An alternative philosophy on the deterioration and design of low volume roads

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***Abstract*— The performance of paved roads is generally assessed in terms of riding quality and rut depth with failure being assumed at various terminal conditions depending on the category of road. The extent of the road affected by this terminal condition also depends on the road category. On this basis, the road will be deemed to have failed when the rut depth over 20 or 50% (Category C and D respectively) of the road exceeds 20 mm and/or the riding quality exceeds 4.6 or 5.1 m/km respectively. Two considerations come into play when assessing the performance of low volume roads near their terminal condition. Firstly, as long as the pavement surfacing is still intact (i.e. not too many un-repaired potholes), the road will always provide a better service/riding quality and lower vehicle operating cost than the equivalent unpaved road. Secondly, the mode of failure of conventional roads is the cumulative permanent deformation (rutting) of the road under heavy axle loads. Low volume roads usually have few heavy loads, the majority of which often occur during the dry season, and traffic induced rutting is minimal – the majority of rutting is a result of early compaction of the layers due to lower densities achieved in the pavement layers during construction. Of greater consequence with these roads is the effect of a few overloaded vehicles (particularly during wet weather or when drainage maintenance has been neglected) causing large strains (or even isolated shear failures) in the layers. These roads, however, are usually still perfectly fit-for-purpose (after localised repairs) and often do not deteriorate further with time, even with minimal surfacing maintenance. Conventional mechanistic empirical analyses carried out on these roads either severely over- or underestimate their structural capacity, with many still providing adequate surface after 20 or more years. More use of the in situ shear strength in designing such roads is thus proposed. This paper discusses different philosophies in designing and predicting the carrying capacity of such low volume roads.**

Keywords—low volume roads, deterioration, mechanistic, shear strength

I. INTRODUCTION

The success of a paved road design is reflected by the road carrying the expected traffic for which the road was designed without it displaying distress exceeding the specified terminal conditions. This is also related to a specified percentage of the road, according to its category [1]. It is assumed that the road has been timeously and correctly maintained. This includes both functional and structural distress. Deficiencies in the functional performance are generally the result of inadequate structural performance, resulting in deformation of the pavement through overstressing, cumulative deformation or localized failures. However, field observations of low volume roads over a number of years have indicated that roads that would conventionally be considered to have failed functionally are in fact mostly still providing an acceptable level of service.

The performance of paved roads is generally assessed in terms of riding quality and rut depth with the road to be considered as failed (functionally) when certain selected limits are reached. Observation and analysis of numerous low volume (Category D or worse) roads have indicated that even though the terminal condition (in terms of rut depth) has often been exceeded the road still provides a level of service much higher than the equivalent unpaved road, with significant concomitant reductions in road user costs. Rutting seldom contributes significantly to poor riding quality and can easily be repaired using, for instance, quick setting slurry seals. However, road failures leading to potholes and patching do have a significant effect on riding quality. The majority of failures on these roads are the result of inadequate or incorrect maintenance (Fig. 1).

Fig. 1. Low volume road showing lack of maintenance, which ultimately leads to road failure

This paper assesses the performance of low volume roads based on the investigation of many such roads [2] and relates it to the proposed pavement design philosophies and structural capacity.

II. Low volume road structure and level of service

Low volume paved roads discussed in this paper are defined by their traffic (generally considerably less than 200 000 equivalent standard axles (ESAs) over a 20 year design life), their social consequences (providing all-weather access to previously isolated areas) and their environmental and sustainability issues (the reduction in sacrificial gravel normally used on unpaved roads). These roads are often designed with little technical input and often consist of only a layer of imported local natural gravel base of nominal thickness (usually 100 to 150 mm) placed on an old unpaved road gravel wearing course and surfaced with an appropriate surfacing. The thickness of gravel in the existing gravel wearing course can vary from almost zero to 150 mm, the more usual condition being towards the lower end, where a new base (often of wearing course quality) has been placed in lieu of regravelling the road, or the existing gravel course has been reworked (ripped and recompacted) to form the new base course.

The riding quality of such roads depends initially on the quality of the construction mostly and then deteriorates with time. This is often due to construction variability (differential settlement under traffic), poor subgrade conditions (e.g. collapsible or expansive soils) or probably most commonly, deficiencies in drainage leading to localized weak areas and failures. Initial rutting is mostly the result of low levels of compaction during construction.

Although the proposed philosophy is not new, certain contentious aspects are discussed, based on field observations and long-term monitoring.

