The evidence for rural road technology in low income countries

Burrow, Michael; Evdorides, Haralampos; Ghataora, Gurmel; Petts, Robert; Snaith, Martin

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Burrow, MPN, Evdorides, H, Ghataora, GS, Petts, R, Snaith, MS

Abstract

Rural road networks in Low Income countries (LICs) and Low Middle Income countries (LMICs) are critical for economic and social wellbeing, however they are mostly unpaved, have poor average condition, can be impassable after periods of rain and have high user costs. There is therefore a need to identify low-cost, proven sustainable solutions for rural roads in these countries. To this end the UK Department for International Development (DFID) commissioned a Systematic Review to identify and appraise technologies appropriate for low volume rural roads which have enabled improved and sustainable rural access in LICs and LMICs. Its findings are summarised in this paper.

The review found that there is an evidence base of engineering related technologies, primarily associated with the use of materials and design philosophies, which can be used to improve the performance of gravel, or earth, rural roads and that proper construction and appropriate maintenance are vital for the technologies to be sustainable in physical terms.

However the review argues that, since there are few empirical studies demonstrating the sustainability of rural road technologies, expert knowledge is needed to support the implementation of its findings.

Introduction

Background

It is estimated that around a billion of the world's population do not have reliable all-season road access, and as a result social and economic development is substantially constrained (Lebo and Schelling, 2001). In particular, rural communities in Low Income countries (LICs) and Low Middle Income countries (LMICs) rely completely on access to volume rural roads (LVRRs) for the pursuit of social interaction, access to schools, health facilities, the workplace, markets and basic needs such as clean water (Knox et al., 2013; Akpan, 2014).

However, the vast majority of these roads are unpaved (typically more than 90%) and suffer from inadequate maintenance.

Predominantly, LVRRs in LICs and LMICs are earth or made from gravel. Both low-cost surface types require regular routine maintenance of camber and drainage systems. However, earth surfaces are normally unable to provide all-season access in many regions. Gravel surfaces also require regular periodic maintenance to replace gravel loss, which can be extreme in many environments, and is relatively expensive compared to the road's initial cost. Replacing lost gravel, which is a finite resource, can be unsustainable. As a result LVRRs in LICs and LMICs are often of poor condition, can be impassable after periods of rain and have high road user costs. Climate change is exacerbating this situation as many regions in LICs and LMICs are experiencing more extreme weather events.

The UK Department for International Development (DFID) commissioned a Systematic Review of the literature, with the aim of identifying and appraising technologies appropriate for LVRRs which have enabled improved and sustainable low volume rural access in LICs and LMICs. This paper describes the results of the review and discusses how expert knowledge can be included within the process to enable the findings to be adequately applied.

Systematic Review

A systematic review is a critical appraisal and synthesis of research findings carried out using explicit, systematic and transparent methods and is often used to inform policy and practice (Gough *et al* , 2013).

The systematic review described hereinafter addressed the following questions: What is the evidence supporting the technology selection for LVRRs in LICs and LMICs and what evidence is there to support the sustainability of different rural road technologies?

Definitions

The systematic review followed a search protocol based on the following definitions. The World Bank's definition of countries was used to identify LICs and LMICs (World Bank, 2016). LVRRs were considered to be roads with an annual average daily traffic (AADT) of up to 300 motor vehicles per day (mvpd) and a design cumulative traffic load of less than 0.5 million Equivalent Standard Axles (MESAs).

Technology for LVRRs was considered to be associated with the planning and building of new roads, providing all-season access through upgrading existing earth and gravel roads and carrying out maintenance. Technology therefore was taken to include: resources (materials, labour, equipment, capital/credit); management tools (e.g. for economic appraisal, planning, computer software); and design, construction and maintenance methods.

The review focused on studies reporting a range of outcomes associated with the implementation of LVRR technology. A technology was considered to be sustainable if it had ensured the capability of an LVRR to perform to its planned, designed and constructed standards, with the available financial and physical resources, using the local operational arrangements and in the local environment.

The search approach adopted

The review questions lent themselves to an unbiased aggregation approach to identify studies which demonstrate the sustainable use of technology in different contexts (Gough et al., 2013). The strategy tried to identify longitudinal studies which have been carried out over a significant part of the life cycle of a LVRR. The sources considered were websites of organisations involved in the road sector, bibliographic databases, internet search engines, hard copies of books and journals, reference lists and professional reports. A systematic review software application, EPPI-Reviewer 4, facilitated the review and was used for screening, coding, analysing and storing retrieved documents (Thomas et al., 2010). The search process is summarised in Figure 1.

Weight of evidence: assessing the quality of studies

A weight of evidence framework was used to assess the quality and relevance of the included studies in three categories (see Table 1): (i) soundness of studies; (ii) appropriateness of study design for answering the review question; and (iii) relevance of the study focus to the review. The studies considered were required to achieve a high rating in at least two categories and a medium rating in the third.

Table 1: Weight of evidence (WoE) (Gough et al. (2013)

WoE	**Tasks**
A. Soundness	**High:** Explicit and detailed methods and results for data collection and analysis; interpretation soundly based on findings. Critical comparison with other work.

