensures that specifications and designs support the functions of different road sections - assessing local environment and limited available resources. EOD assesses whether the standard design is sufficient for problematic areas and whether it is necessary for the good areas. An under-design of poor sections can lead to premature failure and an over-design will often be a waste of resources which would be better applied on the problematic sections. The EOD/SID principle is illustrated in Figure 3.

It is worth emphasising that EOD/SID applies to the appropriate design of **both the surfacing and pavement structure of a low volume road**. Thus, in order to derive the full benefits of an EOD/SID approach, **LVR technology must consider carefully the surface improvement technology options available to the design engineer, as discussed below.**

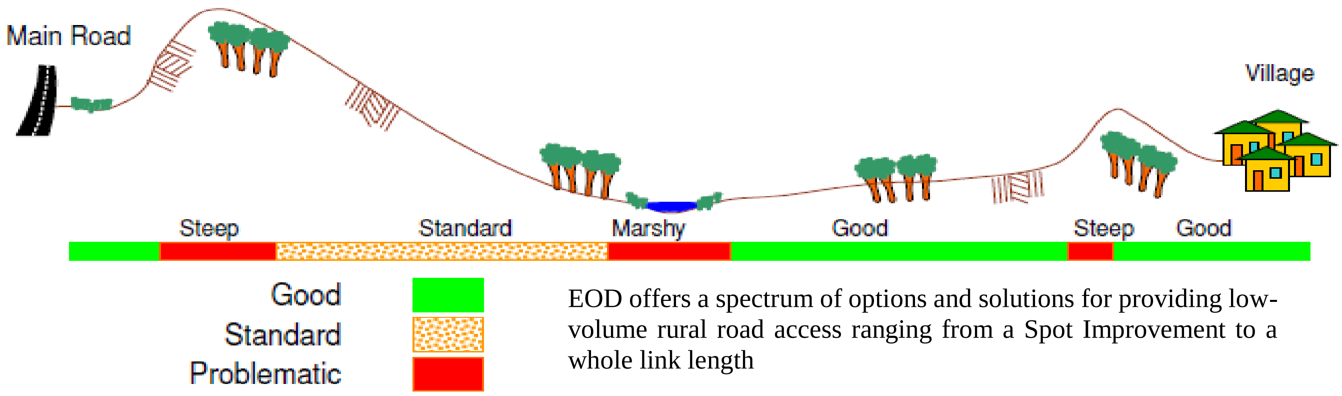

Figure 3 – Environmentally optimized design approach

D. Surface Improvement Technilogy

Gravel and earth roads are particularly vulnerable to the traffic and climatic effects of the road environment. A range of more durable surfacing options are available for LVRs which provide environmentally friendly pavement preservation treatments. These include various types of both thin bituminous and non-bituminous surfacings such as cobble stone, hand packed stone, concrete slabs, concrete strips and concrete blocks.

Improved surfacings may be provided for the entire length of a road, or only on the most vulnerable sections. The approach may include dealing only with individual critical sections (weak or vulnerable sections; roads through villages or settlements) on a road link (spot improvements), or providing a total whole rural link design, which could comprise different design options along its length.

The choice of surfacing type, and when to use it, involves a trade-off between initial cost, level of service and maintenance requirements. For example, cobblestone may use locally available resources and require very little maintenance, but it gives a relatively rough riding surface. In contrast, surface dressings provide smoother riding surfaces but may require more expensive earthworks and pavement layers, as well as imported bitumen, specialised equipment and skilled operators. Appropriate selection will be driven to some extent by the required service level.

E. Geometric Design Standards

In principle, a geometric standard represents a service level that is deemed appropriate for the particular road environment. Typically, this service level increases with traffic and is relatively high for major, highly trafficked, roads and has a clear connection with transport efficiency and economic benefits. For LVRs the benefits of a high service level are less tangible in economic terms and, as a result, a compromise has to be reached between service level and costs. Thus, in order to produce an economic standard, a balance needs to be struck between the cost of improving the alignment, both horizontally and vertically, and the benefits to be derived from so doing – an approach that emphasizes the economic aspects of geometric design which needs to be applied with appropriate understanding of economics and flexibility.