III. Performance of LVRs

Many low volume paved roads have been observed and investigated in South and southern Africa, as well as in various other countries around the world. These roads have varied in age from immediately after construction to many decades old and have in almost all cases still presented a better performance than the previous or alternative unpaved road. Many of the roads had ruts well in excess of 25 mm and deflections up to 2 mm but still had acceptable riding qualities compared with adjacent unpaved roads. Only the almost ubiquitous lack of maintenance affecting lightly trafficked rural roads in South Africa leads to a severe reduction in their serviceability and lives.

Figs. 2 and 3 show a typical example of one of the low volume roads investigated, consisting of an existing gravel wearing course (weathered shale) that was shaped and surfaced with a 13 mm single seal in 1977.

Fig. 2. Low volume road (2005, 28 years after construction)

Fig. 3. Low volume road (2014, 37 years after construction)

The road was tested and sampled in 1992, with the patches at these sites clearly evident in both subsequent photographs. No significant distress is present (except for failure of the patches after 22 years). The road was apparently resealed after 5 years (13 mm single seal in 1982) and not again in the subsequent 32 years. The road is estimated to have carried about 80 000 equivalent standard axles (ESAs), mostly agricultural and delivery traffic in addition to an estimated 4.1 million light vehicles.

IV. Analysis of pavement structures

There is an increasing move in pavement design towards mechanistic empirical analysis of the proposed pavement structures to predict their estimated lives in terms of traffic. Such analyses use calculated stresses and strains to determine the long-term performance of the road, based on comparison of these parameters with the known performance of similar roads. Mechanistic empirical analyses carried out on many low volume roads with stiffness values based on the Dynamic Cone Penetrometer (DCP) test results have indicated that the roads should not have carried more than a few dozen or perhaps few hundred standard axles and yet the roads were still providing a satisfactory service after many years. Other analyses on roads showing significant shear failures indicated that the roads should have carried in excess of 5 million standard axles.

This is not altogether surprising as the layered linear elastic theory used in the traditional mechanistic empirical pavement analysis is strongly based on the assumption that the materials are isotropic and elastic, an assumption valid more for relatively stiff pavement materials under low stress conditions. These assumptions do not necessarily hold for thin pavement structures using low strength local materials as has been seen in the field where the mode of failure is more plastic (elasticity theory is not valid at stress levels approaching failure), resulting in initial fatigue cracking of the road followed by severe deformation caused by individual or a few heavy loads (Fig. 4). This usually occurs as a result of raised moisture contents in the road caused by ineffective drainage (poorly designed initially or due to poor maintenance of the pavement surface or, more usually, the adjacent shoulders). High pore-water pressures generated under the dynamic loading of large vehicles will lead to a reduction in shear strength of the pavement materials and potential failure. Although the mechanistic design method uses a factor of safety against "gradual" shear failure of the granular materials under repeated loading, it appears that the transfer functions may be the main problem. For Category D roads, a factor of safety of 1 occurs at a cumulative traffic count of over 1 MESAs in the transfer function, considerably higher than the traffic normally considered for a low volume road - a factor of safety of 0 occurs at a traffic volume of 1000 ESAs [3].

Fig. 4. Typical shear failure due to overstressing

The use of a standard terminal condition of 20 mm rutting also probably contributes to the underestimation of the structural capacity as this is a function of the empirical transfer functions, mostly derived from traditional pavement structures. Instances have been recorded on LVRs where a rut of 15 or 20 mm develops in the first one or two years, after which little additional rutting occurs.

Rapid shear failures are probably best modelled using ultimate load methods, which determine the potential for shear failure in the short term. It must be borne in mind that the strength and stiffness conditions in a road vary continually with time, as their moisture and temperature vary seasonally. Modelling of the pavement performance is thus usually based on various percentiles of the expected range of properties. These can vary from the worst condition through average to the best conditions, depending on the whim of the designer and the properties of the materials tested.

Oloo [4] has highlighted the deficiencies when using layered elastic theory for weak materials and thin pavement structures and proposed the use of ultimate strength methods. Whereas linear elastic analysis makes use of material stiffness (a notoriously difficult property to measure for weak materials that is affected by many uncontrollable factors in the field) and Poisson's ratio, ultimate strength methods make use of the cohesion and angle of friction, which are slightly easier to measure. The use of Poisson's ratio is a particular dilemma, as a constant value of 0.35 is traditionally used for all natural gravel materials, effectively making the stiffness value the only material variable in all mechanistic analyses.