	Medium: Satisfactory methods and results; interpretation partially warranted by findings. **Low:** The methods and results sections unsatisfactory; no interpretation of findings or interpretation not warranted by findings.
B. Appropriateness of study design	**High:** Road pavement trials covering at least two periodic maintenance cycles (approximately 4-10 years). Road condition data to be collected at least annually and the frequency and type of maintenance carried out recorded. Alternatively, slice-in-time studies of a selection of in-service LVRRs of ages varying from 3 years to at least 12 years. Road condition assessed at the end of the dry and wet seasons. **Medium:** Trials lasting one periodic maintenance cycle (2-5 years). Road condition data collected periodically during this time. Slice-in-time studies to include a selection of in-service LVRRs of ages varying from at least 2 years to at least 5 years. **Low:** Trials covering less than 2 years, or slice-in-time studies of LVRRs of less than 2 years in age.
C. Relevance of the study focus	**High:** More than 10 sections of at least 100 m. **Medium:** Between 1 and 10 sections of at least 100 m. **Low:** One section of at least 100 m.

Synthesis of evidence

The data were synthesised, using narrative methods, to indicate the sustainability of the technology as a function of the parameters which affect road pavement performance, namely: geometry, structural design, maintenance history, traffic composition and natural environment (i.e. climate, soil type and topography).