Unfortunately, for political reasons, there is often a tendency to aim at the highest design standards even when not economically justified. However, most countries in Africa cannot afford such standards and scarce resources need to be judiciously utilized so as to maximize rural accessibility which is still sadly lacking in many countries.

Typically, a designer would be faced with considering the two main options for the geometric design of a LVR, viz:

- Option A. The adoption of a fully engineered alignment which is based on a pre-determined design speed and the need to satisfy various geometric design requirements, such as passing sight distance, stopping sight distance, "engineered" curvature, both horizontally and vertically, etc. This option may be described as "*allowing the design speed to fix the alignment*" and its adoption will invariably incur potentially significant earthworks costs for which the benefits, in relation to relatively low levels of traffic, are likely to be outweighed by the costs.
- Option B: The adoption of a non/partially engineered alignment in which *"the existing alignment will fix the travel speed*". This option will accept the existing, probably non-engineered, alignment as it is, except in potentially problematic areas where traffic safety may be an issue and for which specifically engineered measures, such as appropriate traffic calming, may be required. This option will result in variable travel speeds but will not incur significant earthworks costs.

In many cases, Option B would turn out to be the more appropriate, economic, standard in that it would result in the provision of an alignment that is "fit for purpose" and provides an appropriate level of access at minimum costs. However, should this option be chosen, there are a number of qualifying requirements that should be satisfied in that:

- The road is unlikely to change its function over its design life.
- The road is likely to be used mostly by local people and seldom by other users not familiar with the alignment characteristics.
- Problematic areas, such as very steep curves or grades or other potentially hazardous traffic black spots are addressed by sound engineering solutions.
- Funding is likely to be from domestic sources where budgets are very limited.

F. Road safety

Road safety is of primary importance for all road users in Africa whether they are travelling on LVRs or more highly trafficked trunk roads. There appears to be no statistical evidence to indicate that accident rates on LVRs are much different to HVRs and it has become apparent that the core problem is unacceptable driver behaviour which needs to be addressed, irrespective of the type of road.

It has also become apparent that the safety concerns of LVR users are different to those of HVR users. This is largely because there tends to be a much higher incidence of vulnerable road users (NMT, pedestrians and animals) on LVRs than on HVRs. The challenge in such a situation is to ensure that the speed of motorized traffic is restrained to relatively low levels, particularly within villages. This is not easily achieved because the roads serving these villages often serve two conflicting functions in that they cater for both inter- and intra-village traffic. As a result, specific speed reduction measures are required to minimize traffic accidents. Such measures may be achieved in a number of ways including:

- Appropriate road signage, including traffic signs and road markings.
- Use of well designed road humps and rumble strips in and around villages and other danger spots, such as very sharp bends.
- Pedestrian crossings in urban and peri-urban areas.

- Use of shoulder humps to deter drivers from using the road shoulders.
- Use of relatively wide shoulders (± 1 m), especially in built-up areas.
- Regular and effective law enforcement.

The context specific application of the above measures requires the development of a *"total village treatment"* [14] with the objective of instilling in the driver a perception that the village is a low-speed environment in which driving speed should be reduced. This concept is increasingly being adopted successfully in a number of countries. In essence, the road through the village is treated as being in three zones, namely:

- The approach zone
- The transition zone
- The core zone.

In each of these zones, an appropriate combination of the various measures described above is judiciously deployed within the village environment.

G. Drainage

Moisture is the single, most important, factor affecting pavement performance and long-term maintenance costs. Thus, one of the significant challenges faced by the designer is to provide a pavement structure in which the weakening and erosive effects of moisture are contained to acceptable limits in relation to the traffic loading, nature of the materials being used, construction/maintenance provisions and degree of acceptable risk. This challenge is accentuated by the fact that most LVRs will be constructed from natural, often unprocessed, materials which tend to be more moisture sensitive than traditional materials. *This places extra emphasis on drainage and moisture control for achieving satisfactory pavement life.* There are a number of design considerations that are of critical importance in minimizing the chances of moisture ingress into a LVR pavement. The critical ones include ensuring adequate external drainage and the sealing of the carriageway and shoulders as discussed below.