Investigations of some of the roads showed significant early rutting and cracking in relatively plastic base course materials (Plasticity Index (PI) up to 21%). Fig. 5 shows a road 8 years after the initial investigation that indicated no significant further cracking or rutting (original rut depth 25 mm), although there was significant spalling at the cracks, which was minimal during the initial investigation. Even so, much of the rutting is probably caused by additional traffic compaction after construction, as many of the base courses are only compacted to a nominal 95% mod AASHO density and the underlying layers have only been subjected to traffic compaction in the pre-existing unpaved roads. The potential for rutting is therefore high.

Fig. 5. Low volume road 8 years after initial sampling

This road (Fig. 5) had an in situ base CBR (from DCP) of about 100%, although the laboratory soaked CBR was only about 50%. It was sealed during construction (1981) with a single 13 mm surface dressing with a follow up 13 mm single seal 4 years later. No additional seal work had been done at the time of the photograph (1997). No evidence of shear failure was seen and the poor appearance was only the result of a lack of maintenance. However, shear failure of such roads is not an uncommon problem, particularly when the base course materials are weak (Fig. 4).

Pavements are traditionally analysed in terms of the cumulative equivalent standard axle loadings on the road, which lead to the permanent rut. However, analyses of a number of these calculations for low volume roads has indicated numerous problems:

- No vehicle mass measurements are usually available and the mass (based on estimated load) is usually employed during vehicle counts.
- Vehicle counts are seldom carried out over a sufficiently long duration to get accurate data. A small change in traffic on LVRs over a short period can have a large impact on the counts.
- The relative damage exponent, n, of 4 used for traditional standard pavements may not be applicable to LVRs where the pavements are often deep with strong subgrades [1, 5].
- The majority of vehicles on most LVRs are light and medium, causing minimal structural damage to most roads. However, the load equivalency factor for lighter vehicles increases as the n exponent becomes less than 4.

Oloo [4] analysed the pavement of low volume roads as a foundation and calculated the bearing capacity prior to failure. He also found that the effect of matric suction in unsaturated soil had a significant effect on the behaviour and including this as a factor in the design resulted in significant reductions in required layer thickness. However, bearing in mind that the shear strength of a material is directly dependent on the normal stress, it is clear that determination of the relevant shear stress in the pavement at different depths is necessary before the shear strength of the material can be estimated or measured.

It is interesting to note that close observation of a material (in an unpaved road) with a CBR of 18% , when in a soaked condition, did not show any shear failure after being traversed by a number of heavy vehicles considered to be fully loaded and carrying the normal legal load of 9 tons (88 kN) per axle (Fig. 6).

Fig. 6. Weak material (in a soaked condition) after numerous 88 kN axle passes

Irrespective of the method of analysis chosen, the determination of the input parameters (E, c, φ, etc) can be tedious and complex. A method of design using simpler inputs is thus far more appropriate for low volume roads, where the cost of the pavement is low and it is pointless to invest significant amounts of the funding in laboratory testing, on samples that are often only representative of a short section of the proposed road.

V. Discussion

The definition of failure for a low volume road (Category D or possibly even C) is a maximum rut depth of 20 mm and a minimum International Roughness Index (IRI) of 5.1 or 4.6 m/km respectively. An International Roughness Index (IRI) of between 3.5 and 5.1 m/km depending on the category of road. The extent (in terms of length) of the road affected by this terminal condition ranges from 5 to 50 %, also depending on the road category. Low volume roads normally fall into category C or D. On this basis, the road will be deemed to have failed when the rut depth over 20 or 50% (Category C and D respectively) of the road exceeds 20 mm and/or the riding quality exceeds the limits shown above. The common hypothesis that failure is the result of an accumulation of infinitesimal repeated unrecoverable strains leading to rutting of the road is probably not valid for LVRs where the majority of traffic is light and non-unrecoverable strains are not likely to occur.

It has been noted that many of the roads that have "failed" show signs of shear failure in the base or subbase as a result of the passage of a few heavy vehicles, probably during inclement weather or where drainage has been poor (Fig. 7).

Fig. 7. Failure of a road (patch in this case) after less than 10 heavy vehicles (caused by excessive water)

To avoid such problems it is necessary to ensure that the in situ material strength with depth is sufficient to support the applied loads at all times. Revisiting the original CBR cover curve design method, the appropriate CBR was determined at various depths to ensure that the applied stresses were lower than the equivalent shear strength of the material at that depth, assessed as the CBR.