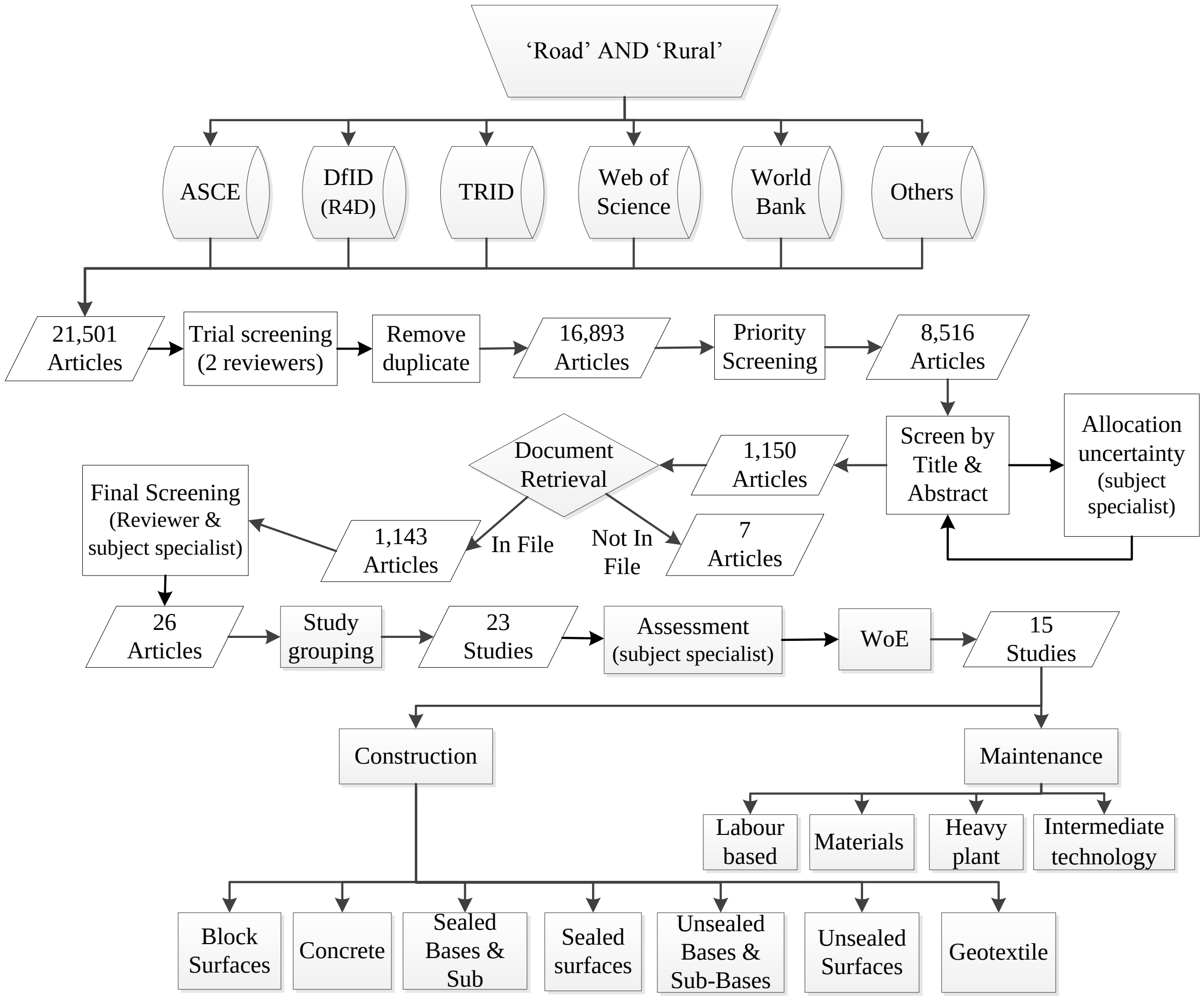

Figure 1: The searching process

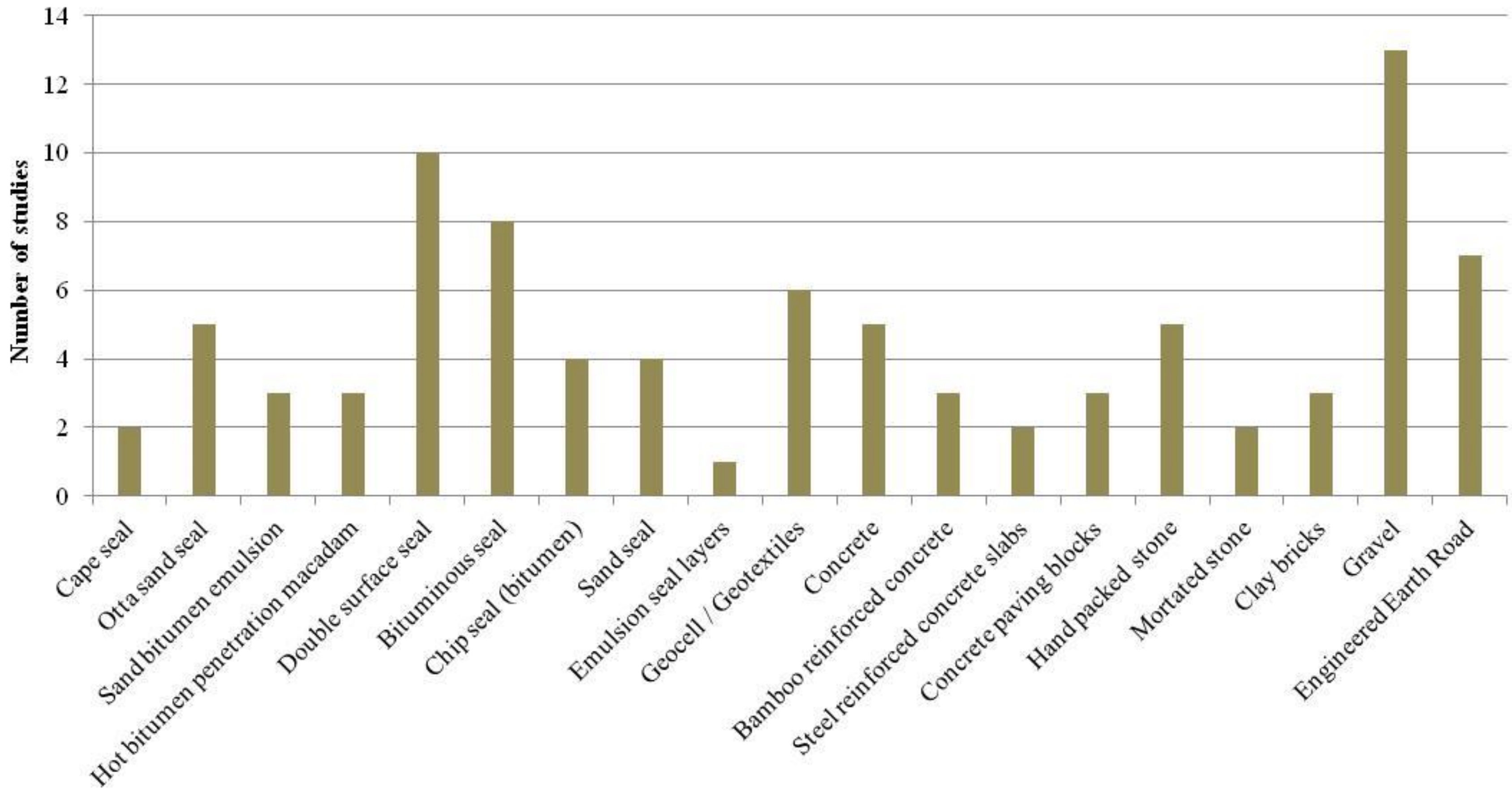

Figure 2: Rural road pavement construction technologies studied

Summary of main findings

Fifteen high quality studies were identified which provided quantitative data which could be synthesised to answer the primary review question. Fourteen of the studies were associated with the materials used for the construction of LVRR (see Figure 2) and one was to do with the means of carrying out maintenance.

Road pavement construction

Block surfaces

Two studies (Roughton, 2013b; TRL, 2009) described the results of trials to assess the performance over 2–5 years of four types of block surfaces i.e. clay-fired brick, concrete bricks, dressed stone and cobble stones (see Figure 3).

The extent to which block pavements may be considered a viable option for LVRR surfacing was found to be influenced by:

(i) the quality of construction

(ii) the compliance with brick crushing strength specifications (20-25 MPa)

(iii) timely routine maintenance

(iv) the low tensile strength of joints.

The studies showed that all of the block surfaces considered are a sustainable option and are particularly suited to high rainfall (>2000 mm/year) and weak subgrade environments (i.e. CBR<10%.). The most durable surface was found to be dressed stone/cobble, which could be considered to be the most sustainable when the stones can be locally sourced and shaped. Fired clay and concrete bricks are less sustainable since they require energy to produce.