To achieve adequate external drainage, the road must also be raised above the level of existing ground such that the crown height of the road (i.e. the vertical distance from the bottom of the side drain to the finished road level at the centre line) is maintained at a minimum height (h_{min}). This height must be sufficiently great to prevent moisture ingress into the potentially vulnerable outer wheel track of the carriageway (Fig. 4). The recommended minimum crown height of 0.75m applies to unlined drains in relatively flat ground (longitudinal gradient, g, less than 1%). The recommended values for sloping ground (g > 1%) or where lined drains are used, for example, in urban or peri-urban areas, may be reduced slightly. Naturally, the capacity of the drain should m. It is also important that the height between the top of the drain (natural ground level) and the bottom of the subbase (d_{min}) is never less than 150 mm eet the requirements for the design storm return period.

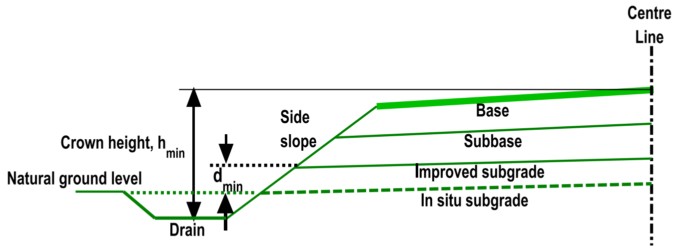

Fig. 4. Minimum drainage requirements

The most effective means of preventing water from entering the road pavement from above is by the use of a durable, waterproof surfacing that is adequately maintained over the design life of the road. There are many types of bituminous surfacings that can used for this purpose, some being more impermeable than others.

It is also critically important to seal the shoulders of LVR pavements. By so doing, lateral moisture infiltration is confined to within the usually un-trafficked shoulder. Thus, even in the rainy season, the moisture content in the outer wheel track of the road is most likely to remain at or below OMC. This is crucially important as the combination of an adequate drainage factor, as discussed above, coupled with the sealing of the carriageway and shoulders, ensures sufficiently favourable moisture conditions to allow the strength of the imported pavement material to be determined at OMC or below – a factor that widens considerably the possibility of using many natural gravels in the road pavement. Of course, there will always be situations, e.g. in low-lying or marshy areas, where it would be prudent to determine the strength of the pavement material in its soaked condition.

IV. PAVEMENT DESIGN

A. General Approach

The general approach to the design of a LVR pavement is a challenging task which differs in a number of important respects from that for high volume roads (HVRs). For example, conventional HVR pavements are generally designed to low risk levels and relatively high levels of serviceability requiring numerous layers of selected or processed materials. However, such standards can hardly be justified for LVRs for which significant reductions in pavement costs can be achieved by reducing the number of pavement layers and/or thicknesses and by making optimum use of in situ materials albeit at higher, though manageable, risk levels and lower levels of serviceability

B. Deterioration Factors

Regional research has also shown that the relative influences of road deterioration factors are significantly different for LVRs compared with HVRs [2]. A critical observation is that for LVRs carrying below 1.0 MESA, pavement deterioration is controlled mainly by how the road responds to environmental factors, such as moisture changes in the pavement layers, fill and subgrade, rather than to traffic, as illustrated in Figure 5. Thus, pavement designs for LVRs need to be responsive to a wide range of road environment factors as discussed below.

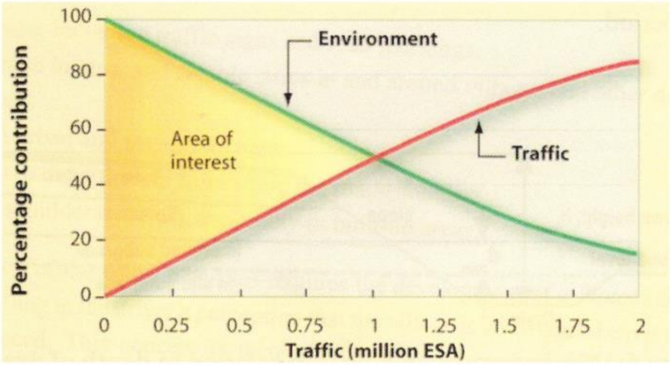

Fig. 5. Traffic loading versus dominant mechanism of pavement distress (schematic only)[1]