Fig. 8 shows the distribution of stress with depth for different contact stresses on the surface of the road based on simple Boussinesq theory (the effect of layers is ignored as there is seldom a big difference in strength between the different layers, and it does not affect the stress distribution). It is clear that, irrespective of the contact stress, the decrease in shear stress with depth is rapid and below about 200 mm, the stress is generally less than about 200 kPa (an estimated CBR of about 18%).

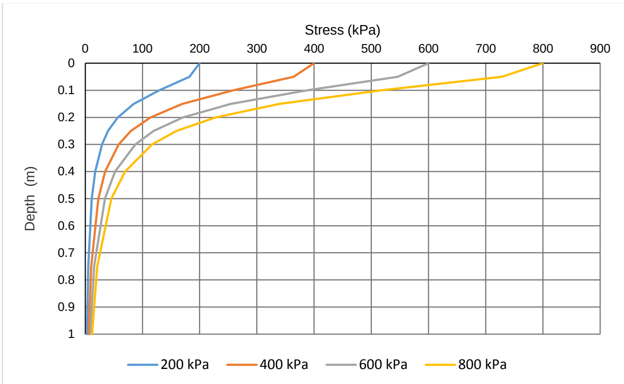

Fig. 8. Stress distribution with depth for different contact pressures

A series of catalogue or layer strength diagrams (LSDs) has been developed for different categories of low volume roads (Fig. 9 and Table 1) based on a back-analysis of various pavements over time [6, 7]. These layer strength diagrams relate the cumulative traffic (million equivalent standard axles, MESA) to various pavement structures, which can be easily assessed using a Dynamic Cone Penetrometer (DCP) survey of the proposed road support conditions to obtain the in situ shear strength (DN in mm/blow). By using the actual in situ strength, problems with modelling the effects of normal stress on the shear strength are minimised.

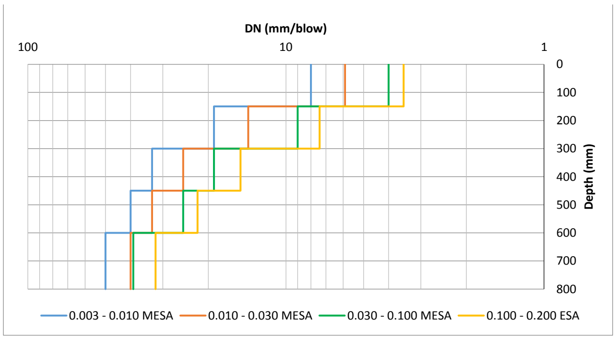

Fig. 9. Layer strength diagrams for different low volume road traffic categories

TABLE 1 LSD IN TERMS OF DN, CBR AND USS

Road category (traffic in ESA)	Strength parameter in upper 4 by 150 mm layers[a]		
	DN (mm/blow)	*CBR (%)*	*USS (kPa)*
0.003 – 0.010 MESA	8, 19, 33, 40	29, 10, 5, 4	324, 107, 52, 41
0.010 – 0.030 MESA	5.9, 14, 25, 33	43, 14, 7, 5	480, 158, 75, 52
0.030 – 0.100 MESA	4, 9, 19, 25	70, 25, 10, 7	790, 279, 107, 75
0.100 – 0.200 MESA	3.5, 7.4, 15, 22	83, 32, 13, 8	939, 358, 145, 88

[a] All properties at expected in situ moisture content

Table 1 can be illustrated in terms of approximate shear strength of the material based on various relationships between DCP-CBR and undrained shear strength (Fig. 10).

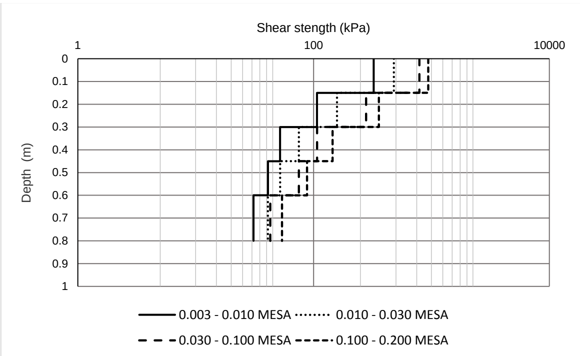

Fig. 10. Layer strength diagram in terms of shear strength for different traffic classes

By superimposing the charts in Figs. 8 and 10 (Fig. 11), it is possible to identify potential weak zones. It is clear that for tyre contact pressures of less than 200 kPa, the LSDs all lie to the right of the stress curve and shear failure will not occur. However, the LSD for the lightest traffic lies to the left of the 400 kPa contact stress curve between 0 and 60 mm and also between about 150 and 210 mm. The potential for shear failure exists in this zone. It can be seen, however, that the higher the design traffic becomes, the shear strength curves move further to the right of the stress curves.