Dressed stone/cobble surfaces, however, have a high roughness and therefore may not be suitable where it is important to minimise road-user costs. The high roughness of these surfaces was also found to encourage motorcyclists and cyclists to use the road shoulder, causing edge wear which over time may cause water ingress into the pavement structure, accelerating deterioration.

Figure 3: Construction of a dressed stone LVRR

Concrete road surfaces

Concrete road surfaces appear to provide an advantage over most other surfaces since they have low roughness when constructed properly, and require little maintenance other than to the joints. However, they have high initial construction costs and therefore are mainly appropriate when all-season access with low road-user costs is required.

Two studies (TRL 2009; Roughton, 2013b) reported trials of concrete LVRRs in Vietnam, Cambodia and Lao PDR. Both studies described trials of bamboo reinforced and non-reinforced concrete slabs, one described the use of a concrete geocell and the other assessed steel-reinforced concrete.

The studies suggested that all four types of concrete surface performed satisfactorily in all environments considered. However the performance of the surfaces in terms of roughness was shown to be directly related to the quality of construction. Inter-slab joints required maintenance after 2–3 years of operation.

Concrete reinforced with steel pavements were found to perform only marginally better on weak subgrades compared to non-reinforced options and as steel is a finite resource and relatively expensive it may be surmised that steel is not a sustainable (or necessary) option.

Both studies showed that concrete sections reinforced with bamboo performed at least as well as those without reinforcement although bamboo-reinforced slabs were found to be more expensive to manufacture, in part due to the requirement to treat them chemically to prevent deterioration. However, a detailed supporting analysis carried out as part of one study (Roughton, 2013b) found that the bamboo disintegrated over time and did not therefore provide reinforcement in the long term.

Sealed surfaces

Sealing roads helps to prevent moisture ingress and provides a satisfactory all-season running surface which can reduce road-user costs through lower road roughness. As a consequence, seals can allow for the use of weaker (marginal) materials within the road pavement, or a reduced thickness of more competent materials.

Ten studies assessed the performance of a variety of seals (see Table 2) and established that sealed LVRRs are sustainable from a durability point of view. Many of the roads examined were found to be performing adequately after the expected lifetime of the seal, despite little or no maintenance, overloading in a number of cases and the use of materials below the recommended standards. One study (Pinard, 2011) suggested that this might indicate excessive over-design.

The review found that the extra thickness of surfacing material provided by double surface dressings and Cape seals makes them the most durable of the seals considered in a wide range of environments, particularly where gradients are steep, at the expense however of higher initial construction costs. In low-rainfall environments where low road roughness is a requirement (for example to transport agricultural goods to market undamaged), an emulsion sand seal may be an appropriate solution as it provides a satisfactory running surface and can be produced and maintained using locally available resources at low cost. Where the annual rainfall is in excess of 2,000 mm/year and low road roughness is required, bitumen, macadam-based seals, or emulsion seals with stone chips, may be a more appropriate choice. However, it should be noted that most seals require the use of scarce material resources and, with the exception of emulsion stone chip seals, necessitate the use of mechanical equipment to construct and maintain.

Construction and maintenance requirements

Poor construction quality was found to affect greatly the performance of both the seal and the road pavement. The studies reported that contractors who had developed prior experience of seals through the construction of trial sections performed better than contractors without such experience.

Seals deteriorate over time and it is vital therefore that timely routine maintenance is carried out to fix edge breaks, patch potholes and seal cracks. Routine maintenance prevents water ingress into the road structure and therefore prevents the softening of the subgrade and possible premature failure. Routine maintenance notwithstanding, periodic re-sealing is required after approximately five years (for single seals) and ten years (for double surfaced dressed seals) (depending on environmental conditions and to a lesser extent on the cumulative traffic loading).

Base and sub-base performance

The performance of seals can be influenced by the base, sub-base or subgrade performance. Lionjanga et al. (1987), for example, demonstrated a link between reflection cracking in seals and lime- or cement-stabilised bases.

Shoulders

Four studies (Rolt et al. (2013); Roughton (2013b); TRL (2009) and Newill et al. (1987)) demonstrated the benefit of sealing the shoulders of LVRRs, enabling a more stable moisture content regime to be maintained under the road pavement, particularly during periods of high rainfall. Sealed shoulders, in conjunction with an adequately designed road drainage system, facilitate the movement of moisture away from the wheel track thereby preventing the softening of load-bearing fine-grained subgrades and hence inhibiting accelerated road deterioration.