C. Simplified Design Procedure

The key to upgrading an unpaved LVR to a paved standard as cost effectively as possible, is by making optimal use of the in situ materials within the prevailing road environment. Over the years and under traffic loading, and wetting and drying cycles, the unpaved road would have achieved a significant degree of subgrade compaction and also re-moulding towards the attainment of a strength-balanced profile, i.e. one that exhibits a smooth decrease in strength with increasing depth [15]. During this process, localized weak areas would have been strengthened and an accumulation of residual gravel wearing course would provide a sound support or foundation for the new, relatively lightly trafficked, LVR. Optimizing the use of these conditions usually results in a reduced need to import large quantities of virgin material by only adding a single new layer, if necessary, to cater for the design traffic.

Appropriate testing with the portable Dynamic Cone Penetrometer (DCP) device can be used to rapidly assess the in situ conditions including material quality and moisture regimes along the road alignment. This simple, economical, method provides a continuous measurement of the in situ strength of the underlying subgrade layers without the need for digging up the existing pavement to obtain samples for undertaking traditional California Bearing Ratio (CBR) testing. Moreover, because many measurements can be made relatively quickly along the road alignment, the device also solves one of the underlying problems of pavement engineering, namely, coping with variability and designing in a statistically valid manner.

The DCP device is also central to a well-documented design method [16, 17] for which the details are outside the scope of this paper. In summary, this method seeks to achieve a balanced pavement structure whilst also optimizing the utilization of the in situ material strength as far as possible. This is achieved by:

- Determining the design strength profile needed for a particular traffic loading (obtained from a DCP design catalogue), and
- Comparing the design strength profile with the in situ strength profile at the anticipated, in-service moisture condition which is used for design rather than soaked values (i.e. an environmentally optimized design approach).
- On the basis of the above, determining the upgrading requirements for each uniform section.

The above procedure is illustrated in Figure 6.

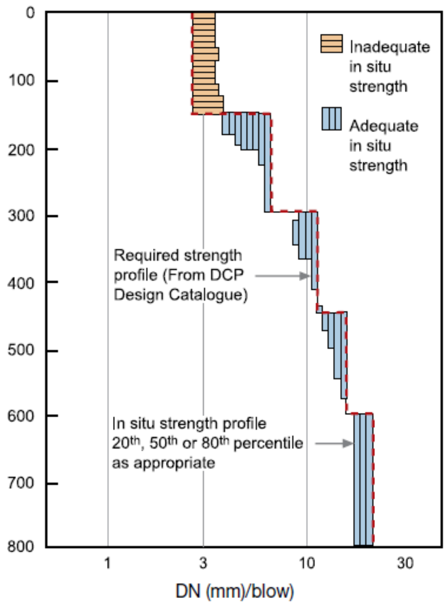

Fig.6. Comparison of DCP design and in situ strength profiles

The DCP design procedure is particularly favoured for application to LVRs for the following reasons:

- Relatively low cost, robust apparatus that is quick and simple to use allowing comprehensive characterization of the in situ road conditions, both in the longitudinal direction as well as with depth (to 800 mm or refusal).
- DCP measurements provide improved precision limits compared with the more traditional CBR test.
- The pavement is tested in the condition at which it performs and the test can be carried out in an identical manner both in the field and in the laboratory.
- The simplicity of test allows repeated testing to minimize errors and also to account for temporal effects.
- The determination of uniform sections based on a cumulative sum analysis of DN values for the upper layers, as well as the full depth (to 800 mm) of the existing pavement which allows section-specific pavement designs to be developed.
- The method is as good as or better than any other method in taking into account variations in moisture content and provides data quickly for analysis.