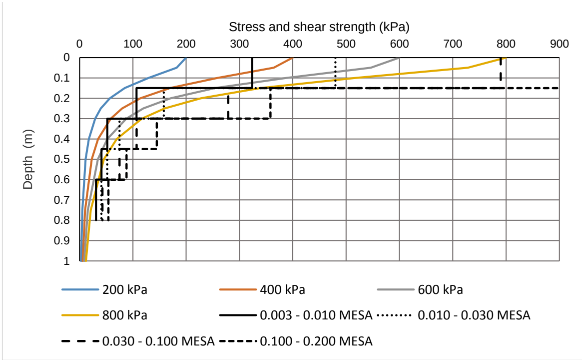

Fig. 11. Superimposed stress distribution and shear strength requirements

The obvious question is then, "why does a road designed for low traffic (< 100 000 ESA) not fail when a vehicle with a tyre contact stress of 800 kPa passes over it? The answer is probably a combination of reasons:

- The pavement is designed for the potentially poorer moisture conditions, which should only occur during less than 20 per cent of the time (assuming 20th percentile is used for design).
- The stress curves in Fig. 8 are based on a uniform material. By applying a layer on the top, the stress distribution will change, depending on the strength ratio of the upper and lower layers. As indicated, for many of the LVRs investigated this ratio is close to unity and the single material scenario is thus valid. However, as the strength of the upper layer increases, more stress is absorbed in this area and the underlying layers are subjected to lower stresses.
- These conditions should theoretically occur only in the outer wheel path of the road if the surfacing remains intact. The low traffic on many of these roads, together with the rut commonly found tends to result in heavy vehicles driving more towards the centre of the road under normal circumstances.
- Excess positive pore-water pressures will only occur when the material is saturated, which is not very common. Conversely, the effects of matric suction (negative pore-water pressures) significantly increase the shear strength of the materials.
- The stresses shown in Fig. 8 are the maxima, beneath the centre of the loaded area. The mean value for the entire loaded area is more representative and thus builds in some safety factor.
- The upper 20 mm or so of many of these roads is strengthened significantly by penetration of the prime into the material.

The attractiveness of this analysis and design technique is that the DCP survey indicates the shear strength of the materials within the pavement structure at the prevailing moisture and density conditions. The density of the materials can only be expected to remain unchanged or increase marginally with time after construction. The moisture content, however, can vary significantly from season to season and the design moisture is thus based on a statistical evaluation of the in situ pavement conditions [6, 7]. All designs are reliant on an accurate estimate of the in service moisture regime as well as the construction and maintenance of an effective side-drain system adjacent to the road. The risk of premature failure, as long as these considerations are taken into account, is thus no higher than for any conventional low volume road.

Another advantage of this technique is that the gap between the stress and the strength curves in Figure 11 gives an indication of the factor of safety. If the two curves touch, the factor of safety is unity and as the strength curve moves (LSD) further to the right away from the stress curve, the factor of safety increases.

It will be noted that despite the earlier proposition in the paper that the cumulative standard axles are not as important as the shear strength of the materials in the structure, the layer strength diagrams do fundamentally make use of this principle. It should be noted that this is not based specifically on rutting or riding quality but more on the "acceptable" performance of known roads and the extrapolation of the estimated traffic carried by them. The design of low volume road using the DCP is thus a combination of using the in situ shear strength with empirical estimates of the structural capacity based on past experiences.

VI. CONCLUSIONS AND RECOMMENDATIONS

Experience has shown that the performance of most low volume roads is generally difficult to predict using conventional mechanistic-empirical design procedures. The failure criteria (used in the mechanistic empirical analysis procedures) for low volume paved roads appear to be somewhat unrealistic. A paved low volume road, provided it is adequately maintained will always provide a better and more cost effective (in terms of total road user costs) road than any unpaved road and is far more sustainable in the long term.

This paper describes a method using DCP test results to design low volume roads that takes into account both the cumulative infinitesimal permanent deformation as well as the potential for shear failure in the upper pavement structure. Issues regarding the determination of elastic modulus (stiffness) and Poisson's ratio, the shear strength in terms of cohesion (C), friction angle (φ) and normal stress (σ_n) are avoided by using the in situ shear strength obtained directly from the DCP.

By comparing the actual pavement strength (layer strength diagrams) with the stress for different vehicle configurations and categories an appropriate pavement design can be developed and the potential for failure can be estimated.

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