Table 2: Studies of seals

Authors	Technologies	Trial	Environment	Outcome (+/-sustainability)
Bhasin et al. (1987)	Within sealed and unsealed roads	5 yr monitoring of trial sections in India	Average annual rainfall: <1,000 mm/yr.; AADT: <300	(+) Seals render Kankar sustainable as base/sub-base
Gourley and Greening (1999)	Seals for Quartzitic, lateritic, calcareous gravels & sand road / sub bases	Back-analysis roads Botswana, Malawi and Zimbabwe	Climate: N-values of ~2 <N <5; Design traffic: 0.05-0.8m ESA; Subgrade CBR 15-30%	(+) Seals enable natural gravel road base materials to be used successfully
Lionjanga et al. (1987)	Locally available calcrete bases & sub-bases in sealed LVRRs.	7-year study of 9 x 100m sections; Botswana	Rainfall: 200- 800 mm & AADT 180-260 mvpd, during experiment; Gradient: 1 in 6	(+) Calcretes as road bases and sub-bases (-) Stabilised materials
Newill et al. (1987)	Seals for volcanic cinder gravel bases and sub-bases	7½ year trial road sections in Ethiopia	Rainfall: ~750 mm/yr; AADT: 150–200 mvpd	(+) Surfaced dressed sections (-) Unsealed gravel roads
Pinard (2011)	2-layered sealed, upgraded gravel LVRRs	Back analysis 2 & 3-layer roads; Malawi	Rainfall: 600-1200 mm/yr. Traffic:~300 mvpd/0.5m ESA	(+) 2-layer pavement system for upgrading gravel roads
Rolt et al. (2013)	Marginal materials	Back analysis of LVSR up to 10 years old; Mozambique	Rainfall: 532–1288 mm; AADT: 166–993 mvpd	(+) Structural condition (+-) Functional condition

Authors	Technologies	Trial	Environment	Outcome (+/-sustainability)
Roughton (2013b)	Double Otta, single Otta with sand & sand seals	5yr trial of road sections. Lao PDR	Rainfall: 1,300-1,500 mm/yr; Traffic: 126,000 ESALs Gradients: Flat (0–3%) to steep (10%-15%)	(+) Otta seals with routine maintenance & periodic resealing (5yrs for single seal, 10 yrs for double seal)
Sahoo et al. (2014)	Thin (20 mm) bituminous surfacing of LVRRs	6½yr monitoring roads built to Indian Road Congress specs	Rainfall: 1,435-2,252 mm/yr; AADT 68-281 cvpd; Subgrade 41-119 MPa	(+) Assuming maintenance after 5 years, 84% of sections performing satisfactorily
TRL (2009)	Thin flexible seals: Double stone chip / sand bitumen emulsions; Triple bitumen surfacing; Pen. macadam; Otta Seal; Dry / water bound macadam; S & DBST; armoured gravel	24–37 mth monitoring of roads built to DCP design method. Vietnam and Cambodia	Rainfall: 1,400–3000 mm/yr; Traffic 1,000-330,000 ESALS; Flat to steep gradients	(+) Pen. macadam and bitumen DBST emulsion most durable options
Wason & Oli (1982)	Moorum road bases/sub-bases in sealed roads	20 sections monitored 4 times in 16 years; India	Rainfall: <1,000 mm/yr; Traffic: 100-150 carts & 10-15 heavy vehicles per day	(+) Sealed surfacing enables use of moorum as base/ sub-base

Bases and sub-bases

The ten studies listed in Table 2 also reported the performance of LVRR sealed roads constructed with a variety of bases and sub-bases. The studies found that in general, LVRRs performed satisfactory from a functional and structural point of view, provided that the road was sealed, designed appropriately and well-constructed. Without periodic maintenance, roads with a single surface dressing started to show signs of significant deterioration after approximately five years (i.e. when resealing would be expected).

Unconventional pavement designs

Many road design procedures used in LICs suggest three-layer road pavement systems to carry adequately traffic loads experienced on high volume roads. These designs have been adopted for LVRRs despite their low traffic volumes. However, two slice-in-time studies by Rolt et al. (2013) and Pinard (2011), investigated the performance of a number of two-layered sealed LVRRs founded on relatively strong subgrades (i.e. CBR ≥30%). The studies showed that in many environments, two-layer designs perform satisfactorily (and beyond their design life in many cases), reducing construction costs by between 166-233%.

Stabilisation

In three of the studies (Lionjanga et al., (1987); Newill et al. (1987) and Wason and Oli (1982)), the performance of marginal materials was found to be enhanced by chemical stabilisation (with lime and/or cement) provided that the stabilisation had been applied according to appropriate standards. Newill et al. (1987) also demonstrated that the behaviour of marginal materials with inappropriate grading characteristics could be enhanced by mechanical stabilisation with fines. Lionjanga et al. (1987) found that roads with bases made of stabilised calcretes did not perform satisfactorily. This was attributed to the lack of a stabilisation reaction in the calcrete and the consequent instability of the bases under traffic loads.

Engineered earth roads (EERs)

Although EERs provide the majority of access for most communities in LICs/LMICs only one high quality study was identified. This slice-in-time study by Rolt et al. (2008) assessed the performance of a large number of existing EERs in Cambodia. The different environments considered by the study were of limited variety in comparison to those which occur in all LICs/LMICs and therefore the study may be considered of limited applicability. Nevertheless, the study shows that a wide range of soils can be used to provide an adequate surface for motorised traffic of up to 50 vpd and higher (particularly if heavy trucks are absent) and in climates with rainfall up to 2,000 mm/year.