V. MATERIALS SPECIFICATION AND SELECTION

A. General Approach

The original DCP design method has been enhanced whereby the suitability of imported materials earmarked for use in the pavement layer(s) is also assessed by the use of the DCP in a laboratory CBR mould [12]. This so-called DCP-DN test provides a measure of the material's resistance to penetration (DN value in mm/blow) at a given density and moisture content in contrast to the more traditional CBR laboratory test. Moreover, the repeatability and reproducibility of the DCP test is much better than that of a CBR test [18] and the values obtained are inherently more accurate because the DCP provides a virtually continuous strength profile through the depth of material in the CBR mould whereas a CBR test is naturally biased towards the top of the mould which in the inverted sample penetrated has had the maximum compaction effort.

B. Criteria for Selection and Specifiaction of Materials

The traditional approach for selecting materials for use in a pavement layer has typically been on the basis of strength (CBR), grading and plasticity criteria. However, the lack of correlation between these parameters and performance [5,6] has often presented uncertainty as to the extent to which some deviation from the specified values can be tolerated. This has prompted a move away from this approach to one in which the suitability of the material is assessed on the basis of its DN value at a particular moisture and density on the premise that in-service performance indirectly takes account of the actual grading and plasticity of the material which do not need to be separately specified for LVRs.

In the DCP-DN approach, the moisture and density dependence of the materials to be used in the imported upper/base layers of the new road must be evaluated so that a full understanding is obtained of the potential performance of the material under the possible moisture conditions that may occur in service. Figure 7 shows a typical relationship between DN, density and moisture content for a naturally occurring material which illustrates the impact of two factors that crucially affect the long-term performance of the road:

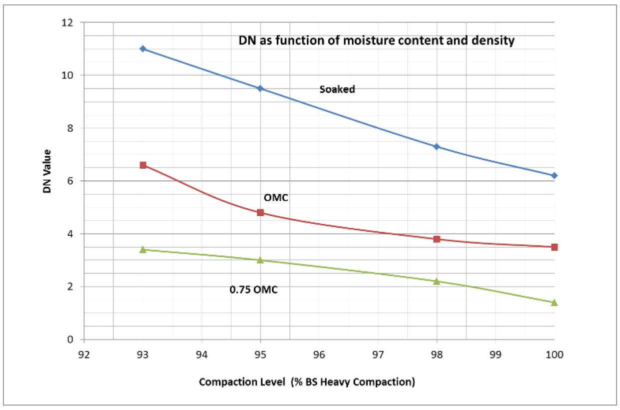

Fig. 7. DN/density/moisture content relationship

VI. CONSTRUCTION ISSUES

A. Compaction

One of the challenges of utilising natural gravels in LVR pavements is to maximise their strength, increase their stiffness and bearing capacity, increase their resistance to permanent (plastic) deformation and reduce their permeability (and, hence, susceptibility to inadvertent moisture ingress). These attributes can be achieved through effective compaction, as discussed below.

Effective compaction of the existing running surface of the gravel road which is to be upgraded is one of the most cost-effective means of improving the structural capacity of the LVR pavement. A well compacted running surface (effectively and typically the subbase of the new LVR pavement) possesses enhanced strength, stiffness and bearing capacity, is more resistant to moisture penetration and less susceptible to differential settlement. The higher the density, the stronger the layer support, the lesser the required thickness of the overlying pavement layers and the more economic the pavement structure. Thus, there is every benefit to achieving as high a density and related strength as economically possible in the subgrade.

Maximising the strength potential of a subgrade soil can be achieved, not necessarily by compacting to a pre-determined relative compaction level, as is traditionally done but, rather, ***by compacting to the highest uniform level of density possible ("compaction to near refusal") without significant strength degradation of the particles.*** In so doing, there is a significant, beneficial, gain in density, strength and stiffness and reduction in permeability, the benefits of which generally outweigh the costs of the additional passes of the roller. For these compelling reasons, where the higher densities can be realistically attained in the field (compaction to near refusal) from field measurements on similar materials or other established information, they should be specified in the tender documents.

B. Moisture

LVR design procedures assume that both the material properties and levels of density specified are achieved in the field. However, in order to attain the specified densities, it is essential to ensure, as far as practicable, the uniform application of water, the uniformity of mixing and uniformity of compaction at or near OMC.

It is also important to note that layers below the one being compacted should be of sufficient density and strength to facilitate effective compaction of the upper layer(s). Adherence to the compaction recommendations given above should ensure this.