Construction and maintenance requirements

Taking into account the findings from the identified study, the generic prerequisites for the sustainable use of EERs include:

- In situ soil soaked strength of CBR ≥15%, although findings from research in non-LICs (Ahlvin and Hammitt, 1975) suggest that lower strengths (CBR >8%) may be sufficient albeit with higher maintenance requirements. Figure 4shows the in situ assessment of the strength of an EER.
- Adequate design with emphasis on drainage including sufficient camber, side, turnout and cross drains arrangements
- Regular routine maintenance of camber and drainage.
- The longitudinal gradient, which progressively increases surface erosion and maintenance requirements, should be limited to below 6%.

Figure 4: In-situ Dynamic Cone Penetrometer test of an Engineered Earth LVRR

Gravel roads

For many years, natural gravel has been the commonly accepted solution for providing all season rural access in developing regions. However, limited and depleted sources of gravel, life-cycle cost and both maintenance and environmental sustainability issues have prompted reconsideration of its use.

The included studies (see Table 3) examined the performance of gravel roads in terms of road condition and the amount of gravel loss as a function of a number of factors, including gravel type and the environment. Although technically feasible for a wide range of situations, the sustainability of natural gravel surfacing was shown to be vitally dependent on a range of influential factors. The factors include:

- achieving appropriate specifications relating to particle grading, plasticity and strength
- restricting application to roads carrying traffic of less than 200 vpd
- restricting application to environments with a rainfall of less than 2,000 mm/year and longitudinal gradients of less than 6%
- ensuring the provision and maintenance of adequate camber and run-off arrangements through side drains, turnout (mitre) drains and cross drainage
- timely provision of re-gravelling to replace material losses.

Table 3: Gravel road studies

Authors	Technologies	Trial	Environment	Outcome (+/- sustainability)
Bhasin et al. (1987)	Within sealed and unsealed roads	5 yr monitoring of trial sections in India	Average annual rainfall: <1,000 mm/yr.; AADT: <300	(+-) Sustainable within a sealed road pavement only
Cook and Petts (2005)	Gravel roads	Back analysis of roads in Vietnam	Rainfall: 800-4,000 mm/yr; AADT: <200; Gradient: > 6%	(-) Gravel roads unsustainable
Hodges et al. (1975)	Lateritic, coral, volcanic, quartzitic, gravel	2-yr monitoring of existing roads in Kenya	Rainfall: 400–2,000 mm/yr; AADT: 25–200; Gradient: 0-5.5%	(-) Gravel roads unsustainable
Jones (1984b)	Lateritic, coral, volcanic, quartzitic, gravel	2-4 yr monitoring of existing roads in Kenya	Rainfall: 500-2,000 mm/yr; Annual traffic: 1,533-81,760	(-) Sustainable for 50–200 vpd depending on gravel
Newill et al. (1987)	Volcanic cinder gravel surfaces	2 yr monitoring of sections in Ethiopia	Rainfall: ~750 mm/yr; AADT: 150–200 vpd	(-) Gravel roads unsustainable
Roughton (2013b)	Gravel control sections within a wider study of alternative surfacing.	5 yr monitoring of trial sections in Lao PDR	Rainfall:~1,500mm/yr; Traffic: 126,000 ESALs; Gradient: flat (0–3%) to steep (10-15%)	(+-) Sustainable when sealed, and providing that resealing can take place periodically
TRL (2009)	Gravel control sections within in a wider study of. alternative surfacing.	24-37 month monitoring of trial sections in. Vietnam and Cambodia	Rainfall : 1,400–3,000 mm/yr Traffic 1,000-330,000 ESALS Gradient: flat to steep	(+-) Sustainable when sealed, and providing that resealing can take place periodically

Road maintenance approaches

The impact of road maintenance approaches on LVRR sustainability

High-income countries aim to mechanise maintenance, as labour is expensive and productivity can nearly always be increased using technology. However, in LICs and LMICs, heavy plant and its operation are significantly more expensive than readily available labour. In addition, heavy plant (and replacement parts), are mainly imported and are therefore problematic to maintain. Thus maintenance of unpaved LVRRs offers scope for both intermediate equipment and labour.

The effectiveness of three different maintenance approaches (heavy equipment, intermediate equipment or labour-intensive) was reported by Jones (1984a). The study showed that intermediate technologies (see Figure 5) that were less expensive in terms of capital expenditure (e.g. tractor towed graders) and more labour-intensive could be considered at least as sustainable as heavy equipment (e.g. a mechanical grader). However, to achieve similar results it was found that labour-intensive technology requires adequate supervision and less-expensive technologies require more frequent maintenance cycles.