Whilst it is necessary for natural gravels to be brought to OMC for efficient compaction, it is equally necessary to ensure that premature sealing does not lock in construction moisture. This can be avoided by allowing a significant amount of drying out to occur before sealing takes place, typically to 50% of OMC, particularly for materials that rely on soil suction forces for strength gain and improved stability.

The variability of natural gravels is a significant factor in the reliability of performance of the pavement. However, various measures can be taken during construction to reduce such variability. These include:

- Careful selection during winning and stockpiling
- Adequate processing of stockpiled material.
- Quality control and assurance.

The latter measure is of paramount importance when using unprocessed, natural gravels for LVR construction. However, compaction quality control using traditional methods such as Sand Replacement, core cutter, rubber balloon and nuclear density gauge, can be slow, hazardous, of uncertain accuracy, and impractical in situations where there is variation in site materials along the tested section. The DCP offers an alternative method of compaction quality control, in terms of both the level and uniformity of compaction which is relatively simple and low cost compared with traditional methods. Moreover, the procedure is based on a specific criterion, the DN value (directly related to the in situ strength) that is the same as that used in the design of the pavement.

As shown in Figure 7 above, for a specific material, the relationship between DN value, density and moisture content can be established. This relationship can then be used for quickly assessing compaction compliance, in terms of the field DN versus required DN value, as indicated in the DCP-DN catalogue. This is only representative after drying back. It is better to use the DN from the mod testing at MDD and OMC for compaction control as this can be measured directly in the field after compaction at the end of the day.

Since, for a given material, variations in the moisture content can significantly influence the DN value (Figure 7), control of field compaction moisture is critical. Thus, determination of the Field Moisture Content (FMC) as a percentage of OMC at each DCP test point by means of a rapid test, e.g. the "Hilf" method, may be warranted to ascertain whether the moisture content at which the DN value is being measured is within an acceptable range of the OMC.

It should also be noted that, due to less confining pressure at the top of the compacted layer, the DN value will tend be higher and not representative for the whole layer. It has therefore been suggested to use 3 seating blows for the DCP before the actual readings for determination of the representative DN value are taken [19]. This is in keeping with the laboratory DN test where, also due to lack of confining pressure at the top of the CBR mould, the first few readings are often not representative of the body of the material and should be disregarded.

VII. SUSTAINABILITY OF LVR PROVISION

A. *Sustaianbility Framework*

Traditional approaches to LVR provision have tended to focus somewhat narrowly on the technical environment with inadequate consideration of the other inter-related environments. The result has often been a lack of responsiveness to the needs of various stakeholders' and a reduced likelihood of achieving sustainable solutions. Lessons learned from the region indicate that if LVRs are to be provided in a more sustainable manner than hitherto then new approaches are required that focus in a more holistic way on a number of factors that affect the sustainability of LVR provision. These factors are illustrated in Figure 8.

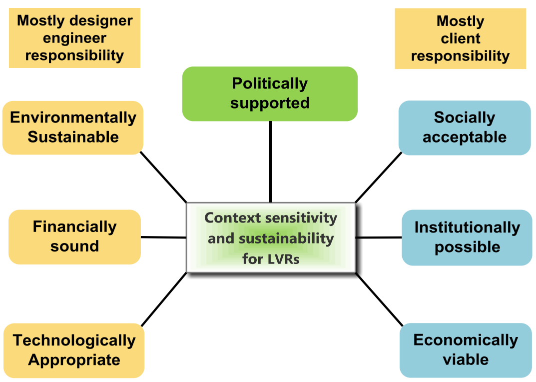

Fig. 8. Framework for sustainable provision of LVRs

B. *Risk Factors*

One of the arguments often voiced against using unconventional designs, materials and techniques for road design and construction is that the level of risk is unacceptable. Whilst it must be conceded that any departure from well-established, conservative material quality specifications may carry some increased level of risk of failure, such a risk should be a calculated one and not a gamble and must consider not just materials but the whole pavement and its environment Thus, in any pavement design strategy, it is necessary to be aware of the main risk factors which could affect the performance of LVRs so that appropriate measures can be taken to minimize them. These factors are summarized below:

- Quality of the materials (strength and moisture susceptibility).
- Construction control (primarily compaction standard).
- Environment (particularly drainage).
- Maintenance standards (drainage and surfacing).
- Traffic and overloading.

The risk of premature failure will depend on the extent to which the above factors are negative – the greater the number of factors that are unsatisfactory, the greater the risk of failure. However, this risk can be greatly reduced by minimizing material variability, ensuring that the construction quality is well controlled, that drainage measures are strictly implemented and maintenance is carried in a timely manner.

VIII. SUMMARY

There is an urgent need to improve rural access in the African region in order to further economic and social development and to reduce poverty. However, the attainment of this goal through the application of traditional methods of LVR provision, including the use of conventional standards and specifications, would be prohibitively expensive. Fortunately, there is a wealth of invaluable research information from the region that has provided practitioners with a better understanding of the performance mechanisms of LVRs than before. This has led to the development of performance-based standards and technical specifications that are increasingly being utilized in the region and are gradually changing traditional practices and thinking by way of new design manuals and guidelines for low volume roads.

Some of the key developments in LVR technology include a better appreciation of a multitude of road environment factors that influence the approach to design. Moreover, the concept of *environmentally optimized design* provides a strategy for utilizing the available resources of budget and materials in a more cost-effective manner than hitherto. When combined with a Spot Improvement approach, the designer is able to ensure that each section of a road is provided with the most appropriate pavement type for the specific circumstances.

In terms of surface improvement technology, the designer now has a much wider array of options than hitherto, including both bituminous and non-bituminous surfacings which have been trialled in a number of countries in the region. Thus, non-bituminous surfacing options such as cobble stone, concrete strip roads and concrete blocks are becoming more common in adverse environments where steep grades and high rainfall combine to rule out the use of the more traditional bituminous surface treatments. Labour-friendly bituminous options such as Cold Mix Asphalt and graded aggregate (Otta) seals are also being more commonly used in a number of countries.

There is increased recognition that in the setting of geometric design standards, a balance must be struck between the cost of improving the alignment and the benefits from so doing. Thus, in some circumstances, fully engineered alignments may not be warranted for very low volume roads. However, this should not detract from the over-riding importance of road safety, for which they should be no compromise. The emergence of the *total village treatment* concept offers much scope for improving road safety in rural environments.

As always, drainage remains the most critical factor affecting the performance of LVRs. However, relatively simple, robust measures, such as the attainment of the *drainage factor* and the sealing of shoulders, coupled with dedicated attention to in-service maintenance, can provide a reasonable assurance of satisfactory pavement performance.

With regard to pavement design, there is now a much better understanding than before on the relative influences of road deterioration factors for LVRs in which the environment, rather than traffic loading, has been shown to play a relatively more dominant role on pavement performance up to about 1 MESA. This emphasizes the importance of minimizing moisture ingress into LVR pavements that are often constructed with moisture sensitive materials.

The Dynamic Cone Penetrometer has been shown to provide a simple, but robust, method for the design of LVRs. The relatively recent resurgence of this method of design, coupled with its use for material selection and quality control, has injected a degree of quality assurance in the design of LVRs not easily possible with the use of the more traditional, and less reliable, CBR method of testing and design.

The importance of adequate compaction, following the concept of *compaction to refusal* has provided scope for producing pavements with enhanced strength, stiffness and bearing capacity.

Importantly, the sustainability of LVR provision can only be assured if various dimensions of sustainability are addressed, including political support for applying aspects of LVR technology that may deviate from traditional practice. In addition, social acceptability, in terms of maximizing the use of local labour, and technical appropriateness of the technology deployed to provide LVRs require consideration.

Finally, the benefits of LVR upgrading are mostly socio-economic and environmental, which are difficult to quantify in economic terms in conventional economic analysis. Nonetheless, when appropriately provided, based on the many developments in LVR technology highlighted in this paper, such roads can go a long way to meeting the basic access needs of rural communities in a sustainable manner, leading to reducing improved economic growth and development, and related improvements in livelihoods of the poor – the over-arching goal of all African Governments.

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