Figure 5: Tractor-towed grader in operation

Discussion

The review showed that the large majority of the technologies identified may be considered to be sustainable from an engineering point of view provided that their design, construction and maintenance are robust. However, the behaviour of roads over time is complex and can be affected by a number of factors, including the environment in which they operate, the design specification to which they are built, the way they are constructed, the quality of construction, the behaviour of their constituent materials and the frequency and effectiveness of their maintenance regimes. Further, the behaviour of an individual component within a road is also influenced by the performance of other components. Therefore since LVRRs deteriorate over time, monitoring programmes lasting at least until a component of the road has reached the limits of its physical life, are required to properly assess durability. During this time, the performance of the road and the environment should also be periodically recorded. Since many sealed LVRRs are designed to last in the region of 20 years, with perhaps the application of up to two to three planned periodic maintenance treatments in that time, it may be argued that such experiments, should take place over at least two planned maintenance cycles so that the effect of maintenance may be established and life-cycle costs determined. Clearly these types of experiments are costly and problematic to undertake. In this review, only one study took place over such a period (Wason and Oli, 1982), although road condition data were captured on only four occasions. Five other studies that reported experiments to determine the performance of LVRRs and their components took place over 5-7.5 years and one other described an experiment which lasted between 2 and 3 years (see Table 2 and Table 3). None of these studies, however, captured the impacts of maintenance. Three other slice-in-time studies (Rolt et al. 2013; Pinard, 2011, and Gourley and Greening, 1999) captured the performance of roads at different stages of their life-cycles and considered the impacts of maintenance Five studies indicated the environmental conditions in which gravel and/or earth roads may perform satisfactorily; one of these took into account the effects of maintenance (Jones, 1984a).

Considering that the vast majority of road transport routes in developing regions are still EERs and many communities rely on these for access, there appears to be a lack of research into EERs.

To this end and to address the above issues in an integrated fashion Table 4 provides a framework to assess the sustainability of the technologies against some key indicators. The average score provided has been calculated assuming that each of the key indicators has the same weighting, and should only be considered as a guide to the sustainability of any of the technologies in a given context or environment. However, to use the approach in practice a weighting should be applied to each indicator to reflect the particular environment at hand. For example, in a region which has a relatively strong subgrade and where it is necessary to have roads of low roughness (for example to minimise the cost of transporting crops which are easily damaged by rough roads) a lower weighting could be given to the indicator "Suitability for use on weak subgrades" and a relatively higher one to that associated with "Achieved road serviceability". There a variety of approaches which could utilize expert opinion to determine weighting factors (see for example, Saaty (1980)).

Table 4: Trial technologies against some key markers (after Roughton (2013b) and TRL (2009))

		Measure of sustainability													
	Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak subgrades**	**Small contractor suitability**	**Local economy advantages**	**Resistance to axle overloading**	**Initial cost**	**Possible whole life cost advantage**	**Environmental impact**	**Achieved road serviceability**	**AVERAGE SCORE**
Surfaces	Emulsion sand seals	1	1	1	3	4	3	1	2	3	1	3	2	2	2.1
	Emulsion stone chip seals	3	1	2	2	2	3	1	2	3	2	2	2	2	2.1
	Sealed dry-bound macadam	3	3	2	1	2	2	2	3	2	2	2	3	2	2.2
	Sealed water-bound macadam	3	3	2	1	2	3	2	3	2	2	2	3	2	2.3
	Hot bitumen stone chip seals	3	2	2	2	2	3	2	2	3	2	2	3	2	2.3

Measure of sustainability

	Technology	Local/marginal material	Labour based	Simplicity of construction	Maintainability	Suitability in high rainfall environs	Suitability for use on weak subgrades	Small contractor suitability	Local economy advantages	Resistance to axle overloading	Initial cost	Possible whole life cost advantage	Environmental impact	Achieved road serviceability	AVERAGE SCORE
	Penetration macadam	3	3	2	2	2	3	2	2	3	2	2	4	2	2.5
	Unsealed water-bound macadam	2	2	2	4	4	3	2	3	3	1	4	3	4	2.8
	Otta seals	4	2	2	2	2	2	2	3	2	2	2	3	2	2.3
	Sealed armoured gravel	2	3	2	2	2	3	2	3	4	2	2	2	2	2.4
Block surfaces	Dressed stone/cobbles	1	1	2	2	1	1	1	1	1	3	2	1	4	1.6
	Fired clay bricks	1	1	2	2	3	1	1	1	2	2	2	2	3	1.8
	Concrete bricks	2	1	2	2	3	1	1	2	1	3	2	1	2	1.8
Concrete surfaces	Steel-reinforced concrete	2	2	3	1	1	1	2	3	1	4	2	3	1	2.0
	Bamboo-reinforced concrete	2	2	2	1	1	2	1	2	1	4	2	2	1	1.8
	Non-reinforced concrete	2	2	2	1	1	2	1	2	1	4	2	2	1	1.8
Bases	Lime stabilised base/sub-base	1	2	3	3	3	3	1	2	2	2	2	3	3	2.3
	Cement stabilised base/sub-base	1	2	3	3	2	3	1	2	2	2	2	2	3	2.2

Measure of sustainability

Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak subgrades**	**Small contractor suitability**	**Local economy advantages**	**Resistance to axle overloading**	**Initial cost**	**Possible whole life cost advantage**	**Environmental impact**	**Achieved road serviceability**	**AVERAGE SCORE**
Emulsion stabilised sub-base	1	4	4	2	2	3	4	3	2	3	2	4	3	2.8
Two-layer pavements	1	3	1	3	2	2	1	2	3	1	3	3	2	2.1
Unsealed natural gravel	1	3	1	4	4	4	1	2	3	1	3	3	3	2.5
Engineered earth roads	1	2	1	3	4	3	1	2	3	1	3	1	3	2.2

1= advantages; 2=possible advantages; 3=neutral; 4 = disadvantages. An average value of less than 3 may suggest that the technology may be considered to be sustainable when used appropriately.

There were also other issues associated with assessing sustainability. For example, none of the studies considered in this review were able to address whether the trialled technologies were economically, socially and environmentally sustainable. Several studies, however, recognised the complexity of these issues (e.g. TRL, 2009; Roughton, 2013b). Studies are required therefore, which will build on the concepts presented, such as environmentally optimised design (TRL, 2009). Others are required which can consider, at the strategic level, the economic, environmental and social sustainability of a variety of rural road design, construction, maintenance and rehabilitation options. In the light of climate change, studies should be carried out to examine how predicted changes in the climate and the occurrence of extreme weather events in particular, may influence both strategy and design choices of LVRRs.

Road institutions context

It is important to note that the selection of a sustainable technology is related not just to the technology itself, but also to the institutional structure of the road administration in which the technology is implemented. For example, sustainability depends on the country context and on the parallel interventions that might be put in place, such a training of local engineers and contractors to make the chosen technology work as effectively as possible.

Selecting a sustainable technology needs to be viewed from the perspective of the decision maker who triggers the construction of a new road or agrees to provide funds for maintenance. This could be a donor agency, a road fund, the ministry of finance or local government, or other responsible ministry. Sustainability therefore needs to be considered in the context of the way road organisations are managed. Examples include:

(i) **Roads managed and financed by a traditional district council**. Typically, there is an acute shortage of qualified technical staff; work is often done by force account, but may also be carried out by local contractors. Design and supervision is problematic and therefore sustainable LVRR technology should be:

- simple and easy to implement with little supervision
- robust enough to remain serviceable without regular routine and periodic maintenance
- inexpensive and use locally available materials
- capable of having routine maintenance carried out by local villagers with minimal training.

(ii) **Roads managed and financed by a central government roads department** Typically a special-purpose rural roads department exists to manage the roads. Usually such organisations are given reasonable budgets for maintenance and employ technically qualified staff including private-sector contractors. Sustainable technology in this context:

- could use advanced engineering technology
- should not require close supervision of construction and maintenance
- should be robust enough to perform adequately under irregular (and often underfunded) maintenance.

(iii) **Contracted out management and maintenance**

Here the roads are managed and maintained by consultants and contractors working as agents for the local road agencies. Within a competitive enabling environment, all road works are audited. In such cases sustainable technology can use cutting-edge engineering technology, because the work is properly designed, the contractor is effectively supervised and all work is subject to a detailed financial audit.

Other factors not present in the studies

It was hoped at the outset of the review that studies would be found which could provide evidence of the use of non-engineering driven technologies, to facilitate for example:

- the development of policies and strategies
- the appraisal of investment in rural road technologies. Economic tools, such as HDM-4, have been used on behalf of road agencies and donor organisations to assess the economic benefits of high volume roads. Such tools perform life cycle analyses based on agency and road user costs. However, in the LVRR context it would be necessary to utilize the findings from these tools within a multi-criteria approach which may capture the wider socio-economic benefits more satisfactorily (see for example Ortiz-Garcıa et al., (2005)).
- the management of construction and maintenance of LVRRs.

Conclusions

There is a sufficient evidence base of technologies which can be used to improve upon the functional and structural performance of earth or gravel LVRRs in LICs/LMICs. These technologies may be considered to be sustainable in engineering terms in specific environments. It is not possible, strictly from the evidence of the review alone, to suggest that these technologies are financially, economically, operationally, environmentally or socially sustainable in all environments. However, the evidence suggests that well-designed roads using available resources, under good construction supervision and subject to appropriate maintenance practice will yield a sustainable road from a wide variety of materials in a wide variety of environments. Further, the selection of sustainable technologies to suit any particular environment may be inferred from the body of existing research based on sound criteria and subsequent analysis drawing on the wealth of existing experience.

It is important to stress that the findings of this review should be considered in a holistic manner by taking into account not only the explicit engineering driven knowledge extracted but also the wider social, economic and institutional environment of the road sector. By so doing the value of the review may be maximised and the findings can be transferred to other contexts. This can be achieved with the use of engineering judgement and expertise that will aim at identifying the commonalities of the prevailing conditions. In particular, the sustainability of the technology should be examined following a methodology such as that suggested in this paper based on appropriately defined measures and associated weighting factors that reflect sufficiently the conditions in the environments concerned.

Recommendations for policy and practice

To consider revising LVRR design standards so that they are performance-based rather than specification-based. This would encourage further innovation including:

(i) two-layered LVRR pavement designs

(ii) the use of marginal materials

(iii) the use of alternative surface materials

(iv) the development of environmentally optimised design

(v) feasible technology options

(vi) the development of more effective quality assurance regimes

To encourage whole-life cost approaches which consider adequately the construction, maintenance and vehicle operating, accident and environmental costs, and the whole-life socio-economic benefits.

To provide a facilitating environment that ensures that LVRRs are constructed to the given design, materials and construction standards.

To introduce effective asset management practices.

To consider institutional and political parallel interventions which may be in existence, or put in place (e.g. the training of local engineers, and contracts), to make the chosen technology work as effectively as possible.

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